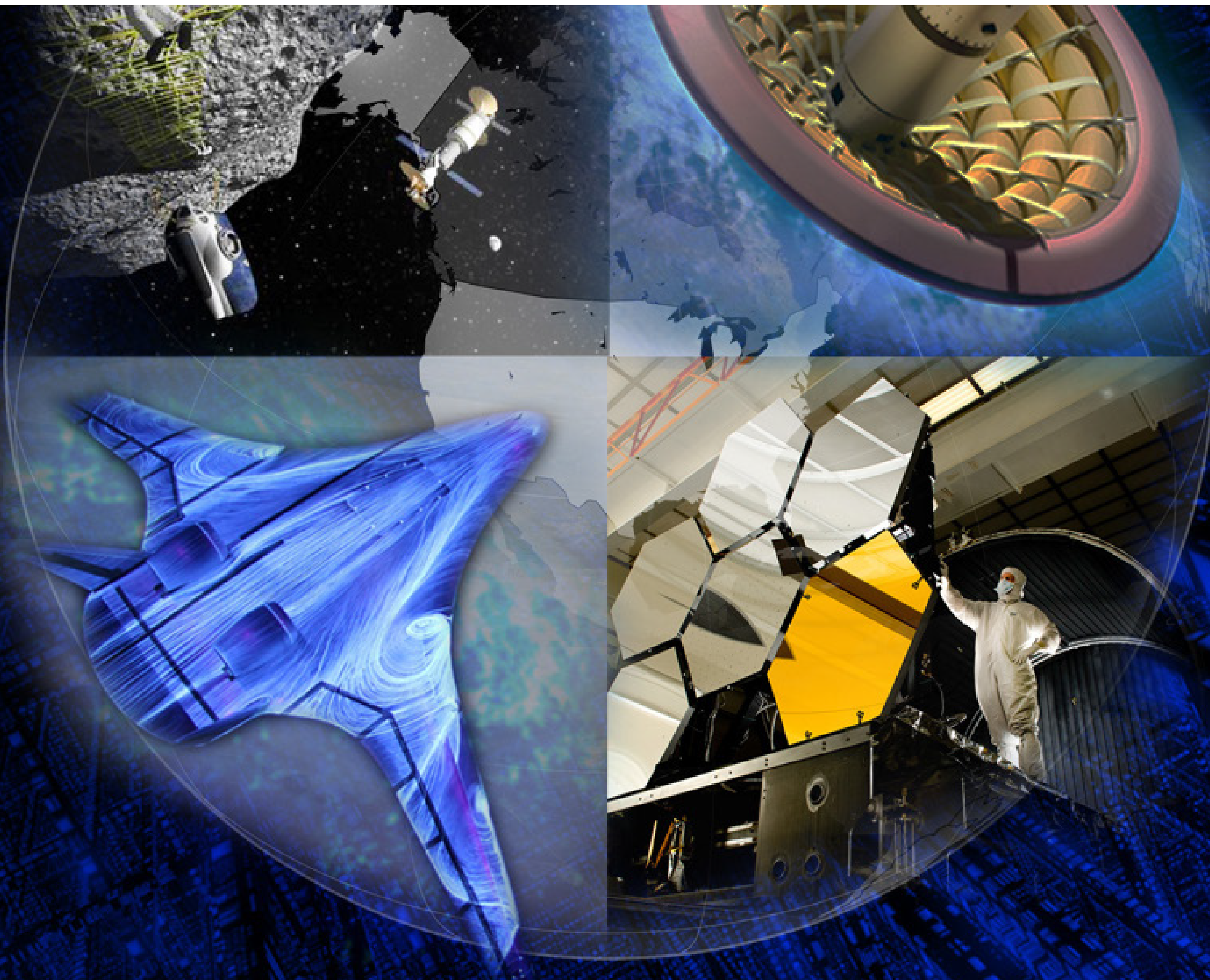
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 4: Robotics and Autonomous Systems

The 2015 NASA Technology Roadmaps have been replaced with the 2020 NASA Technology Taxonomy and the NASA Strategic Technology Integration Framework.

Note: The 2015 NASA Technology Roadmaps will be archived and remain accessible via their current Internet address as well as via the new 2020 NASA Technology Taxonomy Internet page. Please visit https://www.nasa.gov/offices/oct/home/taxonomy to see the Taxonomy.



July **2015**

Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The NASA 2015 Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

Table of Contents

Executive Summary

This is Technology Area (TA) 4: Robotics and Autonomous Systems, one of 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

In the coming decades, robotics and autonomous systems will continue to change the way space is explored in even more fundamental ways, impacting both human and science exploration. For human exploration, the goal is to leverage robots in all phases: as precursor explorers that precede crewed missions, as crew helpers in space, and as caretakers of assets left behind. As humans continue to work and live in space, they will start relying on intelligent and versatile robots to perform mundane activities, freeing human and ground teams to tend to more challenging tasks that call for human cognition and judgment. For science exploration, future generations will continue to send space robots to blaze new trails on distant and hostile worlds, extending the reach of the human race. Smarter and more agile space robots will be better equipped to sense and react to anomalies onboard, making them less dependent on the ground crew. Robots will play a key role in the surveying, observation, extraction, and close examination of planetary surfaces, their natural phenomena, their terrain composition, and their resources. The information they gather will further our understanding of the origins and dynamics of our solar system and expand our knowledge of the universe. For both human and science missions, robots will also play a crucial role in in-space operations, whether it be for assembling a large space telescope, capturing and returning an asteroid, repairing a satellite, deploying an infrastructure on a planetary surface for subsequent human arrival, mining space resources, or deploying assets for a scientific investigation.

Goals

The goal of robotics and autonomous systems is to extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources to help us understand planetary bodies using remote and in-situ sensors, prepare them for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations. Advances in robotic sensing and perception, mobility and manipulation, rendezvous and docking, onboard and ground-based autonomous capabilities, and human-systems integration will drive these goals.

Table 1. Summary of Level 2 Technology Areas

4.0 Robotics and Autonomous Systems	**Goals:**	**Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.**
4.1 Sensing and Perception	Sub-Goals:	Provide situational awareness for exploration robots, human-assistive robots, and autonomous spacecraft; and improve drones and piloted aircraft.
4.2 Mobility	Sub-Goals:	Reach and operate at sites of scientific interest in extreme surface terrain or free-space environments.
4.3 Manipulation	Sub-Goals:	Increase manipulator dexterity and reactivity to external forces and conditions while reducing overall mass and launch volume and increasing power efficiency.
4.4 Human-System Interaction	Sub-Goals:	Enable a human to rapidly understand the state of the system under control and effectively direct its actions towards a new desired state.
4.5 System-Level Autonomy	Sub-Goals:	Enable extended-duration operations without human intervention to improve overall performance of human exploration, robotic missions, and aeronautics applications.

Table 1. Summary of Level 2 Technology Areas - Continued

4.0 Robotics and Autonomous Systems	**Goals:**	**Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.**
4.6 Autonomous Rendezvous and Docking	Sub-Goals:	Provide a robust and safe autonomous rendezvous and docking capability for human and robotic systems.
4.7 Systems Engineering	Sub-Goals:	Provides a framework for understanding and coordinating the complex interactions of robotic systems and achieving the desired system requirements.

Benefits

Robotics and autonomous systems will enable the next frontier in exploration by providing greater access beyond human spaceflight limitations in the harsh environment of space and by providing greater operational handling that extends astronauts' capabilities. Autonomous systems would reduce the cognitive load on humans given the abundance of information that has to be reasoned upon in a timely fashion. They will be critical for improving human and system safety. Robotics and autonomy are also a force multiplier, enabling the deployment and operation of multiple assets without an equivalent increase in ground support. These technologies would reduce the cost and risk of spaceflight, both human and robotic, across all its phases: development, flight unit production, launch, and operations.

External to NASA, the benefits of robotics and autonomous systems are increasingly visible. Their growth in government, industrial, and commercial applications is a testament to the impact that they will have over the next two decades. Examples of their use include manufacturing, transportation (air-traffic management, air transport, self-driving vehicles, and electric cars), energy (smart grids), space (on-orbit inspection and repair, mining), agriculture, healthcare (prosthetics, rehabilitation, surgery), marine environments, education (inspiring science, technology, engineering and mathematics education), public safety (emergency response, hazardous material handling, bomb disposal), and consumer products (household robots). Relevant advances would be leveraged and adapted for NASA's robotics and autonomous systems

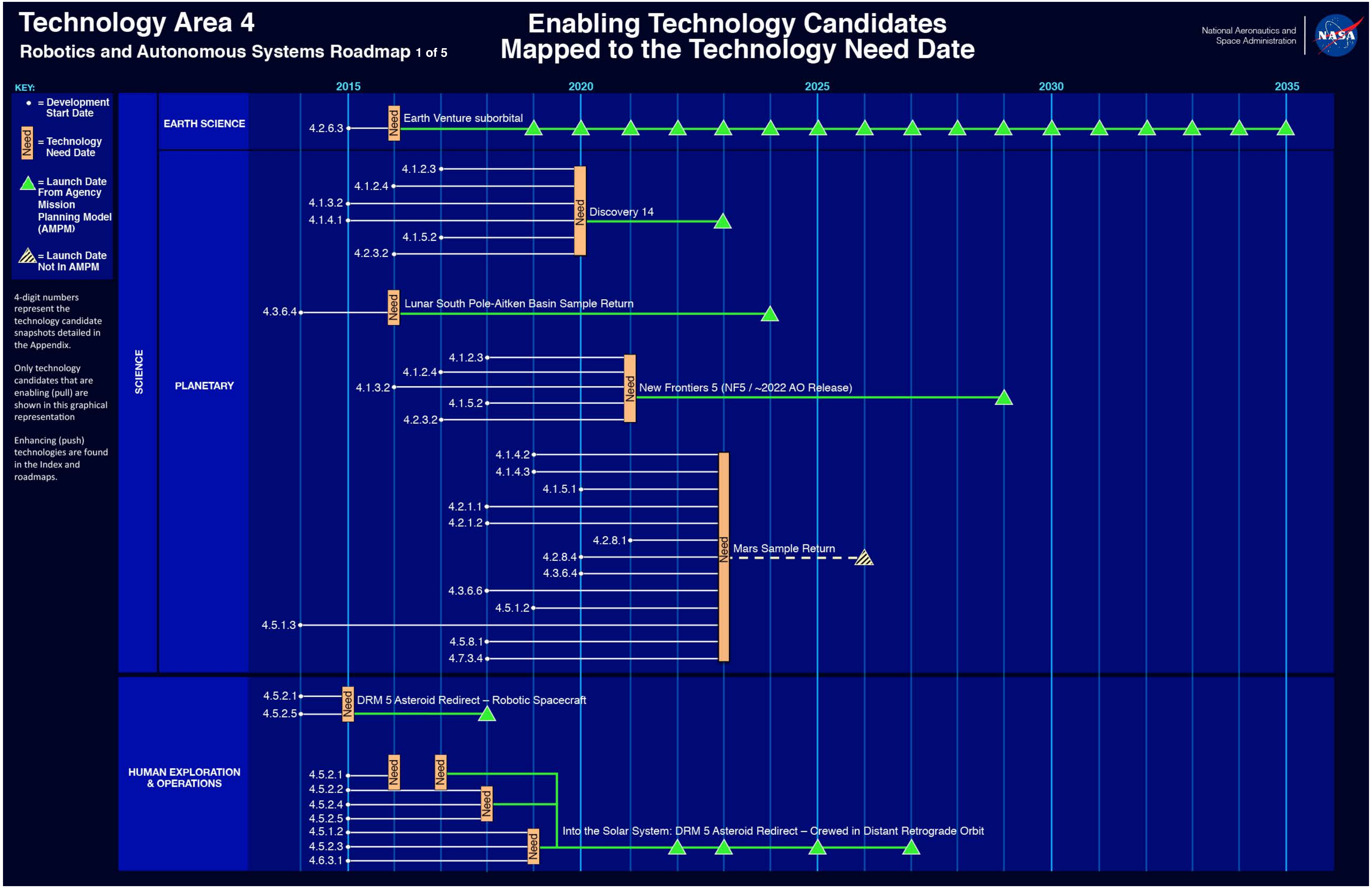


Figure 1. Technology Area Strategic Roadmap

Technology Area 4

Robotics and Autonomous Systems Roadmap 2 of 5

Enabling Technology Candidates Mapped to the Technology Need Date

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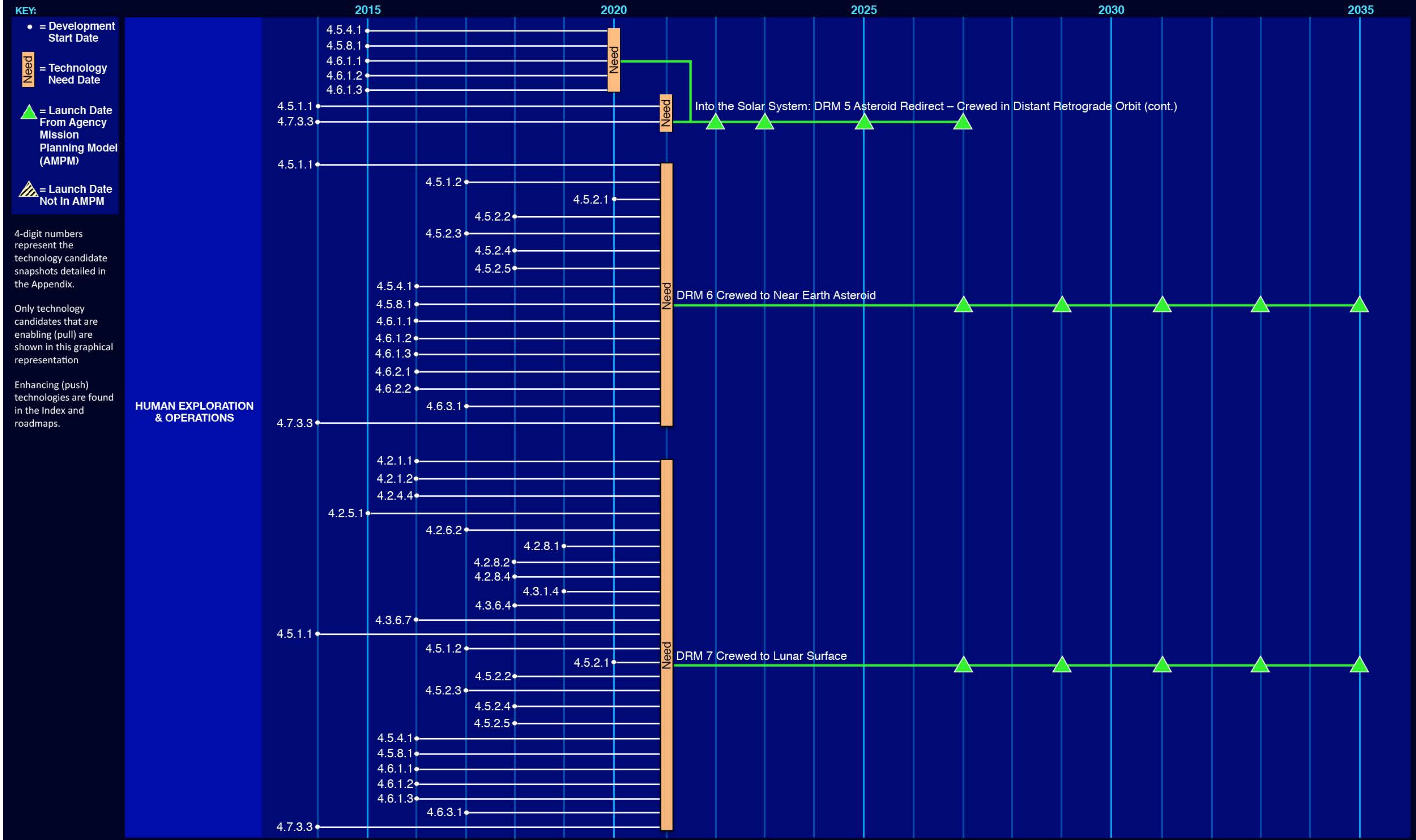

Figure 1. Technology Area Strategic Roadmap (Continued)

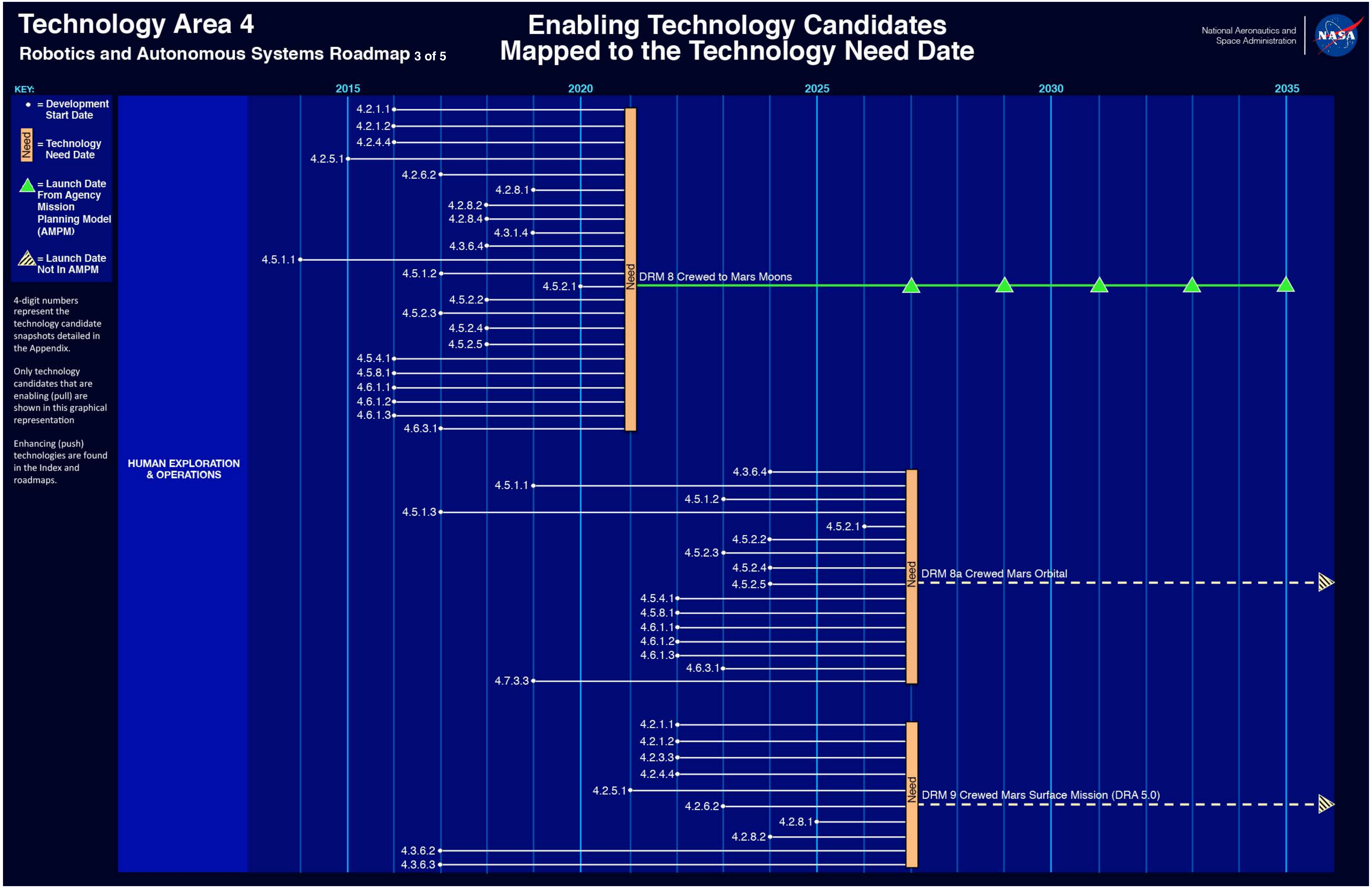

Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 4

Robotics and Autonomous Systems Roadmap 4 of 5

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

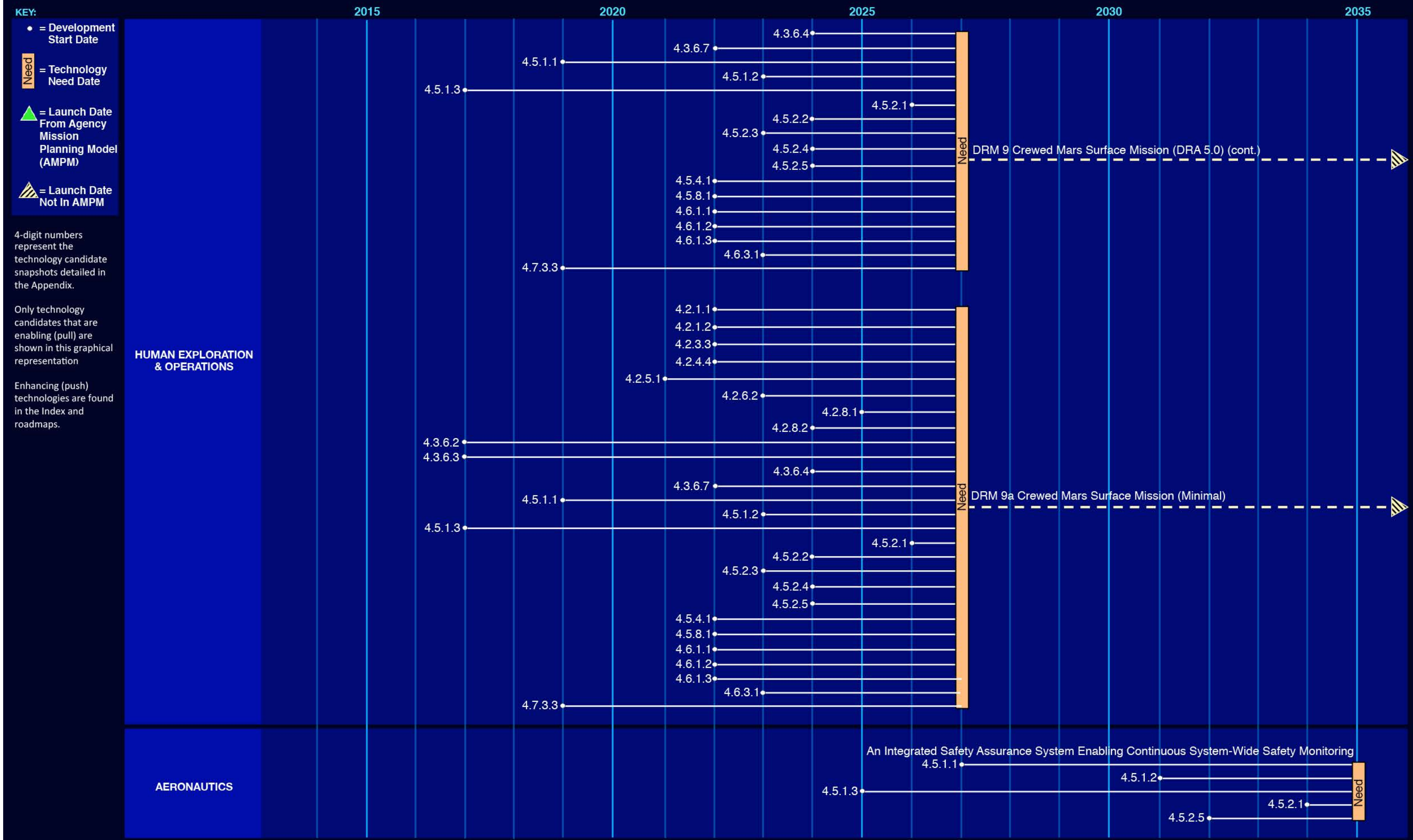

Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 4
Robotics and Autonomous Systems Roadmap 5 of 5

Enabling Technology Candidates Mapped to the Technology Need Date

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4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

The Robotics and Autonomous Systems roadmap follows a breakdown of capabilities and technologies relevant to NASA's missions over the next two decades (Figure 2). These include areas of sensing and perception, mobility, manipulation, human-system integration, system-level autonomy, autonomous rendezvous and docking, and systems engineering. Autonomy (both system- and subsystem-level), cognition, and machine learning are an integral part that span all subareas, including object, event, and activity recognition; robot navigation; dexterous manipulation; intent recognition and reaction; and rendezvous and docking.

4.1 Sensing and Perception

Sensing and Perception seeks to develop new sensors, sensing techniques, and algorithms for three-dimensional (3D) perception; state estimation (including sensing and estimation of internal state); onboard mapping; object, event, or activity recognition; and force and tactile sensing.

Sensing and Perception technologies can be grouped in the following general categories:

- **4.1.1 3D Sensing:** provides 3D measurements of the environment for mobility and for surface and in-space manipulation.
- **4.1.2 State Estimation:** provides multi-sensor, vision-aided pose and velocity estimation for mobility and for manipulation (both objects being manipulated as well as their corresponding manipulators).
- **4.1.3 Onboard Mapping:** provides terrain maps (topographic and trafficability) and landmark models for surface and above-surface mobility and manipulation.
- **4.1.4 Object, Event, and Activity Recognition:** recognizes natural and human-made objects, natural dynamic events, and human activities near robot systems. See also TA 4.4.3 Proximate Interaction
- **4.1.5 Force and Tactile Sensing:** senses forces, torques, and contacts of the mobility or manipulation platform with the environment or with other platforms.
- **4.1.6 Onboard Science Data Analysis:** see TA 4.1.4 Object, Event, and Activity Recognition and TA 4.5.8 Automated Data Analysis for Decision Making.

4.2 Mobility

Mobility pertains to moving from one place to another in the environment, which is distinct from intentionally modifying that environment. Examples include mobility on, into, and above a planetary surface, which spans many forms, such as flying, walking, climbing, rappelling, tunneling, swimming, sailing, and thrusting.

Mobility technologies can be grouped into the following general categories:

- **4.2.1 Extreme-Terrain Mobility:** provides mobility across terrains with challenging topographies and challenging regolith properties for bodies with substantial gravity.
- **4.2.2 Below-Surface Mobility:** provides access to and mobility below a solid or liquid surface.
- **4.2.3 Above-Surface Mobility:** provides coverage of, access to, and mobility above planetary surfaces.
- **4.2.4 Small-Body and Microgravity Mobility:** provides mobility across surfaces of small bodies or microgravity environments without surface contact.
- **4.2.5 Surface Mobility:** provides efficient mobility across non-extreme terrains or liquid surfaces.
- **4.2.6 Robot Navigation:** provides autonomous and supervised mobility for surface, above-surface, and extreme terrains.

TA 4 Robotics and Autonomous Systems

4.1 Sensing and Perception

- 4.1.1 3D Sensing
- 4.1.2 State Estimation
- 4.1.3 Onboard Mapping
- 4.1.4 Object, Event, and Activity Recognition
- 4.1.5 Force and Tactile Sensing
- 4.1.6 Onboard Science Data Analysis

4.2 Mobility

- 4.2.1 Extreme-Terrain Mobility
- 4.2.2 Below-Surface Mobility
- 4.2.3 Above-Surface Mobility
- 4.2.4 Small-Body and Microgravity Mobility
- 4.2.5 Surface Mobility
- 4.2.6 Robot Navigation
- 4.2.7 Collaborative Mobility
- 4.2.8 Mobility Components

4.3 Manipulation

- 4.3.1 Manipulator Components
- 4.3.2 Dexterous Manipulation
- 4.3.3 Modeling of Contact Dynamics
- 4.3.4 Mobile Manipulation
- 4.3.5 Collaborative Manipulation
- 4.3.6 Sample Acquisition and Handling
- 4.3.7 Grappling

4.4 Human-System Interaction

- 4.4.1 Multi-Modal Interaction
- 4.4.2 Supervisory Control
- 4.4.3 Proximate Interaction
- 4.4.4 Intent Recognition and Reaction
- 4.4.5 Distributed Collaboration and Coordination
- 4.4.6 Common and Standard Human-System Interfaces
- 4.4.7 Safety, Trust, and Interfacing of Robotic and Human Proximity Operations
- 4.4.8 Remote Interaction

4.5 System-Level Autonomy

- 4.5.1 System Health Management
- 4.5.2 Activity Planning, Scheduling, and Execution
- 4.5.3 Autonomous Guidance and Control
- 4.5.4 Multi-Agent Coordination
- 4.5.5 Adjustable Autonomy
- 4.5.6 Terrain Relative Navigation
- 4.5.7 Path and Motion Planning with Uncertainty
- 4.5.8 Automated Data Analysis for Decision Making

4.6 Autonomous Rendezvous and Docking

- 4.6.1 Relative Navigation Sensors
- 4.6.2 GN&C Algorithms
- 4.6.3 Docking and Capture Mechanisms and Interfaces
- 4.6.4 Mission and System Managers for Autonomy and Automation

4.7 Systems Engineering

- 4.7.1 Modularity, Commonality, and Interfaces
- 4.7.2 Verification and Validation of Complex Adaptive Systems
- 4.7.3 Robot Modeling and Simulation
- 4.7.4 Robot Software
- 4.7.5 Safety and Trust

Figure 2. Technology Area Breakdown Structure for Robotics and Autonomous Systems

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

- **4.2.7 Collaborative Mobility:** provides a capability for autonomous collaboration among multiple mobility platforms or among robotic platforms and human teams to achieve greater functionality, coverage, and/or access.
- **4.2.8 Mobility Components:** provide key component technologies that impact the design of mobility systems to improve performance.

4.3 Manipulation

Manipulation pertains to making an intentional change in the environment or to objects that are being manipulated. Examples of manipulation include crew task positioning, moving and handling objects in the environment (for example, placing sensors and instruments on planetary bodies), assembling in space and on surfaces, excavating (digging, trenching, drilling), collecting and handling samples, grappling, and berthing. Embodiments of manipulators include arms, cables, fingers, scoops, and combinations of multiple limbs.

Manipulation technologies can be grouped into the following general categories:

- **4.3.1 Manipulator Components:** provide key components that impact the design of manipulators to improve their performance, such as actuators, controllers, and lightweight structures.
- **4.3.2 Dexterous Manipulation:** provides a capability to grasp, change the grasp of, and smoothly articulate objects (for example, positioning and orienting of objects), as well as manipulate interfaces on a spacecraft.
- **4.3.3 Modeling of Contact Dynamics:** see TA 4.7.3 Robot Modeling and Simulation. Relevant to both mobility and manipulation, in particular, for limbed platforms that intentionally make and break contact.
- **4.3.4 Mobile Manipulation:** provides a capability for coordinating mobility and manipulation to expand the workspace of robotic platforms.
- **4.3.5 Collaborative Manipulation:** provides a capability to coordinate and jointly handle and manipulate objects using either multiple robots or robot-human teams.
- **4.3.6 Sample Acquisition and Handling:** provides a capability to extract and handle rock, regolith, or organic samples, at both large and small scales, for resource processing, sample analysis, or sample caching and containment for future analysis or usage.
- **4.3.7 Grappling:** provides a capability to capture, anchor to, or interface with large structured and unstructured objects that are free-floating in space or on a planetary surface.

4.4 Human-System Interaction

Human-System Interaction pertains to the manner in which humans, robots, and autonomous systems (for example, spacecraft life support) communicate about their goals, abilities, plans, and achievements; collaborate to solve problems, especially when situations exceed autonomous capabilities; and interact via multiple modalities (for example, dialogue and gestures)

Human-System Interaction technologies can be grouped into the following general categories:

- **4.4.1 Multi-Modal Interaction:** provides multiple display modalities and communication channels that enhance situational awareness and enable natural human-like interaction. This includes interactive three-dimensional (3D) graphics, immersive displays, and haptic interfaces.
- **4.4.2 Supervisory Control:** see TA 4.4.8 Remote Interaction.
- **4.4.3 Proximate Interaction:** provides control and feedback methods that enable humans (for example, a suited astronaut) to work in physical proximity with autonomous systems, particularly robots. This includes activity and speech recognition, gesture detection, and intent interpretation.

- **4.4.4 Intent Recognition and Reaction:** see TA 4.4.3 Proximate Interaction.
- **4.4.5 Distributed Collaboration and Coordination:** provide tools that facilitate resource and task allocation, trading and sharing of control, and dialogue management.
- **4.4.6 Common and Standard Human-System Interfaces:** see TA 4.7.1 Modularity, Commonality, and Interfaces.
- **4.4.7 Safety, Trust, and Interfacing of Robotic and Human Proximity Operations:** see TA 4.7.5 Safety and Trust.
- **4.4.8 Remote Interaction:** provides control and communication methods that enable humans (for example, flight controllers) to remotely operate autonomous systems and robots. This includes teleoperation, supervisory control, and other control strategies.

4.5 System-Level Autonomy

System-Level Autonomy (in the context of robotics, spacecraft, or aircraft) is a cross-domain capability that enables the system to operate in a dynamic environment independent of external control.

System-Level Autonomy technologies can be grouped into the following general categories:

- **4.5.1 System Health Management:** monitors, predicts, detects, and diagnoses faults and accommodates or mitigates the effects either onboard or through telemetry processing on the ground.
- **4.5.2 Activity Planning, Scheduling, and Execution:** plans and schedules activities onboard or on the ground (with or without human intervention) to prevent resource conflicts; achieve science and engineering goals; handle unanticipated situations that can be resolved by command sequence modification; manage state; and monitor execution of such activities.
- **4.5.3 Autonomous Guidance and Control:** see TA 5 Communications, Navigation, and Orbital Debris Tracking and Characterization.
- **4.5.4 Multi-Agent Coordination:** enables distribution of autonomous functionality across multiple platforms and enables one or more operators to coordinate and manage heterogeneous autonomous assets.
- **4.5.5 Adjustable Autonomy:** provides the user with the ability to specify the degree of autonomous control that the system is allowed to take on, and in which this degree of autonomy can be varied from essentially none to near or complete autonomy. This level has been incorporated into other system-level and subsystem autonomy levels, because it is a feature of autonomous systems.
- **4.5.6 Terrain Relative Navigation:** see TA 4.1.2 State Estimation.
- **4.5.7 Path and Motion Planning with Uncertainty:** see TA 4.2.6 Robot Navigation and TA 4.3.2 Dexterous Manipulation.
- **4.5.8 Automated Data Analysis for Decision Making:** analyzes large data sets to provide time-critical decision-making.

4.6 Autonomous Rendezvous and Docking

Autonomous Rendezvous and Docking (AR&D) pertains to the approach and docking, capture, or berthing of a spacecraft or component to another from up to several kilometers away.

AR&D technologies can be grouped into the following general categories:

- **4.6.1 Relative Navigation Sensors:** provide short-, medium-, and long-range sensors to detect targets across long distances.

- **4.6.2 Guidance, Navigation, and Control (GN&C) Algorithms:** provide approach, guidance, and control algorithms for docking, capture, and berthing.
- **4.6.3 Docking and Capture Mechanisms and Interfaces:** provide standardized, compact, and lightweight docking mechanisms.
- **4.6.4 Mission and System Managers for Autonomy and Automation:** see executive software technology under TA 4.5.2 Activity Planning, Scheduling and Execution.

4.7 Systems Engineering

Systems Engineering here focuses on crosscutting themes for robotics and autonomous systems system-level design methodologies and technologies, interoperability and standardization themes, verification and validation techniques, and engineering tools.

The robotics systems engineering technologies can be grouped into the following general categories:

- **4.7.1 Modularity, Commonality, and Interfaces:** provide the hardware and software components and interfaces that enable greater flexibility and interoperability within and among agencies, while reducing overall cost.
- **4.7.2 Verification and Validation of Complex Adaptive Systems:** provide effective and efficient tools and techniques for verification and validation (V&V).
- **4.7.3 Robot Modeling and Simulation:** provides domain-specific modeling and simulation of sensing, mobility, manipulation, and rendezvous and docking.
- **4.7.4 Robot Software:** provides architectures, frameworks, and advances in robot software to enable the realization of intelligent robots and autonomous systems from component technologies.
- **4.7.5 Safety and Trust:** provide a capability to ensure safe interaction between humans and machines given their physical proximity or safety critical operations that depend on trusted autonomy.

TA 4.1: Sensing and Perception

Appropriate sensing (hardware) and perception (associated software) are essential for robotics and autonomous systems. The state of the art (SOA) for space applications represents the first generation of such technologies. Generally, these are relatively slower, larger, or more power-hungry than desired, and have limitations that still require humans in the loop to review, plan, or approve critical operations. Many desirable capabilities are simply not possible today, such as automatically detecting soft soil for Mars surface navigation and precision landing with position error of tens to hundreds of meters. In addition to the unavailability of necessary sensors, perception generally requires a great deal of computation. Therefore, limitations of current space-qualified computing systems impose significant constraints on perception systems, and progress in this area depends critically on progress in onboard flight computing capability. Unmanned systems can also serve as in-situ observers for Earth science; these need similar capabilities, but, in many cases, can exploit commercially-available sensor and processor hardware.

First generations of most of these capabilities exist and have been flown, but a great deal more capability is required to enable missions that achieve the next generation of science goals. In addition to increases in capability, reductions in the size, weight, and power consumption of sensors and associated processors are essential for affordability of spacecraft as a whole.

Sub-Goals

Enhanced sensing and perception will broadly impact three areas of robotic capabilities: autonomous navigation, tactile sensing for sampling and manipulation, and interpretation of science data. NASA is advancing sensing and perception to enable more capable exploration robots, human-assistive robots, and autonomous spacecraft; and improve drones and piloted aircraft. Perception tends to be very computationally intensive, so progress in this area will be closely linked to progress in high-performance onboard computing.

Table 2. Summary of Level 4.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.1 Sensing and Perception	Sub-Goals:	Provide situational awareness for exploration robots, human-assistive robots, and autonomous spacecraft; and improve drones and piloted aircraft.
Level 3		
4.1.1 3D Sensing	Objectives:	Increase the speed, resolution, and field of regard of 3D sensors while significantly reducing their size, weight, and power consumption.
	Challenges:	Limitations in onboard computing power.
	Benefits:	Improves 3D sensing capabilities, thus increasing the exploration range of surface mobility systems, enabling safe landing in hazardous terrain, and enabling robotic manipulation in space without close human supervision.
4.1.2 State Estimation	Objectives:	Enable real-time, onboard pose and velocity estimation relative to terrain and other spacecraft.
	Challenges:	Fusion of inertial, visual, and other sensors, such as radio navigation aids.
	Benefits:	Provides safer, faster robot navigation, precision landing, small-body proximity operation, and robot manipulation in space, thus reducing dependence on human operators, which is subject to large communication delays.

Table 2. Summary of Level 4.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.1.3 Onboard Mapping	Objectives:	Extend onboard mapping from just representing terrain topography to estimating properties needed for trafficability.
	Challenges:	Large amounts of onboard memory and computing power.
	Benefits:	Provides rapid, autonomous navigation and manipulation for planetary exploration, and enables robotic in-situ observation in Earth science.
4.1.4 Object, Event, and Activity Recognition	Objectives:	Recognize human-made objects (for example, sample caches and tools), natural hazards and landmarks, and dynamic events like weather phenomena.
	Challenges:	Providing appropriate sensors and adequate computing power to run the necessary algorithms.
	Benefits:	Provide cache acquisition for sample returns, in-space robotic servicing, safer navigation where atmospheric phenomena may matter, and opportunistic scientific observation of events that are impossible to react to fast enough if a communication cycle with Earth is required.
4.1.5 Force and Tactile Sensing	Objectives:	Sense and react to the forces and torques that build up in complex mobility or manipulation tasks.
	Challenges:	Six degrees of freedom force-torque sensors, with dual redundancy for each sensing axis and tactile sensor. Miniaturization.
	Benefits:	Increases the safety, reliability, and rapidity of robotic manipulation functions, instrument deployments that involve surface contact, and rendezvous and docking operations.
4.1.6 Onboard Science Data Analysis	See TA 4.1.4 Object, Event, and Activity Recognition and TA 4.5.8 Automated Data Analysis for Decision Making.	

TA 4.1.1 3D Sensing

Three-dimensional sensing of the environment is a foundation for all operations with close proximity to objects of unknown shapes. Three-dimensional perception has been central to autonomous navigation of planetary rovers using stereoscopic 3D perception in daylight. Active optical ranging, light detection and ranging (LIDAR), has been used in AR&D systems and is under development for detecting landing hazards in planetary exploration.

Technical Capability Objectives and Challenges

The objective for 3D sensor technology is to increase frame rates, spatial and range resolution, maximum range, and field of regard while simultaneously reducing size, weight, and power consumption. Specific performance requirements are mission dependent; an example is the need for sensors that produce range images on the order of once per second for rover navigation, with 512 x 512 pixels or over 1 steradian field of view with range resolution on the order of 10 centimeters (cm) at 10 meters (m), with a power consumption on the order of 5 watts (W) or less. Hazard detection for landers requires much greater range, on the order of hundreds of meters. Above-surface mobility systems (see TA 4.2.3 Above-Surface Mobility) require sensors with extremely low weight and power consumption. Creating and processing 3D range data is especially demanding computationally, so limitations in onboard computing power are a significant issue. In addition, understanding the sensor reference frames relative to the vehicle is important for accurate sensing. The SOA is to calibrate the system off-line. The objective is to measure changes to the calibration over the duration of a mission.

Benefits of Technology

Improved 3D sensing capabilities are fundamental to increasing the exploration range of surface mobility systems, enabling safe landing in hazardous terrain and enabling robotic manipulation in space without close human supervision.

Table 3. TA 4.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.1.1.1	Three-Dimensional (3D) Range Imaging Sensors for Surface Mobility	Provide 3D perception of environment with performance appropriate to surface mobility.
4.1.1.2	Three-Dimensional (3D) Range Imaging Sensors for Above-Surface Mobility	Provide array of 3D range data for above-surface mobility (see also TA 9).
4.1.1.3	Three-Dimensional (3D) Range Imaging Sensors for Manipulation	Provide 3D perception of environment with performance appropriate to manipulation and sample acquisition.
4.1.1.4	In-Situ Camera Geometric Calibration Diagnostics and Self-Calibration	Uses onboard algorithms to check camera geometric calibration and update calibration parameters in-situ.

TA 4.1.2 State Estimation

State estimation techniques that fuse inputs from inertial sensors, vision systems, and other sensors provide essential knowledge of the relative position, attitude, and motion of spacecraft near or on the surface of other bodies, as well as the internal state of the system. Rover position and velocity estimation are typically done onboard with a combination of inertial sensors, wheel odometry, and image feature tracking, though methods using images have very slow update rates due to the limitations of onboard processors. Rover positions are updated in ground operations systems by matching onboard data to regional maps, currently with the aid of human operators. The relative state of two spacecraft for rendezvous and docking is determined by matching models of known objects to onboard images and range data, but performance is limited by update rate and accuracy. Terrain-relative velocity estimation for landers has been flown with radar and imaging sensors, but needs further miniaturization, higher speed, and reduced cost. Terrain-relative position estimation for precision landing on Mars and the Moon is under development with methods that match onboard image data to regional maps in real-time during descent; this has not flown yet and needs to be generalized for use on other planetary bodies and other types of spacecraft (for example, navigation of balloons). Estimating the rotation state of small bodies is currently done by downlinking data to Earth. High-precision manipulator or end-effector pose estimation is done by ground operations systems with human operators who are aided by visual detection of fiducial marks on the device.

Technical Capability Objectives and Challenges

The objectives include estimating a robot's relative position or velocity to within centimeter-scale or centimeter-per-second-scale accuracy and with update rates of approximately once per second for safer, faster navigation. Landers and similar descent probes require onboard pose estimation relative to regional maps created from previous remote sensing missions, with a precision from tens to hundreds of meters and update rates on the order of seconds. State estimation relative to other spacecraft is needed over a broad range of scales, accuracies, and update rates for AR&D. Onboard robot estimates for end-effector pose relative to cameras on the vehicle, or relative to objects to be grasped, must be performed with millimeter-scale accuracy with many updates per second. Fusion of inertial, visual, and other sensors, such as radio navigation aids, is often essential for providing these capabilities; in many cases, the required sensors exist or have been proposed for terrestrial applications, but do not have sufficiently low size, weight, or power consumption for space applications.

Benefits of Technology

These capabilities will enable safer, faster robot navigation (for surface, above-surface, microgravity, small-body, and extreme terrain mobility), precision landing on Mars and the Moon (TA 9), precise landing site reconnaissance on Venus, small-body proximity operation (TA 5), and robot manipulation in space without the large delays needed for intervention by human operators.

Table 4. TA 4.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
4.1.2.1	Vision-Based Aiding of Dead Reckoning for Navigation of Surface Vehicles	Uses onboard camera(s) or range sensor(s) to aid inertial and kinematic sensors for dead reckoning.
4.1.2.2	Map-Based Position Estimation For Navigation of Surface Vehicles	Automatically matches data from onboard cameras or range sensors to regional maps to provide vehicle position estimates in the map frame of reference.
4.1.2.3	Vision-Based Aiding of Dead Reckoning for Above-Surface Vehicles	Uses onboard camera(s) or range sensor(s) to aid inertial and kinematic sensors for navigation.
4.1.2.4	Map-Based Position Estimation for Navigation of Above-Surface Vehicles	Automatically matches data from onboard cameras to regional map images to provide vehicle position estimates in the map frame of reference.
4.1.2.5	Radio Frequency (RF) Navigation Aiding for Above-Surface Vehicles	Provides range and bearing measurements between one vehicle and another when both are in-situ.
4.1.2.6	Altimeter for Small Above-Surface Vehicles	Provides altitude for small above-surface vehicles.
4.1.2.7	Manipulator State Estimation	Estimates position and orientation of manipulator end effector relative to a camera and range sensor on the body of the vehicle.
4.1.2.8	Manipulation Object State Estimation	Estimates position and orientation (pose) of an object to be manipulated or being manipulated.

TA 4.1.3 Onboard Mapping

Onboard mapping algorithms use 3D sensors and state estimates to construct and maintain onboard 3D models of the environment that are necessary for robot navigation. Mars rovers automatically create local elevation maps using 3D sensing from onboard stereovision. These maps only express terrain geometry, without explicit estimation or representation of trafficability characteristics (for example, characteristics related to the potential for rovers to slip or sink in the soil). Elevation maps are also created as part of landing site selection processes, but have very little qualitative trafficability modeling. Three-dimensional models of small bodies are created on the ground from orbital remote sensing. Automatic modeling of more complex 3D structures, like lava tubes or large space structures, has been shown in research labs, but has not reached high technology readiness levels (TRLs) in space-relevant development and testing.

Technical Capability Objectives and Challenges

The objective is to generate geometric maps of natural and human-made surfaces and structures, as well as surface and subsurface property maps, that aid in robot navigation or manipulation of objects. This includes improving the accuracy and resolution of maps, the seamless merging from multiple observations, and the map update rates. For surface navigation, onboard mapping capabilities must be extended from mapping terrain topography to also measuring and representing terrain properties for trafficability. This may be approached in multiple ways, from real-time estimation of current wheel slippage or sinking to visual terrain classification, or developing new flight-qualifiable sensors that can measure relevant properties, such as thermal cameras or shallow ground-penetrating radar.

Analogous sensors and mapping capabilities will be required for robotic and crewed missions to primitive bodies. Above-surface mobility systems will need to map terrain to plan trajectories, avoid obstacles, and find safe landing sites autonomously. The ability to map a network of landmarks and recognize those landmarks again from a variety of vantage points, in a variety of lighting conditions, is important for autonomous navigation in several mission scenarios. Onboard mapping of complex 3D structures, such as lava tubes and human-made space structures, is needed for some advanced scenarios, including in-space robotic servicing. Robotic vehicles with onboard mapping have potential applications in Earth science, where such capabilities are needed for navigation in forests and under ice shelves. Onboard mapping requires large amounts of onboard memory and computing power, which is a significant challenge at present.

Benefits of Technology

These capabilities will enable rapid, autonomous navigation and manipulation for planetary exploration and will enable robotic in-situ observation in Earth science.

Table 5. TA 4.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
4.1.3.1	Terrain Mapping for Surface Vehicles	Fuses data from 3D range sensors and other sensors to create maps of terrain geometry near a surface vehicle and to infer terrain terra-mechanical properties that significantly affect trafficability.
4.1.3.2	Terrain Mapping for Above-Surface Vehicles	Fuses data from 3D range sensors and other sensors to create map of terrain geometry beneath an above-surface vehicle and to infer terrain terra-mechanical properties that significantly affect safe landing (see also TA 9).
4.1.3.3	Landmark Mapping from Image Sequences and Other Navigation Data	Estimates the 3D coordinates of a network of landmarks on a planetary surface, using observations of the landmarks in images and other navigation data to constrain the landmark locations.
4.1.3.4	Three-Dimensional (3D) Modeling from Multiple Observations	Estimates geometric of 3D structures, such as the lava tubes, using observations from multiple images or 3D range images obtained from multiple vehicle locations.

TA 4.1.4 Object, Event, and Activity Recognition

Onboard recognition of static objects, dynamic natural events, and dynamic human activities near spacecraft provides awareness of these items and enables onboard decisions about how to react to them. Rocks and craters are automatically detected by remote sensing ground systems for mapping landing hazards. Rock detection and characterization algorithms have been tested on Mars rovers for automated identification of science targets. Software onboard Mars rovers have detected dust devils and cloud events. Software for automatic instrument targeting has also been tested on Earth-orbiting satellites. Automatic recognition and pose estimation of human-made objects, as part of autonomous robotic manipulation systems (see TA 4.3 Manipulation), has been shown in terrestrial research projects, but has not yet been flown. All such capabilities are strongly constrained by the limitations of flight computers.

Technical Capability Objectives and Challenges

Natural objects that are important to recognize include: landmarks that facilitate navigation; obstacles to rovers or landers; and objects that are important to science investigations, such as geologic targets and atmospheric phenomena. Human-made object recognition will be important in retrieving sample caches, AR&D, and robotic inspection, assembly, servicing, and repair operations in space. Dynamic event recognition may be important for more advanced dust devil detection on Mars; for detecting plumes or outgassing on comets, Enceladus, or Titan; or for recognizing weather phenomena on Titan. Recognizing human activities will be important when humans and robotic systems operate in close proximity. Challenges include providing appropriate sensors and providing adequate computing power to run the necessary algorithms.

Benefits of Technology

These capabilities will enable cache acquisition for Mars Sample Return, in-space robotic servicing, safer navigation where atmospheric phenomena may matter, and opportunistic scientific observation of events that are impossible to react to fast enough if a communication cycle with Earth is required.

Table 6. TA 4.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
4.1.4.1	Natural Object Recognition	Recognizes natural objects from predefined classes using onboard sensors; the objects may be landmarks, obstacles, or scientifically significant formations. (See also TA 4.5.8 Automated Data Analysis for Decision Making)
4.1.4.2	Human-Made Object Recognition	Recognizes human-made objects and estimates their position relative to the vehicle, using observations from images, range data, radio beacons, and/or other sources. (See also TA 4.6 Autonomous Rendezvous and Docking)
4.1.4.3	Event Recognition	Automatically processes time sequence data to detect occurrence of natural events (for example, dust devils on Mars, comet outgassing, rainfall or cryo-volcanic emissions on Titan) and human-made events (for example, completing a manipulation operation).

TA 4.1.5 Force and Tactile Sensing

Force and tactile sensors are essential to control contact between spacecraft and other objects, including planetary surfaces and during mobility and manipulation operations. Force and torque sensors are used routinely in terrestrial robotics for controlling manipulators. These sensors have had limited use in planetary exploration to date; for example, the three-degrees of freedom (DOF) force-torque sensor in the wrist of Curiosity is the first use on a Mars rover. Arrays of tactile contact sensors are becoming common in terrestrial robot grasping systems; space qualification of such sensors is challenging due to the materials that are currently used in them.

Technical Capability Objectives and Challenges

The objective is to sense and react to the forces and torques that build up in complex manipulation tasks, such as coring rocks on slopes, engaging and disengaging tools, and docking or undocking modules. The challenge includes developing space-qualifiable designs for six-DOF force-torque sensors, with dual redundancy for each sensing axis and tactile sensor, to enable generalized object grasping in space. It also includes miniaturization and increased affordability for more abundant use in robotic tasks.

Benefits of Technology

This technology increases the safety, reliability, and rapidity of robotic manipulation functions, instrument deployments that involve surface contact, and rendezvous and docking operations, and will be valuable for any missions that involve sampling, manipulation, or servicing.

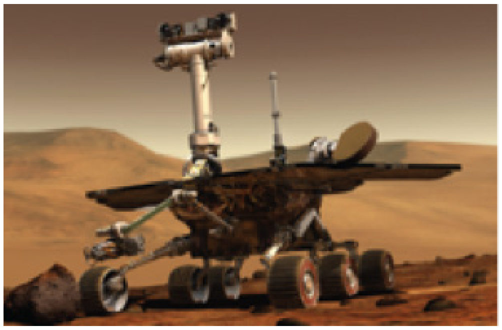
Table 7. TA 4.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
4.1.5.1	Space-Qualifiable Force and Torque Sensors	Provide measurements of forces and torques for individual contacts in a space-qualifiable implementation.
4.1.5.2	Space-Qualifiable Tactile Sensors	Provide array measurements of normal and/or shear quantities (for example, displacements) over extended contact areas.

4.1.6 Onboard Science Data Analysis

Technologies are now covered under TA 4.1.4 Object, Event, and Activity Recognition and TA 4.5.8 Automated Data Analysis for Decision Making.

TA 4.2: Mobility



Mars Rover

Mobility provides a critical capability for space exploration, as witnessed by nearly a decade and a half of recent planetary surface exploration. Multiple forms of mobility offer great promise in exploring planetary bodies for science investigations and to support human missions. Mobility provides coverage and access through multiple forms, including extreme-terrain mobility for science- or resource-compelling sites; above-surface mobility for broader and faster coverage; below-surface mobility through natural and human-made cavities and holes; small-body and microgravity mobility, where gravity levels greatly influence their design; and surface mobility for science investigations and crew transportation. In addition to the various forms, control and autonomy algorithms, such as navigation around hazards for multiple mobility forms (robot navigation) and collaboration among various mobility assets, would allow more effective and affordable exploration and operations. Enhancements and potentially new forms of mobility can be realized through advances in component technologies, such as actuation and structures.

To date, only a few forms of mobility have successfully been deployed on planetary bodies, with several more that have launched but failed to reach their destinations or be fully realized. First-generation autonomous mobility has demonstrated kilometers traversed on planetary bodies. However, much more remains to be done to meet the needs of future exploration. Many creative mobility solutions (both platforms and autonomy algorithms) are being conceived, prototyped, matured, and deployed for a range of challenging environments.

The SOA in surface mobility includes NASA’s Mars rovers (“all-robotic” systems) and the Apollo lunar roving vehicle (a “crewed” system). In small-body or microgravity mobility, the SOA is NASA’s autonomous extravehicular activity (EVA) robotic camera (AERCam) Sprint free-flying inspection camera, which was flown in the late 1990s. Challenges include mobility across a large range of terrains and across a variety of environmental conditions ranging from microgravity to substantial gravity, low- to high-atmospheric pressures, cryogenic to high thermal extremes, planetary extremes (see TA 7.5.2), and under communication constraints. The SOA in above-surface mobility in planetary environments are the Soviet Venus mission's Vega balloon flights but concepts and technologies have been developed for both lighter-than-atmosphere (LTA) and heavier-than-atmosphere (HVA) robotic vehicles for Mars, Venus, and Titan drawing upon significant development in unmanned aerial vehicles (UAVs). These capabilities can be adapted and applied to the exploration of planetary surfaces and weather. Performance metrics for mobility include range, speed, lifetime, mass, and payload capacity.

Sub-Goals

A broad range of future NASA science and human exploration missions would require some form of mobility, particularly those missions that need to reach sites of compelling scientific interest, those that need to access in-situ resources, or those that need to set up infrastructure or transport assets and crew. Given the constraints of space environments, it is less likely that other agencies would develop mobility solutions that would address NASA’s unique challenges and constraints. Specific areas of interest to NASA include extreme-terrain surface mobility, free-space mobility, autonomous navigation, autonomous above-surface mobility with multiple landings and attachment to (and detachment from) the terrain, and below-surface mobility through extreme environments. Coordination of multiple mobility assets would enable new possibilities in planetary exploration and in-space operations. For example, a combination of heterogeneous flying and roving platforms would enable the pairing of long-range sensing from the flyer with the higher-resolution sensing from the rover, leading to improved long-range surface navigation.

Mobility systems challenges include difficult topographies, often unknown terrain properties, thermal extremes, and the radiation environment. Moreover, mass, volume, power, and communication constraints have a much greater degree of emphasis in the design process for NASA missions than other agencies. As a result, mobility systems in a NASA context may require more subtlety compared to a brute force solution that may be well-sutied for other contexts.

Mission success will often depend on reliable and sustained operations, including the ability to move long distances or operate for extended durations through the environment without consuming too much of the mission timeline.

Table 8. Summary of Level 4.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.2 Mobility	Sub-Goals:	Reach and operate at a range of sites of scientific interest in extreme planetary environments or in free-space environments. Transport surface assets, payloads or equipment in support of human missions.
Level 3		
4.2.1 Extreme-Terrain Mobility	Objectives:	Provides access to and traverse across extreme terrain topographies, such as steep and deep craters, gullies, canyons, lava tubes, and soft, friable terrains.
	Challenges:	Large variations in topography. Vertical and lateral mobility against gravity on bodies with substantial gravity.
	Benefits:	Provides on-, above-, and below-surface mobility to reach locations that may be extreme (cliff sides, deep underground) to find the best samples for scientific analysis, thus allowing for in-situ analysis or, with sampling devices, sample return for more extensive analysis.
4.2.2 Below-Surface Mobility	Objectives:	Provides ability to access and explore natural or human-made features below the surface.
	Challenges:	Lack of direct sunlight, lack of direct line-of-sight communication, and the nature of the medium through which they must move.
	Benefits:	Provides below-the-surface collection of pristine samples, considered superior to weathered samples collected from surface material or from underneath liquid surfaces.
4.2.3 Above-Surface Mobility	Objectives:	Provides longer range and greater coverage of planetary surfaces, independent of the terrain topography.
	Challenges:	Multiple landings, especially on bodies with substantial gravity. Environmental compatibility to extreme heat or cold, extremely high or low pressures (density), or chemical composition of the atmosphere.
	Benefits:	Provides greater coverage at a more rapid pace.
4.2.4 Small-Body and Microgravity Mobility	Objectives:	Provides surface coverage and in-situ access to designated targets on small bodies with low gravity, as well as in-space mobility inside and around the International Space Station (ISS) or other future space assets.
	Challenges:	Fine control of mobility platforms. Terrains with largely unknown surface properties. Power, communication, thermal cycling, and mobility in shadowed regions.
	Benefits:	Provides large surface coverage and fine maneuvering for in-situ measurements across the surface of small bodies, thus reducing the risk, cost, and mass associated with landing the main spacecraft. Provides greater access to the exterior of spacecraft beyond the reach of a single robotic arm.

Table 8. Summary of Level 4.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.2.5 Surface Mobility	Objectives:	Increases the traverse speed of both manned and unmanned planetary rovers. Issues related to crew and vehicle safety are addressed in section 4.7.5 Safety and Trust. Increases the capability of onboard sensing and control software to handle more difficult terrain.
	Challenges:	Mobility designs with appropriate suspension and compliant wheels with performance similar to pneumatic tires on Earth (includes challenges associated with high-performance actuators, energy storage, thermal control, and passive and active spring-damper systems).
	Benefits:	Provides long-range exploration with large payload mass fractions and modest energy budgets.
4.2.6 Robot Navigation	Objectives:	Provides a highly reliable, well-characterized, and fast autonomous or semi-autonomous mobility capability to navigate to designated targets on planetary surfaces.
	Challenges:	Limited sensing, energy, and onboard computing for navigation. Verification and valuation of autonomous navigation. Uncertainty in the data that is processed. Lack of *a priori* knowledge of the environment. Lack of appropriate fidelity test beds.
	Benefits:	Allows access to a range of targets through multiple mobility modalities (surface or above-surface) without or with infrequent ground interventions.
4.2.7 Collaborative Mobility	Objectives:	Provides an ability to distribute or collaborate on tasks using multiple mobile platforms or using a combination of platforms and crew. Issues related to crew and platform safety are addressed in section 4.7.5 Safety and Trust.
	Challenges:	Task allocation and information sharing in a heterogonous mobile team. Coordination of physically joint activities (carrying a payload).
	Benefits:	Provides expeditious engineering and construction of habitats. Provides cooperative mobility that includes cooperation of surface and above-surface assets for both terrestrial and planetary science missions (for example, mapping, seismic sounding or atmospheric transmission spectroscopy).
4.2.8 Mobility Components	Objectives:	Provide critical component technologies, such as compliant long-life wheels, fast and high-torque actuators, energy-efficient and miniaturized actuators, strong abrasion-resistant tethers, and all-terrain anchors to meet future mobility needs.
	Challenges:	Limitations of current material properties. Higher torque and power densities. Dissipating waste heat.
	Benefits:	Provide larger payload and mobility mass fractions. Provide safe movement at speeds that are power-limited, not computation-limited, and yet do not tax human attention.

TA 4.2.1 Extreme-Terrain Mobility

AXEL Rover

Extreme terrain mobility pertains to access and traversal of extreme terrain topographies, such as highly-sloped crater walls, gullies, and canyons; soft terrains; or terrains with large rock densities. Key technologies include rappelling and climbing systems and systems that can traverse soft and friable terrains. The SOA for mobility is limited to rovers that can climb low-grade slopes and terrains with relatively high bearing strength. Technology platforms have demonstrated rappelling into and out of volcanoes, cliff faces, steep slopes, and overhangs in a few field tests across limited distances. Climbing systems have demonstrated limited mobility in a lab environment for certain types of rock faces. For rappelling systems, challenges include mobility using tethers and vertical and lateral mobility on steep or vertical surfaces. For climbing systems, challenges include unknown terrain properties and mobility against gravity on highly-sloped surfaces. For soft and friable terrains, challenges include large sinkage and risk of entrapment. The SOA for estimating terra-mechanical properties is limited to qualitative measurements from rover imagery. Ground-penetrating radar, which senses dielectric properties, has been demonstrated as a proxy for sensing terrain density and strength.

Technical Capability Objectives and Challenges

Technical objectives for this area include providing access to and traversing across extreme terrain topographies, such as steep and deep craters; gullies; canyons; lava tubes; and soft, friable terrains. Needed developments focus on increasing the terrain slope and terrain types that platforms are able to traverse, increasing traverse distance as a function of payload carried, enabling excursions over longer durations in extreme terrain, and increasing reliability of the overall system. Technologies include main spacecraft-surface craft tethered rappelling systems, anchor-based climbing systems, and technologies that enable characterization of terrain properties to assess the traversability of extreme terrains with their associated hazards.

Challenges include vertical and lateral mobility against gravity on bodies with substantial gravity. These include traversing steep or vertical surfaces and overhangs and getting into and out of crevasses and lava-tubes, where access to power and communication may be limited. These also include mobility using tethers or umbilicals, and anchor placement and removal on a wide range of terrain surfaces. Other challenges include the ability to navigate terrains with large variations in topography and the ability to remotely and reliably assess hazards to prevent entrapment.

Benefits of Technology

NASA needs to reach locations that may be extreme in order to find the best samples for scientific analysis. On-, above-, and below-surface mobility enables these locations to be reached with instruments for in-situ analysis or with sampling devices for sample return and more extensive analysis. Examples include:

- accessing and sampling recurring slope lineae on crater walls on Mars, which have been hypothesized to be briny water flows;
- accessing volatiles in lunar cold traps for both human and science missions;
- assessing collapsed lava tubes on the Moon and Mars as potential temporary habitats for crewed missions; and
- traversing the extremely rugged surface of Europa for investigating biosignatures.

Table 9. TA 4.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.2.1.1	Rappelling Mobility Systems	Provide robots that can rappel down steep terrain and retract back using assistive tethers.
4.2.1.2	Climbing Mobility Systems	Provide self-mobility that can climb extreme terrain topographies without the aid of a tether.
4.2.1.3	Soft/Friable Terrain Mobility Systems	Provide self-mobility that can traverse extremely soft or friable terrains on bodies with substantial gravity.

TA 4.2.2 Below-Surface Mobility

Below-surface mobility pertains to access through naturally-occurring terrain cavities, such as lava tubes and deep crevasses; through human-made terrain cavities, ice boreholes, or trenches; and through granular or liquid media. The process of intentionally modifying the medium to generate the cavities or holes, through deep drilling or excavation, is covered in TA 4.3.6 Sample Acquisition and Handling.

Below-surface mobility has not been used on planetary surfaces other than Earth. On Earth, below-surface mobility has been used for underwater and underground operations. The latter has primarily been driven by the oil and gas and mining industries through deep-directional drilling and underground mining operations. Remotely-operated vehicles (ROVs) and autonomous underwater vehicles have been used for scientific exploration and commercial applications. Prototype platforms have been developed to access lava tubes, skylights, and cenotes. Prototype burrowing robots that employ counter-rotating augers to move through sand have been tested but are currently limited to near-surface operations.

Challenges of below-surface mobility include deep mobility through a challenging medium: cavities and tight holes or through solid or liquid media. Other challenges include power requirement and access to energy and communication sources given lack of direct sunlight and line-of-sight for communication.

Technical Capability Objectives and Challenges

The objective is to provide a capability for accessing and exploring natural or human-made features below the surface, and achieving greater depth, length, and speed of the traverse as well as reducing the energy required per traverse distance. For natural environments, these include under-surface mobility through skylights, regolith, rocks or ice or under-liquid mobility through Titan's lakes, Enceladus' subsurface lakes, or Europa's subsurface ocean. Mobility through crevasses and skylights may overlap with some aspects of extreme-terrain mobility. For human-made features, these include deploying platforms through tight and deep cavities like drilled boreholes, where in-situ measurements and samples can be collected and the subsurface strata and structure can be mapped.

Below-surface mobility is made particularly difficult by, and must account for, the lack of direct sunlight, the lack of direct line-of-sight communication, and the nature of the medium through which they have to move (for example, abrasiveness of regolith for burrowing or acidity and salinity of the liquid media). Moreover, for burrowing robots, breaking rocks or disturbing regolith yields a larger volume than undisturbed material. As such, platforms that transport through such media require some method of disposing of the excess volume of spoils. For a vehicle moving to significant depth, some method must be arranged to evacuate the excess spoils out of the hole, such as a tube as part of the power tether to the surface. On Earth, fluids are customarily used for transporting cuttings from drill holes. For planetary missions, in-situ fluids may not be available, which makes transporting cuttings very challenging. On Mars and Venus, the predominantly carbon dioxide (CO_2) atmosphere can be compressed into a very low-viscosity liquid or supercritical fluid for transporting cuttings.

Additional challenges include mobility through narrow and deep tunnels that could be tens of kilometers in depth in rocky terrain (for example, Mars) or through ice at cryogenic temperatures (for example, Europa or Enceladus). Deep subsurface access has not been seriously considered to date because it is a very challenging technical capability.

Benefits of Technology

Reaching the putative liquid-water aquifer on Mars, which is up to tens of kilometers deep and thought to be globally interconnected over geologic time, could reveal biomolecules indicating the presence of extant or recent life, analogous to the single-celled life now known to flourish deep underground on Earth. Collecting pristine samples at depth is typically considered superior to weathered samples collected from surface material or from the sides of cliffs.

Table 10. TA 4.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
4.2.2.1	Subsurface Access Through Natural Cavities	Provides access to and across natural occurring subsurface cavities such as lava tubes and crevasses where resources such as sunlight and line-of-sight are very constrained.
4.2.2.2	Subsurface Access Through Human-Made Holes	Provides mobility through narrow and deep human-made holes for in-situ measurements.

Table 10. TA 4.2.2 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
4.2.2.3	Burrowing Mobility	Provides platforms that can burrow deep into a planetary surface.
4.2.2.4	Long-Endurance Submerged Mobility	Provides under-liquid mobility for extended periods of time for in-situ observations.

TA 4.2.3 Above-Surface Mobility

Above-surface mobility for space and aeronautics missions is categorized based on how lift is produced, which includes ballistic lift (also known as "hoppers"), static lift, dynamic lift, and powered lift.

Technical Capability Objectives and Challenges

The objective is to provide longer range and greater coverage of planetary surfaces, independent of the terrain topography. This includes improvements to payload capacity (or payload-to-total-mass ratio), power (or specific power to maintain level flight), speed, and endurance in terms of time or distance. The type of above-surface mobility used on planetary bodies will be driven by environmental considerations and mission-specific requirements, which would include operation duration, coasting attitude, and the frequency of contacts with the surface.

A challenge for all above-surface mobility platforms includes environmental compatibility to extreme heat or cold, extremely high or low pressures (density), and chemical composition of the atmosphere (for example, sulfuric acid on Venus). Additional challenges include power, communication, energy collection and storage, weight of structures and avionics, and resilience of materials to the environment (for example, for long-duration operations, low-permeability balloon materials). Other challenges include controllability and autonomy (including high-speed mobility), and reusability of engines in the case of dynamic-lift systems.

Moreover, validating system-level capabilities in relevant environments can prove to be challenging if not impossible and, when possible, can only be done in parts in many cases. Destinations such as Venus and Titan allow for powered lighter-than-air vehicles that might have essentially unlimited endurance with significant payloads, based on solar or nuclear power. Examples of above-surface mobility that have been proposed for Mars include the Mars helicopter and the "grasshopper," which separates the atmosphere into a reactive combination that can be used for brief rocket-based hops. Many above-surface mobile systems will need to land safely a successive number of times to regenerate. This is a special challenge, especially if there is an atmosphere with significant motion or turbulence. For static lift systems, challenges include a lack of large enough test chambers that can provide relevant atmospheric conditions.

Benefits of Technology

Global-scale exploration can be achieved by above-surface mobility with performance far outstripping that which can be achieved by surface mobility, generally with a penalty in terms of payload, endurance, and expected mission lifetime.

Table 11. TA 4.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
4.2.3.1	Ballistic Systems	Ballistic-lift systems provide mobility through ballistic hops and can be fired from a base, leap through self-actuation, or use periodic reaction (thrust). No atmospheric interaction is needed, although an atmosphere may or may not be present.
4.2.3.2	Static-Lift Systems	Static lift systems are buoyant and provide mobility using the difference between the densities of the atmosphere and the vehicle's buoyant gas. Static-lift systems may be powered or unpowered. Examples are balloons (tethered and untethered aerostats), dirigibles, and hybrid lift.

Table 11. TA 4.2.3 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
4.2.3.3	Dynamic-Lift Systems	Dynamic-lift systems utilize vehicle motion through the atmosphere or atmosphere movement (wind) to generate lift, and may be powered or unpowered.
4.2.3.4	Power-Lift Systems	Powered-lift systems, a critical enabler for vertical takeoff and landing (VTOL) capability, use thrust to overcome weight for lift. An advantage of powered lift systems is that they can be used in a range of atmospheric environments.

TA 4.2.4 Small-Body and Microgravity Mobility

Small-body and microgravity mobility pertains to mobility across the surfaces of small moons, asteroids, comets, and near-Earth objects, as well as mobility inside and around the ISS and other spacecraft.

NASA SPHERES

Currently, there have been no successful deployments of a small-body mobility platform, although there have been successful deployments of microgravity mobility platforms. Successful microgravity mobility included the deployment of the synchronized position hold, engage, reorient experimental satellites (SPHERES) platforms inside the ISS and the AERCam Sprint deployed outside the Space Shuttle in 1997. Under development are a hopper concept to retrieve or capture a boulder off the surface of a large asteroid, and a “touch and go” asteroid sample return approach to collect a small (> 60 grams (g)) sample at the asteroid, Bennu, in 2017. Several technology prototypes for microgravity and small-body mobility platforms have been developed and tested in microgravity test beds, drop towers, and on parabolic flights.

Technical Capability Objectives and Challenges

The objective is to provide surface coverage and in-situ access to designated targets on small bodies with low gravity, as well as in-space mobility inside and around the ISS or other future space assets. For small bodies, the mobility type would largely be driven by environmental considerations, such as gravity level, surface properties, thermal environment, and available power generation resources. It would also be driven by mission-specific requirements like operation duration, instrument payload, and the need to collect, ingest, or return samples to other assets or to Earth. For microgravity mobility, the mobility type would be largely driven by the operation or activity to be performed, whether it includes non-contact or contact operations, which may require further dynamic interaction with other assets.

Development needs for small bodies include improving traverse distance and surface coverage area, traverse speed, accuracy in accessing specified targets or in station-keeping, payload capacity (or payload-to-total-mass ratio), required power, endurance in terms of time or distance, and safety if operating in the vicinity of humans or other assets. For microgravity operations, the focus is on controllability, operational speed, safety, and force that could be imparted.

A challenge for small-body mobility includes controlling mechanisms or platforms, including fine control, in a low-gravity environment where motions are no longer quasi-static but fully dynamic. Challenges also include mobility across terrains with largely unknown surface properties. Other challenges include power, communication, thermal cycling, and mobility in shadowed regions. Validation of platforms and mobility algorithms for microgravity and small bodies is particularly challenging given the limitations of current test beds and test platforms.

Benefits of Technology

This capability would enable both large surface coverage and fine maneuvering across challenging terrain topographies of small bodies at a fraction of the cost and mass of landing an entire spacecraft. Affordable, low-mass microgravity mobility platforms lend themselves to parallel exploration using multiple redundant units. This capability would benefit human precursor missions for characterizing the hazards of the environments, as well as for science missions that study the origin and evolution of our Solar System. For human-made structures, they enable greater access to the exterior of spacecraft beyond the reach of a single robotic arm.

Table 12. TA 4.2.4 Technology Candidates – not in priority order

TA	Technology Name	Description
4.2.4.1	Free-Floating Robots	Provide self-positioning and self-orientation in microgravity for sensing and operations.
4.2.4.2	Hopping/Tumbling Surface Robots	Provide mobility on the surface of small bodies with low-gravity using hopping and tumbling maneuvers.
4.2.4.3	Anchoring Robots	Provide mobility on the surface of small bodies by anchoring and de-anchoring onto the surface.
4.2.4.4	Wheeled/Tracked/Hybrid Robots	Provide mobility on the surface using wheels, tracks, limbs, or a hybrid of these.

TA 4.2.5 Surface Mobility

The SOA in surface mobility includes six-wheeled, passive-suspension, rocker-bogie mechanisms with front and back steerable wheels; examples include NASA's Mars rovers. These rovers have demonstrated mobility across tens of kilometers of relatively flat terrain with low-grade slopes (< 25 degrees) covered with widely-separated positive and negative obstacles and other terrain hazards, such as sand-dune slip hazards. Traverse speed has generally been under five cm/second(s). The rovers demonstrated the ability to climb obstacles of a wheel radius in diameter.

Challenges include mobility across a large range of terrains with limited power, computation, and control of wheels to minimize energy and wear and tear on the vehicle. For human surface exploration, the challenges include efficient mobility for crew and payloads across natural terrain. Examples of the latter include mobility of in-situ resource processing facilities, habitats, science analysis facilities, and other surface assets, such as cranes, haulers, and davits.

Technical Capability Objectives and Challenges

The objective is to transport payloads, equipment, and other surface assets at much higher traverse speed for both manned and unmanned missions and increase the robustness of their onboard sensing, control, and navigation software. This includes addressing issues related to safety of crew on or near vehicles operating at relative high speeds, which is covered in TA 4.7.5 Safety and Trust. Human drivers have a remarkable ability to perceive terrain hazards at long range and to pilot surface vehicles along dynamic trajectories. Despite the limitations of human sensing and cognition, it is generally observed that experienced drivers can pilot their vehicles at speeds near the limits set by physical law (frictional coefficients, tip-over, and other vehicle-terrain kinematic and dynamic failures). This fact is remarkable, given the huge computational throughput requirements needed to quickly assess subtle terrain geometric and non-geometric properties (for example, visually estimating the properties of soft soil) at long-range fast enough to maintain speeds near the vehicle limits. This ability is lacking in today's best obstacle detection and hazard avoidance systems. Additional focus is on improving payload mass fraction, specific power, speed, and endurance in terms of time or distance.

Challenges include the development of appropriate suspension and compliant wheels having performance similar to pneumatic tires on Earth, high-performance actuators, energy storage, thermal control, passive and active spring-damper systems, and others.

Benefits of Technology

Surface mobility enables long-range exploration and transportation of large payload mass fractions with modest energy budgets.

Table 13. TA 4.2.5 Technology Candidate – not in priority order

TA	Technology Name	Description
4.2.5.1	Mobility Subsystem for Crewed Surface Transport	Self-transports a payload system, including a crew in a pressurized cabin, on planetary surfaces with acceptable safety and reliability.
4.2.5.2	Mobility System for Uncrewed Surface Transport	Self-transports small and large payloads to designated target areas on planetary surfaces, potentially at relatively high speeds.

TA 4.2.6 Robot Navigation

Robot navigation pertains to the autonomous mobility of surface, above-surface, and extreme-terrain platforms. Using onboard sensors, these platforms maintain a mobility objective (for example, reaching a designated target for surface mobility or maintaining an altitude and directional velocity for an above-surface platform). For surface navigation, Mars rovers have demonstrated hundreds of meters of autonomous traverses at average speeds of 12 to 20 meters per hour (m/hr). Technologies for autonomous surface and above-surface navigation have been demonstrated in rough outdoor terrains and urban settings where vehicles have achieved autonomous driving speeds of tens of kilometers per hour (km/hr). Several commercial entities have been pursuing autonomous driving in urban settings and on highways, where technologies have been demonstrated to autonomously drive vehicles on the road at normal driving speeds for hundreds of kilometers.

Technical Capability Objectives and Challenges

The objective is to provide a highly reliable, well-characterized, and fast autonomous or semi-autonomous mobility capability (> 200 m/hr) to navigate to targets of interest on planetary surfaces. In the near term, the focus will be on autonomous navigation of surface platforms. However, the long term objectives are to extend such a capability to navigating extreme terrains under tether constraints, navigating above surface using dynamic platforms, navigating on small bodies and in microgravity where sensors experience large motions, and navigating below surface with limited sensors.

The nature and constraints of autonomous mobility would vary based on mobility and sensing modalities. However, the objective is to enable autonomous mobility where models and parameters adapt to the environment and learn from past experiences and where the amount of sensing and processing is automatically tuned based on hazard densities or terrain properties, or to degraded vehicle performance or component failure. This integrated set of capabilities leverages sensing and perception algorithms, state estimation algorithms, machine-learning algorithms, motion and route planning, and activity-planning algorithms, to name a few. It requires the ability to make decisions in a timely manner for fast traverses of quasi-static platforms (for example, surface rovers) and dynamic platforms (for example, helicopter). For efficient operations, perception range, terrain models, and optimal trajectories and motions are paramount. Additionally, algorithms should be adaptable to different mobility chasses, be able to adapt their computation based on terrain information, and be able to learn from past experience.

The challenges include the large uncertainty in the data that is processed; limited sensing, energy, and computation resources; and the complexities and lack of prior knowledge of the environment in which such platforms operate. Other challenges include the lack of appropriate fidelity test beds and the difficulty of characterizing autonomous navigation performance. For autonomous navigation of crewed platforms, system reliability would have to meet stricter standards for human safety.

Benefits of Technology

Future Mars missions require faster autonomous navigation across more challenging terrain. For the Sample Return Mission, this may also include a long and possibly round-trip traverse that may require multi-sol autonomous operations. Lunar and other planetary surface missions would also benefit from faster and higher overall performance of surface navigation.

Table 14. TA 4.2.6 Technology Candidates – not in priority order

TA	Technology Name	Description
4.2.6.1	Adaptive Autonomous Surface Navigation	Assesses hazards for a given mobility platform using multi-sensory inputs, rapidly plans and executes motions to avoid such hazards, and adapts models based on prior experience.
4.2.6.2	Autonomous Navigation for Tethered Systems	Uses multi-sensory inputs to assess traversability for rappelling tethered systems; plans and executes motions to avoid such hazards, and adapts models based on prior experience.
4.2.6.3	Low-Altitude Above-Surface Navigation	Uses multi-sensory input to autonomously control above-surface platforms to traverse to designated locales and avoid mountainous terrain.
4.2.6.4	Below-Surface Navigation	Provides self-sensing and self-perception of the surface environment and then self-selection of optimal routes to achieve sub-surface traverse goals.
4.2.6.5	Small-Body/Microgravity Navigation	Provides self-assessment of hazards in microgravity with motion planning and execution for hazard avoidance.

TA 4.2.7 Collaborative Mobility

This area pertains to collaboration among mobility assets or between mobility assets and astronauts to achieve a common goal. Examples include multi-asset site surveys, job site preparation or clean up, laying a line-of-sight communication grid in mountainous terrain, or map building. In all these examples, mobility assets need to communicate with one another and, in some cases, with humans to coordinate their individual activities. For example, when two or more mobility assets are carrying a large and bulky load in uneven terrain, coordination is even more challenging. Unless there is frequent communication, the load could fall disproportionately on one member of the team while others take little or no load. This instability can lead to dropping the load when the limits of the overburdened member are exceeded.

Technical Capability Objectives and Challenges

The objective is to provide an ability to distribute or collaborate on tasks using multiple mobile platforms. Collaborative mobility encompasses multi-vehicle systems up to and including swarms, colonies, and other bio-inspired cooperative vehicle activities for surveying, mapping, excavating, and constructing. The focuses are increasing the reliability of cooperative tasks, flexibility, the range of tasks that can be accomplished, and the scalability of the technologies to a large number of platforms, including heterogeneous ones. Examples include coordinating the motion of two or more vehicles to transport a large, bulky object or surveying a large area by delegating responsibility to multiple vehicles. Complementary capabilities are also covered in TA 4.3.4 Mobile Manipulation and TA 4.5.4 Multi-Agent Coordination. Many of these areas are brought together in terrestrial settings, such as a mountain search and rescue operation searching a large area and hauling an injured person out on a stretcher using a combination of multi-person coordination, cooperative mobile manipulation over extreme terrain, and tether winches.

Collaborative mobility will be required following initial human missions to Mars or to the lunar surface to prepare the surface for permanent habitation. Much as a team of construction workers is required prior to permanent habitation of any locale on Earth, even prior to construction, mapping, surveying, terra-mechanics studies, and other collaborative efforts are required to design the foundations for any permanent installation. This will be especially true if a permanent nuclear power or in-situ resource utilization (ISRU) system, such as atmospheric processing into propellant, is built on a planetary surface.

Benefits of Technology

Permanent installations may be required for permanent human habitation of Mars or the Moon. These installations presumably require foundations whose engineering and construction is most expeditiously accomplished by a team of robots or human-robot teams, analogous to how such endeavors are accomplished on Earth. Almost any terrestrial effort that is performed by a team would similarly be done by a team on another planetary surface, and hence involve cooperative mobility. These also include cooperation of surface and above-surface assets for both terrestrial and planetary science missions (for example, for mapping, seismic sounding or atmospheric transmission spectroscopy).

Table 15. TA 4.2.7 Technologies

TA	Technology Name	Description
4.2.7.1	Collaborative Mobility Algorithms	Provides algorithms that control and coordinate the mobility of a group of planetary platforms to achieve a higher-level objective that cannot be performed by a single platform.

TA 4.2.8 Mobility Components

Mobility components include tractive elements, such as wheels, tracks, anchors, and footpads; long-life actuators tailored for mobility, in terms of speed and torque range and ability to withstand thermal extremes; and special-purpose elements, such as terrain-properties sensors and field-programmable gate array (FPGAs) for perception, terrain classification, and mobility hazard assessment.

Terrestrial wheels are almost always compliant by way of pneumatic pressurization, which are generally unsuitable for space environments experiencing huge thermal swings. Mars rovers to date have had rigid wheel rims that do not conform to the terrain. The Apollo lunar roving vehicle had compliant mesh tires made of steel wire, but these are not believed to be suitable for very long-range missions. Tracked vehicles distribute the load over a much larger area and are frequently used on Earth for soft terrain, but the tendency of rocks to become entrained in the running gear requires either very high torques to crush the rocks, or elasticity that makes “throwing a track” unlikely. Footpads for landers can be very light, but have not as yet been applied to walking vehicles due to their low power efficiency.

Mobility actuators are generally at the extremities of a vehicle and have to operate under a wide range of temperatures dipping to cryogenic temperatures and are thus not easily thermally protected. The Mars rovers have required significant power to heat the wheels and steering actuators prior to startup in the mornings. Dissipating waste heat can also be an extreme challenge. For example, motors for lunar cargo vehicles have to sustain thermal cycles lasting ~29.5 Earth days, and are thought to require heat-pipe or similar technology to get rid of the heat during the lunar day while “disconnecting” thermally from the environment to prevent heat loss at night. Existing Mars rover wheel actuators are designed to have a rim thrust equal to half the weight of the vehicle to allow the vehicle to extricate itself from holes, even though the peak-power operating point is typically associated with a rim thrust less than 5 percent of the vehicle weight. In a terrestrial vehicle, this is accomplished using a multi-speed transmission, but in rovers it has been achieved through serious design compromises to preserve simplicity. Future legged systems may incorporate some sort of bio-inspired elastic energy storage into their actuators so that reasonable efficiency can be achieved, but this may introduce control challenges.

Terrestrial rover prototypes have demonstrated continuous and “fast” autonomous navigation through the use of FPGA for perception and hazard assessment. In addition to their use for speeding up perception (stereovision, terrain classification, pose estimation), they are used in mobility algorithms to assess hazards and evaluate the safety of paths to prevent flip overs, high centering, or sinkage. Of course, all these elements not only need to be developed, but also flight qualified.

Technical Capability Objectives and Challenges

The objective is to provide critical component technologies, such as compliant long-life wheels, fast and high-torque actuators, energy-efficient and miniaturized cryogenic-capable actuators, strong abrasion-resistant tethers, and all-terrain anchors, to meet future mobility needs.

Human exploration missions to Mars will require surface mobility systems that are too heavy for the SOA wheels used by current Mars rovers. Compliant, long-life, or easily replaceable or repairable wheels need to be able to carry heavy loads at 1 to 4 psi (7-30 kPa) uniform ground pressure over their respective contact patches. These need to be developed so that complete Mars outpost systems can be tested in terrestrial analog sites. Similarly, efficient, lightweight actuators that can meet the torque, speed, and thermal requirements for Mars and the Moon need to be developed. These actuators need to operate in the temperature extremes of the planetary bodies respectively and incorporate torque sensing, fail-safe brakes, low-friction dust seals, and other features often unique to mobility actuators. Flight-qualified FPGA systems for vision processing, analyzing traversability, and other real-time, mobility-unique functions need to be developed so that comprehensive terrestrial analog testing can take place in time for planned human missions to Mars. Other components, such as strong durable terrain tethers and multi-terrain anchors, would enable more extreme types of mobility.

Benefits of Technology

Mobility is essential for exploration. Human exploration requires a quantum leap in mobility speeds over what robotic rovers have achieved. Human exploration vehicles should be able to move safely at speeds that are power-limited, not computation-limited, and yet do not tax human attention, which should be used for the more productive observation functions. This technology would provide fast and safe mobility for future exploration missions.

Table 16. TA 4.2.8 Technology Candidates – not in priority order

TA	Technology Name	Description
4.2.8.1	Wheels for Planetary Surfaces	Provide wheels that survive thermal and other environmental challenges, have compliance with near-constant ground pressure over contact patch, and allow appropriate grousers to be included.
4.2.8.2	Actuators for Mobile Robots	Provide light-weight, extreme-environment-capable actuators with gearboxes generating high torque at low speed and high speed at low torque (multi-speed gearbox, solid-state analogs of traditional "series-wound" motors, advanced motor controller for permanent magnet motors, etc.).
4.2.8.3	Terrain Adhesion	Provides mobility aids for rolling, crawling, or flying platforms and traction, adhesion, or anchoring (including their reverse operation) to different terrain types.
4.2.8.4	Sensing Terra-Mechanical Properties	Provides stand-off or contact sensing of properties, such as load bearing strength, friability, and anchor strength verification.

TA 4.3: Manipulation

Manipulation provides a critical capability for positioning crew members and instruments in space and on planetary bodies. It also provides a capability for extracting and handling samples of multiple forms and scales from various depths, as well as handling objects in support of both science and human missions. To date, several manipulators have been used in space and on planetary bodies. The SOA for space manipulation includes the Robonaut 2 limb and the robotic arms on NASA's landers and rovers. Challenges include strong, energy-efficient, and lightweight arms that can perform dexterous manipulation. Performance metrics include payload capacity (mass and volume), reach, dexterity, speed (for dynamic handling), lifetime, mass, accuracy, and repeatability. Manipulation is important for human missions, human precursor missions, and unmanned science missions.

Robonaut 2 working inside the International Space Station

Sub-Goals

The goal is to increase manipulator dexterity and reactivity to external forces and conditions while reducing overall mass and launch volume and increasing power efficiency. For multiple manipulators or assets, the goal is to enable robust execution of collaborative tasks by integrating 3D sensing and perception, advancing multi-arm and mobile manipulation control in space and planetary environments, and by improving overall hand-eye coordination. For sampling, the goal includes deeper drilling, sample acquisition of volatiles, and transfer of such samples to caches that ensure appropriate containment and integrity and minimize contamination. Each of these goals supports the advancement of manipulation technologies for primary use in future human exploration and science missions, such as the exploration of near-Earth asteroids (NEAs), cis-lunar space, and the moons of Mars.

Table 17. Summary of Level 4.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.3 Manipulation	Sub-Goals:	Increase manipulator dexterity and reactivity to external forces and conditions while reducing overall mass and launch volume and increasing power efficiency.
Level 3		
4.3.1 Manipulator Components	Objectives:	Provide advanced actuator design modeling tools. Develop lightweight material manufacturing. Improve current and voltage handling.
	Challenges:	Lack of advanced actuator design modeling tools. Absolute position sensing. Composite and lightweight metal manufacturing techniques. Current and voltage handling techniques, small form factors for processing capability, and radiation tolerant electronics.
	Benefits:	Provide ability to develop space-rated manipulators that can operate in deep-space environments.

Table 17. Summary of Level 4.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.3.2 Dexterous Manipulation	Objectives:	Reliably handle, position, and control objects and interfaces on spacecraft, equipment, tools, and natural objects. Achieve compliant force resolution for safe operations in the vicinity of humans.
	Challenges:	Control of a large number of degrees of freedom (DOF), real-time computation and reaction to external forces, and power requirements. Lack of advanced multi-modal control systems, lack of advanced actuator stacks, and lack of robust, high-resolution sensor arrays within the hands and fingers that can sense contact anywhere on the hand.
	Benefits:	Provides dexterous manipulation arms and end effectors, which can operate in deep-space environments.
4.3.3 Modeling of Contact Dynamics	See TA 4.7.3 Robot Modeling and Simulation.	
4.3.4 Mobile Manipulation	Objectives:	Dynamically extend the manipulation workspace through simultaneous coordination of mobility and manipulation. Provides localization with force control.
	Challenges:	Coordinated motion, force control across the entire system, and fusion of localization with force control.
	Benefits:	Provides in-space assembly of large structures and prepares a site in anticipation of crew arrival by enabling efficient operations across a large workspace.
4.3.5 Collaborative Manipulation	Objectives:	Develop force control systems with human interaction. Develop multi-point contact methodologies.
	Challenges:	Coordination of systems with large degrees of freedom (DOF). Wide array of human interaction modalities superimposed on a force control problem, multi-point contact problems, and robust safety systems.
	Benefits:	Provides space-rated collaborative manipulation capability, which can operate on planetary surfaces as well as in deep-space environments.
4.3.6 Sample Acquisition and Handling	Objectives:	Advance dry drilling as well as regolith and volatile-handling techniques.
	Challenges:	Handling of samples and raw materials and system cleaning approaches to avoid contamination and cross-contamination. Lack of power storage systems, worksite lighting systems, and autonomous system operations capability. Lack of regolith acquisition with smart size sorting and a lack of capabilities in autonomous operation, autonomous drills, and innovative non-drilling methods. Lack of options for sample collection at depth and acquisition of volatiles and samples without losing or contaminating the samples or volatiles.
	Benefits:	Provide space-rated sample acquisition and handling capability that can operate to needed performance levels on planetary surfaces as well as in deep-space environments. Enables robotic systems capable of assembling drill strings autonomously and acquiring samples at medium depths. Enables autonomous sampling with predictive fault detection, as well as effective sample sorting and storage. Provide effective recovery of volatiles and samples for use in ISRU applications.
4.3.7 Grappling	Objectives:	Grapple and manipulate natural and human-made free-flying objects.
	Challenges:	Objects in dynamic spin or free drift.
	Benefits:	Provides grappling systems that can operate in deep space environments. Enables capturing of orbiting sample caches for sample return missions. Increases vision and control system capabilities to handle larger structures for assembly of on-orbit spacecraft for future human exploration missions to near-Earth asteroids (NEAs) and planetary bodies.

TA 4.3.1 Manipulator Components

Manipulation components include actuators tailored for manipulation, in terms of speed and torque range, compliance, size, and mass; lightweight structures; embedded controllers; and joint sensors for extreme environments. The SOA is found in the Robonaut 2 limb, which incorporates fast, high-torque, extreme-environment-capable actuators, lightweight structures, and distributed motor controllers to create a manipulator that can be controlled with high precision in force and position. These capabilities enable a large operational workspace to allow stand-alone operations, as well as cooperative operations with humans.

Technical Capability Objectives and Challenges

The objective is to advance technology in three main areas: actuators, lightweight structures, and motor controllers. For actuators, the objective is to develop advanced actuator designs and modeling tools. For lightweight structures, the objective is to perform lightweight material manufacturing. For motor controllers, the objective is to develop enhanced current and voltage-handling techniques.

Challenges for actuators include a lack of advanced actuator design modeling tools, as well as challenges in improving absolute position sensing. Challenges for lightweight structures include composite and lightweight material manufacturing techniques. Challenges for motor controllers include the development of current and voltage handling techniques, small form factors for processing capability, and radiation-tolerant electronics.

Benefits of Technology

The benefit of these technologies to future missions is their ability to develop space-rated manipulators that can operate in deep-space environments. Advances in actuator, lightweight materials, and motor controller technologies will overcome cold temperatures and high radiation challenges.

Table 18. TA 4.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.3.1.1	Actuators	Generate forces and torque to create motion of a robot.
4.3.1.2	Lightweight Structures	Provide structures developed from lightweight materials for robotic arm designs.
4.3.1.3	Motor Controllers	Provide control and power electronics and intelligence to run an actuator to meet performance requirements.
4.3.1.4	Manipulator Concepts	Provide new manipulator concepts with improved kinematic configuration (serial, parallel, hybrids), dynamic performance (structural stiffness), packaging efficiency, and payload to mass ratio.

TA 4.3.2 Dexterous Manipulation

Dexterous manipulation pertains to the design of manipulators and end-effectors, as well as the algorithms that control their motions to generate smooth, human-like arm trajectories and fine end-effector motions that can flexibly manipulate objects. The SOA in manipulation includes the Robonaut 2 limb, which combines a dexterous manipulator arm with a multi-fingered dexterous end-effector that is capable of compliant grasps of natural objects. The limb is capable of working with interfaces designed for use by humans, and extends beyond human performance to smaller scale and greater agility.

In-space technology has advanced from position control to impedance control, with end-point force sensing to embedded joint torque control. The SOA in dexterous manipulation on planetary surfaces includes the Mars rovers' arms. In commercial and industrial applications, compliant and dexterous robotic arms work side-by-side with humans on factory floors, handling a range of parts and conducting large, small, and fine assembly tasks. Challenges include the control of a large number of DOF, real-time computation and reaction to external forces, and power requirements.

Technical Capability Objectives and Challenges

The objective for dexterous manipulation is to reliably handle, position, and control objects and interfaces on spacecraft, equipment, tools, and natural objects, and to achieve compliant force resolution for safe operations in the vicinity of humans. It also includes developing advanced multi-modal control systems, as well as advanced actuator stacks. Performance metrics include number of arms, DOF, reach, strength, position resolution, force resolution, speed, operational lifetime, radiation tolerance, and operational thermal limits.

The objective for dexterous end effectors is to provide reliable grasping of objects of various geometries, swapping of tools, and actuating interfaces while minimizing the need for specialized tools. Another objective is to improve robustness and resolution for sensor arrays, as well as improve pre-grasp sensing. Performance metrics include grip strength, maximum object mass and size, tactile force resolution, radiation tolerance, operational lifetime, and operational thermal limits.

The challenges currently impeding the development of these capabilities are a lack of advanced multi-modal control systems, lack of advanced actuator stacks, and lack of robust, high-resolution sensor arrays within the hands and fingers that can sense contact anywhere on the hand. Additional challenges include high-specific-power actuators, miniaturized computing networks, improvements in pre-grasp sensing, integrated tactile perception, force control, grasping reflexes, grasp learning, tool use, and autonomous object manipulation.

Benefits of Technology

The benefit to future missions is the use of dexterous manipulation arms and end-effectors, which can operate in deep-space environments. Advances in dexterous manipulator arms and end-effector capabilities will overcome challenges with cold temperatures and high radiation.

Table 19. TA 4.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
4.3.2.1	Dexterous Manipulator Arms	Provide handling, positioning, and controlling of objects and interfaces on spacecraft, equipment, tools, and natural objects.
4.3.2.2	Dexterous Manipulator End Effectors	Provide an ability to reliably grasp diverse objects, swap tools, and actuate interfaces.

TA 4.3.3 Modeling of Contact Dynamics

See TA 4.7.3 Robot Modeling and Simulation.

TA 4.3.4 Mobile Manipulation

Mobile manipulation combines mobility and manipulation to extend the usable workspace of a robotic arm. The SOA has been limited to the sequential use of mobility and manipulation. For example, a mobile platform base places the arm over a desired area of interest and the arm performs motions while the base is stationary. This is exemplified in the arm operations of the Mars rovers and has been demonstrated in prototype deployments of Robonaut 2 on the Centaur mobile platform base. Systems have been demonstrated in research labs that simultaneously control the mobility and manipulation DOF to enhance the manipulability and workspace of the system. Examples include mobile manipulators opening and walking through doorways. Challenges include the fine control of the manipulator's end-effector motion while the mobile base is in motion across uneven planetary terrain.

Technical Capability Objectives and Challenges

The objective is to dynamically extend the manipulation workspace through simultaneous coordination of mobility and manipulation tasks, and the fusion of localization with force control. Coordinated moves allow the manipulation subsystem to aid in managing the center of gravity for mobility and the mobility function to expand the range of motion for manipulation.

Challenges that are currently impeding the development of these capabilities include coordinated motion, force control across the entire system, and fusion of localization with force control.

Benefits of Technology

These technologies enable in-space assembly of large structures and allow sites to be prepared in anticipation of crew arrival by conducting efficient operations across a large workspace.

Table 20. TA 4.3.4 Technology Candidates – not in priority order

TA	Technology Name	Description
4.3.4.1	Mobile Manipulation	Provides a manipulation capability across a large work region.

TA 4.3.5 Collaborative Manipulation

Similar to collaborative mobility, collaborative manipulation involves the use of multiple robotic manipulators that are either rigidly connected to a common base (for example, two robotic arms on a single rover) or to independent mobile bases. Terrestrial multi-robot handling systems include small and large combinations, including swarm approaches. Collaboration includes coordinated motions, where multiple manipulators are physically connected, as in the case of handling of a common load, or cooperating to achieve a common goal. In the latter case, manipulators can share information about their intent to avoid collision and coordinate their tasks. Robots that jointly handle shared objects have been demonstrated with terrestrial robots, such as NASA's Robonaut. Challenges include coordinating systems with large DOF.

Technical Capability Objectives and Challenges

The objective is to advance human interaction modalities superimposed on a force control problem, multi-point contact methodologies, and advanced safety systems. For collaborative manipulation, the required technical capability is to provide a teamed approach for multiple robots or teams of humans and robots working with objects, equipment, or samples. This activity encompasses multi-robot and human-robot object handling, including low-latency telerobotics, to accomplish large-scale operations.

Challenges currently impeding the development of these capabilities include a wide array of human interaction modalities superimposed on a force control problem, multi-point contact problems, and robust safety system development. Advancements in collaborative manipulation system capabilities will overcome these challenges.

Benefits of Technology

The benefits of these technologies to future missions are that they enable the development of space-rated collaborative manipulation capability, which can operate on planetary surfaces as well as in deep-space environments.

Table 21. TA 4.3.5 Technology Candidates – not in priority order

TA	Technology Name	Description
4.3.5.1	Collaborative Manipulation	Provides a teamed approach for multiple robots or teams of humans and robots working with objects, equipment, or samples.

TA 4.3.6 Sample Acquisition and Handling

NASA autonomous rover equipped with drills

Sample acquisition and handling involves moving rocks and regolith for surface preparation, placing in-situ instruments, scooping, trenching, drilling (shallow and deep), coring, excavating, extracting samples, transferring samples to onboard instruments for analysis or handling, and sealing samples in containers for later analysis or for return to Earth in a manner consistent with science and planetary protection requirements. The SOA in shallow surface removal includes surface scoops and the arm-mounted rock abrasion tool (RAT) used by landers and rovers on the Moon and Mars. Rakes, pneumatic nozzles, and dozer blades have been demonstrated in laboratory environments. The SOA in subsurface sample acquisition includes percussive drilling technology on a Mars rover arm and the collection and transfer of powdered samples. Prototypes of coring drills and auger systems have been demonstrated. Sample acquisition on planetary bodies has been limited to extracting samples from a depth of only a few centimeters. For regolith and volatile sample handling and transfer, the SOA includes the Apollo sample return boxes and several NASA sample return missions. On Earth, the acquisition of material at depth has largely been driven by the oil, gas, and mining industries through deep directional drilling (thousands of meters) and down-hole tooling. Sample containment and downstream processing has primarily been advanced by medical and hazardous material-handling applications.

Technical Capability Objectives and Challenges

The objective is to develop sample acquisition approaches, sample conveyance techniques, and cleanliness and contamination prevention strategies. The objective for handling and transferring regolith and volatile samples is to develop options for sample collection from shallow to deep subsurfaces, as well as acquisition of volatiles and samples without losing the volatiles or inappropriety contaminating them or the acquisition system (see also TA 7.5.2 and TA 13.2.5).

Robots are needed to drill into natural materials to place sensors, extract cuttings, or produce core samples. A drilling device is required for subsurface regolith and volatile samples at depths greater than one meter, though other devices need to be explored. Challenges include developing tools for dry drilling, handling samples and raw materials, and developing system-cleaning approaches to avoid cross contamination. Advances are needed for increasing drilling depth and hole diameter, as well as for reducing system power and mass.

For shallow subsurface sample acquisition, up to three centimeters in depth for surface or shallow acquisition down to one meter in depth for subsurface acquisition, the required capability is the development of smart sample acquisition devices that robotically pick up surface rocks and loose surface dust or regolith. Challenges include a lack of regolith acquisition with smart size sorting and a lack of capabilities in autonomous operation. Advances are needed to increase the depth and diameter of the sample size and reduce digging forces.

The objective for regolith and volatiles sample handling and transfer is to acquire and contain regolith or rock samples for transfer to the end user or instrument for characterization. In the case of volatiles, special sealing methods may be required to prevent sublimation losses. Challenges include a lack of options for sample collection down to one meter in depth and acquisition, containment, and preventing their contamination and that of the sample acquisition system. Advances are needed in sample size, canister sealing and verification capability, and sample caching capability.

Robotic excavation removes surface regolith materials, either to expose lower strata or to deliver excavated bulk material for science or ISRU applications. Challenges include a lack of power storage systems, worksite lighting systems, and autonomous system operations. Advances are needed to increase sample mass and excavation depth.

Benefits of Technology

Sample acquisition and handling is a critical capability for both science and human exploration missions. For science, it is the means by which samples get ingested into instruments for further analysis. Therefore, proper handling of samples that contain volatiles is critical to avoid contamination or losing the sample. For human exploration missions, the ability to handle large samples is critical for science and ISRU applications, modification of landing or habitation zones, and modification of habitat shielding.

These technologies will lead to space-rated sample acquisition and handling capability that can operate on planetary surfaces, as well as in deep-space environments.

Table 22. TA 4.3.6 Technology Candidates – not in priority order

TA	Technology Name	Description
4.3.6.1	Robotic Drilling	Drills into natural materials to place sensors, extract cuttings, or produce core samples.
4.3.6.2	Deep Robotic Drilling	Provides hundreds of meters of drilling into natural materials to extract subsurface regolith, cuttings, or volatile samples, to collect small core samples, or to emplace sensors for exploration.
4.3.6.3	Surface/Shallow Robotic Sample Acquisition	Provides smart sample acquisition devices for robotically picking up surface rocks and loose surface dust or regolith up to 3 centimeters in depth.
4.3.6.4	Subsurface Robotic Sample Acquisition	Provides smart sample acquisition devices for collecting regolith and volatiles up to 1 meter in depth.
4.3.6.5	Sample Handling	Provides a means to move, transfer, or modify samples that have been acquired, loading them into instruments or packaging systems.
4.3.6.6	Regolith/Volatiles Sample Handling and Transfer	Provides a system that contains, stores, and transfers regolith and rock samples to the end user or instrument for characterization. Special sealing and verification methods may be required in case of volatiles to prevent sublimation losses and in the case of solids for planetary protection reasons.
4.3.6.7	Robotic Excavation	Provides a means to remove surface regolith materials, either to expose lower strata or to deliver excavated bulk material for other use.

TA 4.3.7 Grappling

Grappling pertains to handling large objects or free flyers in microgravity environments. The SOA is the assembly of ISS modules using the seven-DOF Space Station Remote Manipulator System (SSRMS). It also includes positioning EVA astronauts for servicing and repair activities. Future missions will use grappling techniques for NEA exploration, where de-spinning an object is a challenge, and for assembling space structures.

Technical Capability Objectives and Challenges

The objective is to enable robots to grapple natural and human-made free-flying objects using surface features, and then to berth these objects to the robot’s spacecraft through a rigidized interface. Challenges include the ability to grapple asteroids and natural objects, and any objects in dynamic spin or free drift. Advances are needed to enable grappling targets with greater object mass, object speed and rotation rates, and to improve the arm’s reach.

Benefits of Technology

These technologies benefit future missions by enabling development of grappling systems that can operate in deep-space environments. These new capabilities will increase vision and control system capabilities to handle larger structures for assembly of on-orbit spacecraft for future human exploration missions to NEAs and planetary bodies.

Table 23. TA 4.3.7 Technology Candidates – not in priority order

TA	Technology Name	Description
4.3.7.1	Grappling	Provides robots that can grapple objects and free-flying spacecraft using surface features, then berth them to the robot's spacecraft through a rigidized interface.

TA 4.4: Human-System Interaction

Making human-system interaction effective, efficient, and natural is crucial to future space exploration. The ultimate efficacy of robotic systems depends greatly upon the interfaces that humans use to operate them. As robots and the tasks assigned to them grow more complex, the demands placed on the interfaces used to control them also increase.

Space exploration requires human-system interaction across multiple spatial ranges, in the presence of multiple control loops, and over a wide range of time delays. A robot may be remotely operated by an astronaut in close proximity, by an astronaut in-orbit above a planetary surface, or by mission controllers on Earth with progressive reductions in situational awareness and response time. Different time delay regimes also require distinct levels of autonomy and modes of control to prevent harm to crew or damage to the system as operators become increasingly remote.

To date, different human-system interaction approaches have been employed in human and deep-space robotic missions. Human missions have all been conducted with near-continuous communication (data and voice) and minimal delay. Telerobotic operations, such as the Shuttle Remote Manipulator System (SRMS), have focused on positioning external payloads using multiple cameras and manual control. These activities generally follow pre-planned procedures and schedules, which are used for ground-based training and then on-orbit manual execution. In contrast, robotic missions have traditionally centered on the use of supervisory control in the presence of high delay (tens of minutes). For these missions, carefully designed and validated command sequences are intermittently uplinked by mission control to the robot for autonomous execution. The robot, such as a planetary rover on Mars, functions independently for long periods without communication to operators at mission control.

Human-System Interaction includes classical areas of telerobotics (such as haptics), human-system interfaces, and augmented reality with newer topics that include human-system integration, human safety, human-robot teams, crew decision support, interaction with the public, and supervision across the time delays of space. Performance metrics include efficiency indices like the mean time for a human to intervene in a system. These technologies complement data interaction related technologies described in TA 11.4.7 Human-System Interaction that focus on interfaces to mission operation functions, scientific data analysis, and hazard analysis.

Sub-Goals

The goal of human-system interaction is to enable a human to rapidly understand the state of the system under control and effectively direct its actions towards a new desired state. This development area explores advanced technologies for improving a human operator’s situational awareness, capturing the operator’s intent, and enabling a robot’s safe operation in the vicinity of humans and critical systems. Due to the limited number of astronauts anticipated to be on planetary exploration missions and their constrained in-space schedules, ground personnel will likely need to assist and remotely supervise some autonomous systems.

Since coordinating a heterogeneous team of humans and autonomous systems is complex, a key challenge is to develop tools and techniques that allow each agent to have multiple command paths and degrees of autonomy. Another key challenge is to develop advanced user interfaces that enable humans (both ground control and astronauts) and autonomous systems to communicate clearly about their goals, abilities, plans, and achievements; collaborate to solve problems, especially when situations are beyond autonomous capabilities; and interact via multiple modalities (dialogue, gestures), both locally and remotely.

Table 24. Summary of Level 4.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.4 Human-System Interaction	Sub-Goals:	Enable a human to rapidly understand the state of the system under control and effectively direct its actions towards a new desired state.
Level 3		
4.4.1 Multi-Modal Interaction	Objectives:	Provides virtual environments that can be naturally explored by the human operator.
	Challenges:	Enabling the operator to effectively utilize multiple sensory modes and mitigate the negative impacts of virtual environment (VE) implementation. Human-paced interaction with robots, accuracy of recognition, adapting dialogue, and graceful degradation.
	Benefits:	Provides effective interaction of humans with machines, thus reducing the necessary training and ultimately enabling humans to control a larger number of robotic and autonomous assets.
4.4.2 Supervisory Control	See TA 4.4.8 Remote Interaction.	
4.4.3 Proximate Interaction	Objectives:	Provides interoperable, robust, and usable hardware and software systems that can recognize user activities and intent, and respond appropriately in a timely manner. Effectively communicate system state, goals, and high-level indications. Provides a physical interface between robots and astronauts' suits, habitat, and/or rover.
	Challenges:	Uncertainty in recognizing user activity, gaze, gestures, speech, and other elements as indicators of implicit operator intent; behavioral models capable of predicting future operator actions; and planning systems capable of responding appropriately. Communicating large volumes of complex system-state information to users in a short period of time. Robot interfaces to suits in vacuum and dusty environments, and effective control of robotic systems attached to the suit by the crew member.
	Benefits:	Provides effective interaction between humans and machines, thus reducing overall demands on astronauts' time for future exploration missions.
4.4.4 Intent Recognition and Reaction	See TA 4.4.3 Proximate Interaction.	
4.4.5 Distributed Collaboration and Coordination	Objectives:	Provide a distributed system that is capable of managing control and telemetry information among heterogeneous agents.
	Challenges:	Effective communication of goals, abilities, plans, and achievements between humans and machines. Appropriate metrics, reusable software framework for in-line processing and assessment of telemetry and historical data, and automatically reporting on performance at different levels of abstraction to different users. Algorithms for event detection methods for summarization and techniques for delivering and displaying notifications and summaries.
	Benefits:	Provide more effective interaction between humans and machines, thus reducing overall demands on astronauts' time for future exploration missions.
4.4.6 Common and Standard Human-System Interfaces	See TA 4.7.1 Modularity, Commonality, and Interfaces.	

Table 24. Summary of Level 4.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.4.7 Safety, Trust, and Interfacing of Robotic and Human Proximity Operations	See TA 4.7.5 Safety and Trust	
4.4.8 Remote Interaction	Objectives:	Provides manual and supervisory control of complex remote systems across a space communications link in the presence of short delays.
	Challenges:	Mitigating the effects of latency on manual control, facilitating operator situational awareness, minimizing bandwidth requirements, and minimizing performance variation due to operator differences. Effective decision support tools. Effective use of open standards and protocols, supporting interoperability, minimizing the effort and time required for supporting new functions or adapting to new missions, and enabling high usability.
	Benefits:	Provides effective interaction between humans and machines, thus reducing overall demands on astronauts' time for future exploration missions.

TA 4.4.1 Multi-Modal Interaction

Current user interfaces are generally uni-modal; that is, they rely heavily on visual displays to communicate system state to an operator and a single control mode at any given time. Displays typically show sensor data (camera images, battery voltage), system health, and other parameters using two-dimensional (2D) text or 3D graphical representations. Some interfaces aggregate data into an integrated view, such as an interactive 3D visualization of a planetary rover in unstructured natural terrain. A variety of control modes ranging from manual to supervisory control are employed for commanding distant robots, which is generally implemented using command sequencing. Control modes are generally manually selected, though some systems employ either adjustable autonomy or mixed-initiative planning.

X1 Exoskeleton

In contrast, multi-modal human-system interaction employs multiple display modalities and multiple communication channels. This approach has significant potential to enhance situational awareness and enable more efficient, human-like interaction. Virtual environments, for example, may combine interactive 3D computer graphics, immersive displays, head and body tracking, haptics, spatialized sound, and other non-visual displays to create a sense of "presence." Although virtual environments have not yet been used for flight mission operations, they have been employed for science data visualization and for remotely operating research robots in numerous analog field tests.

As another example, multi-modal dialogue systems combine multiple communication methods to enable a user to communicate with an autonomous system (software agent or robot) in a human-like manner. In particular, several mid-TRL research systems have successfully demonstrated multi-modal dialogue between humans and robots, which incorporates spoken natural language, deictic and iconic gestures, and computational cognitive models.

Technical Capability Objectives and Challenges

The objective is for systems to provide an effective sense of "presence" for a complex planetary surface mission and to develop a transparent human-robot dialogue for proximal and remote interaction. Challenges include enabling the operator to effectively use multiple sensory modes, perceive system state, understand the remote environment, issue commands, and mitigate the negative impacts of virtual environment (VE) implementation, such as spatial display distortions, system latency, and display resolution. Other challenges include achieving human-paced interaction with robots; ensuring accuracy of speech or gesture recognition; adapting dialogue to the user, situation or context, and bandwidth; and supporting graceful degradation.

Benefits of Technology

The benefit of multi-modal interaction is to enable more effective interaction of humans with machines, thereby reducing the necessary training and ultimately enabling humans to control a larger number of robotic and autonomous assets.

Table 25. TA 4.4.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.4.1.1	Virtual Environment (VE)	Immersive, interactive, virtual image displays enhanced by non-visual display modalities (auditory, haptic, etc.).
4.4.1.2	Multi-Modal Dialogue	Rich communication between humans and robots that incorporates natural language, gesturing, spatial dialogue, etc.

TA 4.4.2 Supervisory Control

See TA 4.4.8 Remote Interaction.

TA 4.4.3 Proximate Interaction

Proximate interaction involves control and feedback methods that enable humans to work safely and effectively in physical proximity to autonomous systems. For example, these methods allow a suited astronaut to attach and directly interact with a robot, such as a large positioning manipulator or a free flyer. Control represents fundamental user input into the system, which may be commands or information. Feedback includes signaling and communication, which are used to convey command confirmation, system status, and information from the system to the user.

Current research in proximate control methods focuses on recognizing user activity, gaze, gestures, intent, and speech. Recognition may require constructing and maintaining a variety of models (user behavior, task). Although research systems have demonstrated significant progress with structured tasks, a great deal more work is required to achieve reliable performance for unstructured tasks. A structured task is work that involves a well-defined routine or standardized sequence of operations, like routine maintenance. An unstructured task is work that involves ambiguity and uncertainty or for which no standardized procedure or routine practice exists, such as contingency handling.

There are many ways to provide feedback during proximate interaction, and common categories of techniques include:

- visual mechanisms, such as light arrays, point lights, text readouts, and graphical interfaces;
- body language, such as movement and gestures;
- auditory techniques, such as synthesized speech and sounds; and
- force displays, such as haptic and tactile displays.

Numerous research systems have demonstrated proof-of-concept with a variety of signaling and communication methods for proximal interaction between humans and autonomous systems. Moreover, significant research and development in human-computer interaction and industrial design have successfully used these approaches for a wide range of consumer products.

Technical Capability Objectives and Challenges

One objective is to provide interoperable, robust, and usable hardware and software systems that can recognize user activities and intent and respond appropriately in a timely manner. Another objective is to provide the means for effectively communicating system state, such as subsystem health, errors, and faults; goals; movement intention and control mode; and high-level indications, such as task progress, information, and intervention need. A third objective is to provide a physical interface between robots and astronaut's suits, habitats, and/or rovers.

Challenges include uncertainty in recognizing user activity; gaze, such as direction and target; gestures, such as affect, deictic, and iconic; speech; and other elements as indicators of implicit operator intent. Other challenges in this area include behavioral models capable of predicting future operator actions and planning systems capable of responding appropriately. They also include communicating large volumes of complex system-state information, such as subsystem health, errors, faults, goals, and task progress to users in a short period of time. Interfaces for mating and de-mating robots to suits in a vacuum and dusty environments, and the effective control of robotic systems attached to the suit by the crew member is no trivial feat.

Benefits of Technology

This technology enables more effective interaction between humans and machines, reducing overall demands on astronauts' time for future exploration missions.

Table 26. TA 4.4.3 Technology Candidates – not in priority order

TA	Technology Name	Description
4.4.3.1	Robot-to-Suit Interfaces	Enables suited astronaut to attach and directly interact with a robotic system.
4.4.3.2	Intent Recognition and Reaction	Enables autonomous system to detect, recognize, and/or react to human intent.
4.4.3.3	Feedback Displays for Proximate Interaction	Enables user to receive feedback (status, information, etc.) and to monitor activity or intent of autonomous system.

TA 4.4.4 Intent Recognition and Reaction

See TA 4.4.3 Proximate Interaction.

TA 4.4.5 Distributed Collaboration and Coordination

Space missions require a large ground control team to:

- minimize the potential for error and risk of mission loss;
- support detailed analysis, system monitoring, resource modeling, and contingency handling;
- handle the complexity inherent with space operations, including deep-space communications, timing synchronization, operations scheduling, and diagnostics and prognostics; and
- plan and execute mission-specific activities, such as field geology using robot-mounted science instruments.

To reduce the costs associated with co-locating a large team, mission operations have become increasingly geographically distributed. Coordinating a distributed team of humans is complex. The challenge is compounded when the team includes systems with varying levels of autonomy and competency.

One approach to improving distributed collaboration and coordination is to employ an interaction architecture. Interaction architectures are structured software frameworks that support human-system coordination, communication, and collaboration. These architectures generally include methods for resource and task allocation, trading and sharing control, and dialogue management. Significant research has focused on developing interaction architectures during the past several years, particularly for supporting ubiquitous and context-aware applications, including robots.

Other techniques to improve distributed collaboration and coordination include performance monitoring, summarization, and notification. Performance monitoring, particularly systems capable of continuous, in-line assessment, help increase situational awareness and more effective system operation by evaluating operational efficiency, task performance, and/or effort. Summarization and notification can also make joint system operation more effective by helping operators better understand task performance, system state, and trends over time. Research systems have demonstrated proof-of-concept with these techniques for a variety of applications, including water plant management and mobile robot site surveys. However, the robustness and performance of these systems under flight conditions and over long durations have not yet been proven.

Technical Capability Objectives and Challenges

The objective is to provide a distributed system for a mix of humans, robots, and (multi-agent) autonomous systems that is capable of managing control and telemetry information among heterogeneous agents. The system should be capable of evaluating actual versus planned performance, detecting key events, generating appropriate notifications, and producing informative summaries from telemetry streams.

The challenges include effective communication of goals, abilities, plans, and achievements between humans and machines and collaboratively solving problems. Other challenges include developing appropriate, descriptive, and powerful metrics; designing a reusable software framework for in-line processing and assessment of telemetry and historical data; and automatically reporting on performance at different levels of abstraction to different users, such as the flight director or subsystem engineer. Additional challenges include developing algorithms for event detection, such as real-time and post-processing of telemetry; methods for summarization, such as narrative and graphical; and techniques for delivering and displaying notifications and summaries.

Benefits of Technology

This technology enables more effective interaction between humans and machines, reducing overall demands on astronauts' time for future exploration missions.

Table 27. TA 4.4.5 Technology Candidates – not in priority order

TA	Technology Name	Description
4.4.5.1	Interaction Architecture	Provides software framework that facilitates coordination, communication, and collaboration between humans and autonomous systems (including robots and software agents).
4.4.5.2	In-Line Performance Metrics	Provide software that continually assesses the operational efficiency, task performance, and/or effort of a human-system team (individual or joint).
4.4.5.3	Notification and Summarization	Provide software that facilitates human-system operations by providing automated notification and summarization of key events or activities, system state, and operational data.

TA 4.4.6 Common Human-Systems Interfaces

See TA 4.7.1 Modularity, Commonality, and Interfaces

TA 4.4.7 Safety, Trust, and Interfacing of Robotic/Human Proximity Operations

See TA 4.7.4 Robot Software.

TA 4.4.8 Remote Interaction

Remote interaction involves control and feedback methods that enable humans to remotely operate robots and autonomous systems. A wide range of remote control strategies has been developed over the past 50 years for a variety of devices, vehicles, and systems. Feedback includes signaling and communication that are used to convey command confirmation, system status, and information from the remote system to the user.

Control methods for remotely-operated space systems range from manual to supervisory control. Manual control, also known as direct teleoperation, involves the operator directly operating the remote system. Remotely driving a vehicle using joysticks and rate control and remotely positioning a manipulator arm using a force-reflecting master and slave controller are examples of manual control. With supervisory control, the operator intermittently commands and monitors an automated system, intervening only when necessary. The remote operation of the Mars exploration rovers by daily “uplink” of command sequences and “downlink” of recorded data is an example of supervisory control.

Regardless of control method, operators of remote systems require a variety of decision support tools. These tools, which are often components of a larger ground data system, enable operators or a team of operators to monitor system status, assess task progress, perceive the remote environment, and make informed operational decisions, such as tactical plans. These tools may include simulation; telemetry and data replay; feedback displays, including auditory, force and haptics, 2D and 3D maps, and 2D and 3D graphics; and groupware for computer-supported collaborative work.

Technical Capability Objectives and Challenges

The objective is to provide capabilities for both manual and supervisory control of complex remote systems across a space communications link in the presence of a short, < 1 second, delay. The eventual objective is to have smaller ground control teams that can achieve the same or better performance as larger teams through the use of decision support tools.

Challenges include mitigating the effects of latency on manual control, facilitating operator situational awareness, minimizing bandwidth requirements, and minimizing performance variation due to operator differences such as proficiency, training, and fatigue. It also includes providing effective decision support tools, including summarization, notification, and in-line performance metrics. Other challenges include making effective use of open standards and protocols, supporting interoperability, minimizing the effort and time required to support new functions or adapt to new missions, and enabling high usability, including minimal training, workload, and barriers to use.

Benefits of Technology

This technology enables more effective interaction between humans and machines, reducing overall demands on astronauts’ time for future exploration missions.

Table 28. TA 4.4.8 Technology Candidates – not in priority order

TA	Technology Name	Description
4.4.8.1	Direct Teleoperation	Provides a system for performing manual control of a remote platform.
4.4.8.2	Supervisory Control	Provides a system for performing supervised control of a remote platform.
4.4.8.3	Decision Support Tools for Remote Interaction	Provides systems that enable users to make informed reactive (including interruption), tactical, and/or strategic decisions for operating remote systems.

TA 4.5: System-Level Autonomy

Autonomy is the ability of a system to achieve goals while operating independently of external control. There is a spectrum of autonomy in a system that ranges from local autonomy within a subsystem, where actions may be executed in response to a stimuli or local information, to system-level autonomy, which manages actions and handles constraints across subsystems. Subsystem autonomy is addressed within their respective Level 2 sections: 4.1 Sensing and Perception, 4.2 Mobility, 4.3 Manipulation, 4.4 Human-System Interaction, and 4.6 Autonomous Rendezvous and Docking. This section focuses on system-level autonomy. Fully autonomous systems would be able to act independently and intelligently in dynamic and uncertain environments.

Autonomous system development seeks to improve performance with a reduced burden on crew and ground-support personnel, achieving safe and efficient control and enabling decisions in complex and dynamic environments. Autonomous system metrics include the number of humans needed to operate a system, mean time between human interventions, and number of functions performed per intervention.

The SOA for onboard system-level autonomy has limited operational use across missions. The primary barriers to use are the lack of onboard computation and storage and the challenges associated with scaling up the state of the technology to more complex scenarios where they can handle unanticipated anomalies and learn from past experience. The key areas in system-level autonomy are system health management, activity planning, scheduling, execution, multi-agent coordination, and automated data analysis for decision making.

Two application areas of autonomy are: increased use of autonomy to enable an independently-acting system, and automation to augment human operation. Autonomy's fundamental benefits are increasing system operations capability, enabling cost savings by reducing human labor needs and increasing efficiencies, and increasing mission assurance or robustness in uncertain environments.

Sub-Goals

Autonomy can provide significant performance improvements, operational efficiencies, and other benefits to many technology areas in the roadmaps. The need for autonomy is evident when:

- the cadence of onboard decision making is beyond communication constraints (delays and communication windows);
- time-critical decisions must be made onboard the system or vehicle, such as control, health, and life-support;
- decisions are better informed by the richness of onboard data compared to limited down-linked data;
- local decisions improve manageability and robustness of overall system architecture and reduce complexity; and
- autonomous decision making reduces overall cost or improves effectiveness.

Autonomy is a critical crosscutting technology for improving performance and reducing risk for a wide range of NASA human exploration (crew vehicles, habitats), robotic (spacecraft, rovers, in-situ systems), and aeronautics (airspace, airport, and aircraft) applications.

Table 29. Summary of Level 4.5 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.5 System-Level Autonomy	Sub-Goals:	Enable extended-duration operations without human intervention to improve overall performance of human exploration, robotic missions, and aeronautics applications through increased autonomy.
Level 3		
4.5.1 System Health Management	Objectives:	Identify off-nominal behavior and detect faults, analyze resulting data to identify probable causes and effects, take action to keep system operating, and alert crew.
	Challenges:	Timeliness and accessibility to system data. Adequate onboard computational and storage resources for analyzing and storing current and historical data trends. Verification and validation (V&V) of model-based approaches.
	Benefits:	Enables longer-duration operations and survivability in spite of degradations or failures of individual or subsystem components given limited communication with Earth.
4.5.2 Activity Planning, Scheduling, and Execution	Objectives:	Operate spacecraft using a goal-based approach that enables autonomous operation.
	Challenges:	Adequate computational resources and tools. Scalability of the technologies to more realistic scenarios. Mixed-initiative input of human- and auto-generated plans. Generation of safe, correct, and verifiably optimal plans. Traceability of plans to the initial activity requirements.
	Benefits:	Provide autonomy for missions with challenging communication constraints and where models of the environment are only partially understood.
4.5.3 Autonomous Guidance and Control	See TA 5.4 Position, Navigation, and Timing.	
4.5.4 Multi-Agent Coordination	Objectives:	Distribute autonomous functionalities, operations, or simulations across platforms and coordinate the distributed functionalities to generate intelligent behavior.
	Challenges:	Heterogeneity of the hardware agents and software tools that need to be interfaced. Verification and validation of the complex agent interactions. Managing a system of agents to achieve a specific goal.
	Benefits:	Reduces astronauts' and ground operators' time in managing and coordinating autonomous capabilities on multiple assets be it in space, on crewed missions, or on the ground.
4.5.5 Adjustable Autonomy	Adjustable Autonomy is a feature of both subsystem and system-level autonomy, which has already been subsumed under Level 3 TAs in this roadmap.	
4.5.6 Terrain Relative Navigation	See 4.1.2 State Estimation.	
4.5.7 Path and Motion Planning with Uncertainty	See 4.2.6 Robot Navigation and 4.3.2 Dexterous Manipulation.	

Table 29. Summary of Level 4.5 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.5.8 Automated Data Analysis for Decision Making	Objectives:	Automatically analyze large and heterogeneous data sets to synthesize information for operational decisions.
	Challenges:	Adequate onboard computational and storage resources for analyzing and storing current and historical data trends. Heterogeneous nature of the data and its large uncertainties. Availability of partial or incomplete models. Verification and validation of decision-making systems.
	Benefits:	Provides onboard autonomous systems to perform the decision-making and process-monitoring that is currently performed by ground control. Increases the use of autonomy to improve the affordability, efficiency, reliability, and safety of civil airspace, airport, and aircraft (manned and unmanned) operations. Provides civil aviation dynamic route planning (in response to traffic and weather), precision airport approach and departure management, payload directed flight, and in-flight compensation for degraded or failure of aircraft systems.

TA 4.5.1 System Health Management

For system health management diagnostic and prognostic tools, the SOA NASA systems have primarily employed a monitor-and-respond approach based on local system thresholds without knowledge of the state of the system. This approach results in static logic or procedures for detecting, isolating, and recovering from faults with fault logic verified and validated through exhaustive testing prior to launch. Moreover, this provides only limited modeling of interactions among subsystems.

For ground-based tools that have access to more advanced computing and storage capabilities, custom tools have been deployed to analyze spacecraft health. Typically, such approaches have largely used manually-generated fault trees and procedures. For some systems, real-time tools are used; however, all ground-based solutions are subject to communication constraints and blackout periods.

In aeronautics, advances have been made through the use of Aeronautical Radio, Inc. (ARINC) standards that enable system health management. The use of Aircraft Communications Addressing and Reporting System (ACARS) standards enables the communication of maintenance information between flight and ground crews. Helicopters have used health usage monitoring systems toward this end.

Today's technologies for system-health management include reliability-based, model-based, and statistics-based prognostic and diagnostic tools using data-centric or adaptive model-based approaches. For data-centric approaches, commercial products can diagnose both known and unanticipated faults using a diagnostic reasoner that adapts through learning; such systems have been used in test beds at various NASA centers. Other systems include Jet Propulsion Laboratory's (JPL) Beacon-based Exception Analysis for Multi-missions (BEAM), JPL's Spacecraft Health Inference Engine (SHINE), Ames Research Center's Inductive Monitoring System (IMS), and the G2 real-time expert system. The JPL BEAM uses integrated, onboard or off-board data analysis for fault detection, anomaly detection, and prognostics. The ARC IMS uses data mining clustering techniques to isolate off-nominal interaction between parameters. The G2 is an artificial intelligence (AI) expert system demonstrated onboard the ISS for payload monitoring and is also in use at some commercial satellite facilities to control formation systems. JPL's SHINE is a high-speed expert system (stateless rule-based system) and inference engine for the diagnosis of spacecraft health. Model-based approaches use maintenance information and physics-based models to predict future failures.

Technical Capability Objectives and Challenges

The objectives are to provide an automated hardware and software system that can identify off-nominal behavior, analyze resulting data to identify probable causes and effects, take action to keep the system operating, and alert the crew or ground control (diagnostics). The desired metrics for onboard hardware and software as well as ground-based software include:

- very low false positives (< 1-3 sigma) and false negatives (< 1-3 sigma);
- fast response time (time to criticality), which would be context specific but generally within the time window for corrective action;
- the ability of such systems to adapt to new situations, such as failures or degradation in performance of subsystems; and
- the ability to learn from past experience.

Another objective is the ability to anticipate impending faults and predict remaining useful life (prognostics) based on trends in data and inferred system health state, either onboard or on the ground, using data histories. Flexibility and scalability are also key attributes that determine how well these general systems can be adapted to missions of increased complexity, either crewed or robotic.

Challenges include timeliness and accessibility to system data and sufficient onboard computational and storage resources for analyzing and storing current and historical data trends. Onboard systems have greater access to real-time telemetry and system-state data, but have limited computation and storage. Conversely, ground software has limited and non-real-time data due to communication delays and bandwith limitations, but has abundant computation, given access to super-computing resources and data storage. Prognostic and diagnositic systems should be considered an integral part of the system architecture and not an afterthought. Approaches have included model-based and data-centric techniques. Model-based approaches would amount to a paradigm shift in developing such systems, which makes the barrier for their adoption greater. Challenges include ensuring model correctness. Alteratively, data-centric approaches need to have sufficient data to identify nominal behavior. Given the probablistic nature of these approaches, verification and validaiton of such capabilities are notoriously challenging.

Benefits of Technology

This technology has broad applicability to most future robotic and crewed missions. The complexity of operating a crewed interplanetary vehicle is perhaps comparable to that of a nuclear submarine. The latter typically has over one hundred crew members. The former, the interplanetary vehicle, has to be managed by a crew of less than half a dozen, which would require a significant level of autonomy for system-health management given limited communication with Earth.

Table 30. TA 4.5.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.5.1.1	Onboard Real-Time Fault Detection, Isolation, and Recovery (FDIR)	Onboard system (hardware and software) that continuously monitors and detects faults and failures in a spacecraft.
4.5.1.2	Ground-Based Fault Detection, Isolation, and Recovery (FDIR)	Processes telemetry (bandwidth limited and time-delayed) using ground-based computational resources (including supercomputers) to isolate faults, analyze root causes, and recommend actions for recovery.
4.5.1.3	Integrated Vehicle Health Management (IVHM)	Identifies trends based on telemetry and models that would predict impending failures and remaining useful life.

TA 4.5.2 Activity Planning, Scheduling, and Execution

The SOA for operating an unmanned spacecraft system is primarily accomplished through sending low-level commands and receiving telemetry from spacecraft sensors. Activities, from which low-level commands are generated, are typically planned and sequenced on the ground with significant involvement of ground operators. Time-based commands using fixed-sequence logic with pre-planned contingencies are subsequently uploaded for onboard execution. A sequence command failure results in aborting the execution of the sequence and all subsequent activities until the next communication cycle.

Having ground control in the loop places severe limitations for handling time-critical information, which is one of the key challenges. For time-critical events, such as planetary entry, descent, and landing, customized autonomous onboard solutions are devised. Manually generating time-based command sequences is time consuming and costly and does not allow for the rapid optimization of operational activities, particularly for environments with large uncertainties. Such environments would require the continuous repair of complex plans. Time-based command sequencing does not allow for verifiable command sequences with traceability to the initial activity requirements. As such, operational activities must be based on worst-case time estimates to avoid prematurely aborting the plan. Time-based sequencing requires that commands provide an accurate time-duration estimate. This does not lend itself to autonomous operation at the subsystem level. Consider, for example, autonomous surface navigation of a planetary rover that observes and detects hazards and plans its traverse accordingly. Due to the lack of prior perfect knowledge of the environment, the execution of such autonomous subsystem capability cannot be accurately predicted. Using worst-case time and resource estimates results in suboptimal use of already severely limited computational and power resources.

The SOA in planning and sequencing tools within NASA are the Hubble Space Telescope, the Mars rovers, the Deep Space Network (DSN), and astronaut crew time aboard the ISS. For example, the DSN has a team of 30 people to centrally generate the communications schedule for all missions.

Technolgies that exist today include automated, constraint-based planning and scheduling tools, which are used in several domains, such as manufacturing and production. Online usage of automated planning and scheduling for spacecraft applications has been limited to specific instruments. Examples include Ames Research Center's ISS power plan analysis and solar array management and JPL's automated planning and scheduling system on the Autonomous Sciencecraft Experiment (EO1). There are some synergies between planning and scheduling and V&V, where techniques from both communities have been used interchangeably. Model checkers and timed game automata have been used to verify flexible plans. State-centric systems, which control and manage system state and state histories to achieve goals, as well as several executive languages and software engines have been prototyped and demonsrated.

Technical Capability Objectives and Challenges

The objective is to transition from the current paradigm of operating spacecraft using command or telemetry to a goal-based approach that would enable autonomous operation. For such a system, activities can be planned, scheduled, executed, and monitored onboard to prevent resource usage violations. Ground-based planning and scheduling can be carried out with or without human intervention. This capability requires an integrated approach for managing system state onboard and on the ground. This becomes more critical for challenging and dynamic environments, where activities need to be adjusted or re-planned. Advances are needed in:

- computation to autonomously generate plans from activities and constraints;
- system-response time to generate and repair plans for timely actions;
- flexibility and scalability to handle more complex mission scenarios and challenging environments, where accurate models may not exist;
- generation of verifiable and optimal plans; and
- low false-positives and false-negatives for the corresponding V&V tools.

Challenges include:

- the need for advanced computational resources and tools, particularly when considering more realistic constraints of a spacecraft system;
- the scalability of the technologies to more challenging and realistic scenarios;
- the generation of safe, correct, and verifiably optimal plans, for example, scheduling communications for the DSN;
- the mixed-initiative input of human- and auto-generated plans, which makes plan verification more challenging; and
- the traceability of plans to the initial activity requirements.

Existing plan validation methods rely on fixed configurations, therefore such flexibility in the plans make them harder to validate.

Benefits of Technology

The benefits are broadly applicable to all NASA science and human exploration missions. This is particularly critical for missions with more challenging communication constraints and where models of the environment are only partially understood. Examples of these types of scenarios include exploration missions where above-surface mobility platforms have to deal with atmospheric conditions, such as on Titan and Venus.

Table 31. TA 4.5.2 Technology Candidates – not in priority order

TA	Technology Name	Description
4.5.2.1	Onboard Real-Time Planning and Scheduling	Plans and schedules onboard activities while managing resources and preventing conflicts and violations of constraints.
4.5.2.2	Ground-Based Mixed Initiative Planning and Scheduling	Provide on-ground planning and scheduling of activities for uploading, and preventing conflicts and violations of pre-defined constraints with or without human intervention (includes mixed initiative planning).
4.5.2.3	Plan/ Sequence/Schedule Verification Tools	Verifies the validity of plans, sequences, or schedules that are generated by automated and manual tools.
4.5.2.4	Onboard Executives	Executes and monitors the progress of activities generated by an automated or manual process and intervenes as necessary.
4.5.2.5	State Management	Provides an integrated management of system state between onboard assets and the ground systems.

TA 4.5.3 Autonomous Guidance and Control

See TA 5 Communications, and Navigation, and Orbital Debris Tracking and Characterization.

TA 4.5.4 Multi-Agent Coordination

The SOA platforms have primarily relied on centralized systems, when it comes to computational intelligence, with very few examples of distributing intelligent behaviors across multiple agents. The SOA in multi-agent coordination is the Orbital Communications Adapter Monitoring System (OCAMS). The OCAMS is one of the few multi-agent systems certified for use on an active space system. The OCAMS uses agent systems to represent and model the activities of multiple mission operations systems and tools. These agents coordinate between directed goals while managing constraints and executing procedures to move data files between ISS onboard systems and the ground-based mission operations systems. Outside of NASA, multi-agent systems have been used for dynamic load balancing of networked systems.

Technical Capability Objectives and Challenges

The objective is to provide an infrastructure and algorithms for distributing autonomous functionalities, operations, or simulations across platforms with a means for coordinating the distributed functionalities to generate intelligent behavior. This provides a capability for leveraging distributed computational resources on Earth and in space. Improvements are needed for system response time, overall system reliability and resilience to failed agents, the range of operations that can be performed, and the range of hardware and software systems that can be integrated. Challenges include the heterogeneity of the hardware agents and software tools that need to be interfaced, the verification and validation of complex agent interactions, and the management of agents to achieve a specific goal.

Benefits of Technology

This technology would reduce astronauts' and ground operators' time in managing and coordinating autonomous capabilities on multiple assets, be it in-space on crewed missions or on the ground. This would be relevant to crewed lunar and martian missions as well as missions to a NEA.

Table 32. TA 4.5.4 Technologies

TA	Technology Name	Description
4.5.4.1	Multi-Agent Coordination	Provides an infrastructure for distributing autonomous functionalities across platforms.

TA 4.5.5 Adjustable Autonomy

Adjustable Autonomy is a feature of both subsystem- and system-level autonomy, which has been subsumed under Level 3 TAs in this roadmap.

TA 4.5.6 Terrain Relative Navigation

See TA 4.1.2 State Estimation.

TA 4.5.7 Path and Motion Planning with Uncertainty

See TA 4.2.6 Robot Navigation and 4.3.2 Dexterous Manipulation.

TA 4.5.8 Automated Data Analysis for Decision Making

Humans-in-the-loop largely drive the SOA in decision-making data analysis. Operators rely on customized, specific tools that often work on certain data sets. Correlations between data sets are harder to identify and identifying trends in data are harder to extract. The SOA in data analysis for decision making is very limited. Examples are of a Mars planetary rover's end-of-sol (i.e. end-of-martian day) pointing of the mast to acquire higher-resolution images of rocks with interesting features that were analyzed in images acquired by the lower-resolution cameras and its identification of images that contained dust devils that were prioritized for downlink.

Significant advances have been made recently in technologies that can analyze large, heterogeneous data sets for trends using information technologies. While onboard computation will remain a significant limitation for applying such technologies onboard spacecraft, techniques could be applied on ground-based telemetry to better inform decisions for onboard operations.

Technical Capability Objectives and Challenges

The objective is to automatically analyze large and heterogeneous data sets from spacecraft telemetry, where data may have large uncertainties and conflicting information and where only partial models are available, to synthesize information for operational decisions. The analysis of such large data volumes can be done on the craft whenever sufficient resources are available onboard. The objective is to provide an ability that can exceed human performance in addressing conflicting information in large data sets. Advances are needed in quality of service, estimate of computation time for decision-making, and time to make a decision. While some aspects may overlap with TA 4.1.4 Object, Event, and Activity Recognition, this area goes beyond the analysis of data from sensors to include reasoning about sensed data, system state, and data histories.

Challenges include the heterogeneous nature of the data and its large uncertainities, the availability of partial or incomplete models, the verification and validation of decision-making systems, and the unavailability of advanced computational resources for onboard data analysis applications.

Benefits of Technology

This technology has broad applicability to all future robotic and crewed missions, where data volumes exceed available human resources to identify subtle correlations and make decisions in a timely fashion. Robotic missions to NEAs or comets will require onboard autonomous systems to perform the decision-making and monitoring processes currently performed by ground control. In aeronautics, the increasing use of autonomy is driven by requirements to improve the affordability, efficiency, reliability, and safety of civil airspace, airport, and aircraft (manned and unmanned) operations. Desired capabilities in civil aviation include dynamic route planning in response to traffic and weather, precision airport approach and departure management, payload-directed flight, and in-flight compensation for degraded or failed aircraft systems.

Table 33. TA 4.5.8 Technologies

TA	Technology Name	Description
4.5.8.1	Autonomous Decision Making	Analyzes large data sets with large uncertainties and conflicting information to provide operational decisions.

TA 4.6: Autonomous Rendezvous and Docking

Transfer Vehicle Rendezvous with the ISS

Every future exploration architecture NASA is considering has, at its core, the need to rendezvous and dock with other vehicles or bodies. Future manned and unmanned vehicles need to be able to do so with both cooperative and uncooperative vehicles and objects. The latter are either not designed for or not properly operating to assist servicing. Currently, many rendezvous and docking platforms include automation and require very little oversight and interaction from ground mission control. Current unmanned spacecraft visiting the ISS perform a great deal of lower-level functions automatically; however, ground control is still heavily in the loop. With future spacecraft operating outside of low-Earth orbit (LEO), and with potentially significant one-way communication times, it is imperative for the spacecraft to have a mature Autonomous Rendezvous and Docking (AR&D) capability. Whereas, each set of individual guidance, navigation, and control algorithms are reasonably mature, the maturity of a given system remains in question. While demanding more performance from AR&D sensors is a challenge, the greater challenge is in the systems integration arena. This is not surprising considering the fact that AR&D is, at its heart, a systems integration challenge.

Sub-Goals

Autonomous rendezvous and docking can enable future human exploration missions, such as the Asteroid Retrieval Mission, enable the exploration of NEAs and the moons of Mars, and provide efficiencies for ISS operations. The goal is to provide a robust, safe AR&D capability for human and robotic systems that reduces the reliance on human interaction.

Autonomy is a critical crosscutting technology for improving performance and reducing risk for a wide range of NASA human exploration (crew vehicles, habitats), robotic (spacecraft, rovers, in-situ systems), and aeronautics (airspace, airport, and aircraft) applications.

Table 34. Summary of Level 4.6 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.6 Autonomous Rendezvous and Docking	Sub-Goals:	Provide a robust, safe autonomous rendezvous and docking capability for human and robotic systems.

Table 34. Summary of Level 4.6 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.6.1 Relative Navigation Sensors	Objectives:	Improve detector sensitivity, reliability, field of view, and performance.
	Challenges:	Operating ranges of the sensors, field of view (FOV), performance, and packaging constraints. Power of lasers, as well as whether they are required to be eye-safe or mounted behind glass.
	Benefits:	Permits two vehicles to rendezvous, perform proximity operations, and dock/capture anywhere in the solar system, independent of communications with the ground.
4.6.2 Guidance, Navigation, and Control (GN&C) Algorithms	Objectives:	Develop algorithms that are independent of gravity field.
	Challenges:	Performance in non-central body gravity fields.
	Benefits:	Provide more robust and flexible software at lower cost to address a wider range of future missions that require AR&D.
4.6.3 Docking and Capture Mechanisms and Interfaces	Objectives:	Develop a robust, lightweight docking mechanism built to an international standard for human spaceflight missions.
	Challenges:	Applying autonomous robotic capture to non-cooperative target vehicles in which the target does not have capture aids, such as grapple fixtures. Working in conjunction with automated rendezvous and proximity operations systems to enable docking of vehicles with a wide range of masses.
	Benefits:	Provide a wider range of interoperable systems that can support a variety of human exploration mission scenarios.
4.6.4 Mission and System Managers for Autonomy and Automation	See 4.5.2 Activity Planning, Scheduling and Execution	

TA 4.6.1 Relative Navigation Sensors

The requirements for rendezvous, proximity operations, and docking depend on the application. Key requirements include bearing accuracies, range, and relative attitude. Current commercial implementations for optical, laser, and radio frequency (RF) systems and combinations of these are mid-TRL and require flight experience to gain reliability and operational confidence. Moreover, integrated communication capability at mid-field to near-field range greatly enhances the responsiveness and robustness of the AR&D guidance, navigation, and control (GN&C) system. It also enhances its portability.

Technical Capability Objectives and Challenges

The objectives for relative navigation sensors include increasing the sensitivity, reliability, and performance of sensors needed for AR&D. The requirements for AR&D sensors depend on the concept of operations of the particular vehicles between which rendezvous occurs. Each class of sensor has its own unique challenges. The operating ranges of the sensors, field of view (FOV), and performance, as well as packaging constraints (size, weight, power) all make relative navigation sensors a particular challenge. In addition, depending on the type of target, the rendezvous could be cooperative (mounted reflectors or target holding a particular attitude) or uncooperative (tumbling vehicle or asteroid). Relative navigation sensors need to perform rendezvous and docking or capture with both types of targets. The challenges for relative navigation sensors are accuracy and maturity.

Benefits of Technology

The often-stated goal of developing AR&D sensors is to facilitate a healthy set of options to choose from in order to meet the requirements of future exploration and servicing missions (manned or unmanned). A sensor suite consisting of 3D imaging sensors, visible-wavelength cameras, and long-wave infrared (IR) cameras provide a robust, lighting-independent, overlapping sensor suite that would allow two vehicles to rendezvous, perform proximity operations, and dock or capture anywhere in the solar system, independent of communications with the ground.

Table 35. TA 4.6.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.6.1.1	Three-Dimensional (3D) Imaging Sensor	Provides a 3D image of a target over a large dynamic range (see TA 4.1.1 3D Sensors).
4.6.1.2	Visible Camera	Provides radiation-tolerant, high-definition (HD) optical navigation sensors and star trackers with large dynamic range for light sensitivity to detect faint objects (target vehicle) and bright objects (Earth, Moon, etc.) in field of view.
4.6.1.3	Longwave Infrared (LWIR) Camera	Provides relative navigation sensors with large dynamic range for thermal sensitivity to detect faint objects (target vehicle) and bright objects (Earth, Moon, etc.) in field of view.

TA 4.6.2 Guidance, Navigation, and Control (GN&C) Algorithms

Spacecraft have been using onboard targeting algorithms to perform rendezvous since Gemini. The maturity and flexibility of these algorithms vary depending on the application and need. Much of current proximity operations, capture, and docking guidance is predicated on the Hill Clohessy-Wiltshire paradigm, which describes the relative motion in terms of linear equations. While this paradigm is still valid in the case where the target is rotating or tumbling, it is not valid when performing proximity operations in a weak gravity field, as in a distant retrograde orbit (DRO). In addition, it may not be beneficial to use a model of a gravity field when operating around an asteroid. Closed-loop guidance laws, whether in a linear quadratic regulator methodology, a terminal controller framework, or other linear paradigm, may prove just as useful for treating the gravity and solar radiation pressure as disturbances.

Technical Capability Objectives and Challenges

The objectives include developing new guidance algorithms that encompass the need to rendezvous with and perform operations, such as docking to rotating or tumbling target vehicles or bodies. These also include making guidance and targeting algorithms gravity-field independent; that is, able to operate in near-field free-space all the way to a strong central-body gravity field. For the first 50 years, rendezvous-targeting algorithms have operated in strong gravity fields, but now need to be developed to operate in weak gravity fields. In the case of operating around asteroids, where the gravity field is not well known or well modeled, a fair amount of work needs to be devoted to expressing the gravity field in ways that a rendezvous targeting set of algorithms can use in an efficient manner.

If a great deal of autonomy is needed for a rendezvous operation, then the targeting algorithm needs to be flexible enough and be able to retarget to account for phasing constraints, such as lighting changes. Manned missions have limited consumables and need to achieve rendezvous within certain time constraints, unlike unmanned missions that can afford to perform a more leisurely rendezvous.

Benefits of Technology

Advancing the SOA in AR&D algorithms will provide robustness and flexibility in software development and cost for future missions. Whereas most of the effort, particularly on the algorithmic front, goes into the V&V of the algorithms translated into flight software, maturing and gaining experience will allow these algorithms to be adequately evaluated under varying stress conditions.

Table 36. TA 4.6.2 Technology Candidates – not in priority order

TA	Technology Name	Description
4.6.2.1	Rendezvous Targeting	Provides delta-V and time of ignition (TIG) for long range and medium range rendezvous targeting (can be open-loop).
4.6.2.2	Proximity Operations/Capture/ Docking Guidance	Provides delta-V and TIG for proximity operations, capture, and docking, allowing for constraints and is in general closed loop.

TA 4.6.3 Docking and Capture Mechanisms and Interfaces

The SOA technologies for docking and capture mechanisms include current ISS capture and berthing mechanisms, and the NASA Docking System Block 0 and Block 1 designs. Issues associated with most of these mechanisms include complexity, high mass, high-impact loads during docking, and special purpose designs. New designs and concepts need to be developed to support future missions like the Asteroid Redirect Mission, as well as missions to NEAs and the moons of Mars.

Technical Capability Objectives and Challenges

The objectives for Docking and Capture Mechanisms and Interfaces include reducing docking mechanism weight and complexity while still meeting imposed design and performance standards, such as capture envelope and loads limits for use with ISS and future exploration missions. NASA is planning for the imminent construction of a new ISS docking mechanism that will be built to an international standard for human spaceflight missions. A smaller common docking system for robotic spacecraft is also needed to enable cost-effective robotic spacecraft AR&D. Assembly of large vehicles and stages used for beyond-LEO exploration missions will require new mechanisms with sufficient capture envelopes and less weight than any docking system currently used or in development. Berthing methods may also be used when warranted by mission requirements. Furthermore, for satellite servicing or rescue, development and testing are needed for applying autonomous robotic capture to non-cooperative target vehicles in which the target does not have capture aids, such as grapple fixtures. AR&D capability must be compatible with the capture envelopes of all of these systems.

NASA is planning for the eventual construction of a docking mechanism that will support all crewed Design Reference Missions (DRMs) for the Human Exploration and Operations Mission Directorate (HEOMD). This capability will provide a mechanism, or family of docking mechanisms, using common technologies and components that are significantly lower in mass than current mechanisms, and work in conjunction with automated rendezvous and proximity operations systems to enable docking of vehicles with a wide range of masses. The SOA NASA docking mechanisms in development for the ISS are designed to ISS and U.S. heritage vehicle structural loads and docking piloting capabilities. Challenges include developing a low-mass, low-output force docking system, and providing a high probability of capture for a wide range of spacecraft classes with different mass properties. Specific advances are needed to reduce docking mechanism mass; increase the capture envelope; handle larger contact velocity, lateral, and angular misalignments; and widen the options for docking masses.

Benefits of Technology

The benefits of these technology advances in docking and berthing mechanisms will allow for a wider range of compatible systems that can support a variety of human exploration mission scenarios, such as the Asteroid Redirect Mission, exploration of NEAs, and the moons of Mars.

Table 37. TA 4.6.3 Technology Candidates – not in priority order

TA	Technology Name	Description
4.6.3.1	Integrated Docking and Automated Rendezvous Systems Design	Assesses characteristics and performance of automated rendezvous and docking systems that result in lowest-integrated system mass and lowest life cycle and production cost.
4.6.3.2	Docking System for Exploration	Provides a docking mechanism or a family of mechanisms to meet the docking needs of all Crewed DRMs for HEOMD.

TA 4.6.4 Mission and System Managers for Autonomy and Automation

Mission managers are a key technology for autonomous rendezvous and docking. As vehicles venture farther from Earth, the one-way communication time makes it infeasible for the ground to be in the loop. Communications constraints will drive the need for autonomy in managing overall health and enabling mode switching as necessary.

Technical Capability Objectives and Challenges

The objectives for Mission and System Managers for Autonomy and Automation include developing a scalable spacecraft software executive that can be tailored for a wide range of exploration missions, as well as accommodate varying levels of autonomy and automation depending on the mission scenario. Whereas rendezvous around the Moon could still allow for the ground to remain in the loop, it would constrain any rendezvous that occurs to the near side. Any operations on the far side would, by their very nature, necessitate autonomy. Additionally, in the unlikely case of loss of communication with the ground, a mission would need to be aborted if the vehicles did not have autonomous capability. In light of this, autonomy becomes necessary for mission success. For the case of a lunar-orbit rendezvous, the timeline associated with the rendezvous is so short that any ground intervention would be minimal, further underscoring the need for autonomy to manage system health and mode switching. The mission manager must be able to command the sensors to operate at their designated operating conditions. The mission manager also needs to be cognizant enough to recognize failures and take the necessary action to put the spacecraft in safe mode and re-plan activities to maintain crew safety and achieve mission success.

For specific technologies, see 4.5 System-Level Autonomy and 4.5.2 Activity Planning, Scheduling, and Execution.

Benefits of Technology

This technology would manage onboard activities and spacecraft health to yield a reliable autonomous rendezvous and docking for scenarios where ground communication is unreliable or absent.

TA 4.7: Systems Engineering

This section addresses topics related to a robust life-cycle approach to the design, creation, and operation of robotics and autonomous systems. All other standard systems engineering methods are described in the NASA Systems Engineering Handbook (NASA/SP-2007-6105).

For robotics and autonomous systems, similar to other systems, a requirements analysis is performed first to define the customer needs and desired outcome. It uses a functional allocation and analysis to decompose complex systems into simpler subsystems with clearly-defined internal and external interfaces and functionality. A period of synthesis follows where alternative system concepts are modeled and simulated, traded off, and evaluated. Interfaces are refined and defined in more detail. After an iterative process, a solution is chosen and product realization occurs, which includes V&V of the requirements. The continuing evolution of systems engineering also includes developing and identifying new methods and modeling techniques. These models support the specification, analysis, design, verification, and validation of a broad range of complex systems.

Robotic systems are inherently multi-disciplinary and complex, and they may include heterogeneous teams that work together or with humans to achieve a common goal. In both cases, the interactions must be clearly understood through protocols and high-level communications and commands. Systems engineering provides the framework for achieving this coordination and achieving the desired system requirements. This roadmap focuses only on the unique system engineering aspects that affect and enhance robotic and autonomous systems performance and outcomes.

Sub-Goals

The higher degrees of complexity and criticality that accompany increased capability will depend on new systems engineering techniques and software modeling methods. “On the fly” changes and re-configurations or sudden human interactions will require a systems response to an unpredictable input, which means that the system must have unprecedented abilities to cope with multiple unplanned concepts of operations. These evolving systems must be automatically re-verified and validated to ensure that the original goals and requirements are still being met. All of this may happen in real time, requiring substantial computing power, autonomous synthesis, and advanced algorithms to achieve efficient system solutions. Future systems engineering will need to provide a framework for understanding and incorporating these requirements at the beginning of the design process.

Table 38. Summary of Level 4.7 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
4.0 Robotics and Autonomous Systems	Goals:	Extend our reach into space, expand our planetary access capability and our ability to manipulate assets and resources, prepare planetary bodies for human arrival, support our crews in their space operations, support the assets they leave behind, and enhance the efficacy of our operations.
Level 2		
4.7 Systems Engineering	Sub-Goals:	Provides a framework for understanding and coordinating the complex interactions of robotic systems and achieving the desired system requirements.

Table 38. Summary of Level 4.7 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
4.7.1 Modularity, Commonality, and Interfaces	Objectives:	Increase robotic systems flexibility, including cooperating heterogeneous robots and common human-robot interfaces.
	Challenges:	Reconciling heterogeneity with modularity and commonality.
	Benefits:	Allows multiple robots or autonomous systems to operate together, thereby making servicing of the robotic components (either by humans or other robots) easier. Enables new design approaches and systems configurations, which will allow increased flexibility and responsiveness of robotic systems. Provide intuitive and familiar control of the robot by the human with increased productivity, reduced training time, and reduced errors.
4.7.2 Verification and Validation of Complex Adaptive Systems	Objectives:	Provide seamless, automated V&V, allowing system changes on-demand.
	Challenges:	V&V of a changing or evolving system. Automated verification and validation on demand.
	Benefits:	Automates verification and validation with software and sensors so a robotic or autonomous system can self-certify for use after an executed configuration change.
4.7.3 Robot Modeling and Simulation	Objectives:	Provide software tools to assist in synthesis, trade studies, and optimization of complex robotic systems, as well as preview and optimize operations using concurrent dynamic simulation of alternative control options.
	Challenges:	Maturity of the models. Limitations of current dynamic modeling tools; in particular, for interacting with planetary environment (e.g. surface granular media, atmospheric conditions). Complexity of the system due to the dramatic increase in possible use cases. Computational cost of simulating complex dynamic systems.
	Benefits:	Tests and virtually optimizes system models through iterative design and synthesis, trade studies, and performance analysis. Provide superior engineering cost and time savings. Increases efficiencies and reduces production-related errors. Enables performing optimal actions given state of system and environment.
4.7.4 Robot Software	Objectives:	Provides architectures, frameworks, and advances in software to enable the realization of intelligent robots and autonomous systems from component technologies.
	Challenges:	Support for heterogeneous robotic capabilities. Scalability and managing complexity.
	Benefits:	Enables interoperability of frameworks and software across missions, thus reducing cost and improving reliability.
4.7.5 Safety and Trust	Objectives:	Develop proximity operation technologies that will allow humans to work safely side-by-side with robots or be safe on or around robotic vehicles.
	Challenges:	Dealing with a wide range of unpredictable human actions. Preventing direct or indirect harm to humans or machines.
	Benefits:	Robots working side-by-side with astronauts will massively amplify crew capabilities and productivity by assisting with assembly, maintenance, inspections, and handling of hazardous situations. Enables the safe mobility of crew and payloads.

TA 4.7.1 Modularity, Commonality, and Interfaces

Modular, self-reconfigurable robotic technologies are applicable to machines with changing morphology. Their promise of high versatility and robustness could have significant value in enabling field replacement of failed components, leading to self-adaptable and self-repair systems.

Modular interfaces, which may include mechanical, electrical, fluid, and pneumatic interfaces, form the basis for robotic assembly and servicing. Examples include tool change-out on robotic arms for rovers or for in-space robotic assembly and servicing. Tools and end-effectors developed in a modular manner have a reduced logistics footprint over dedicated arms with specialized tools. These interfaces also allow new space operations and architectures to be realized. One example is on-orbit re-fueling and servicing, which has the potential to change space mission architectures.

Modular and common interfaces are also the building blocks for reconfigurable and self-assembling, and perhaps even self-replicating, robotic systems. Such system design allows deployed systems to respond to changing needs and system failures through in-situ reconfiguration of mechanical, electrical, and computing assets.

Current existing technologies include: refueling interfaces, modular serviceable interfaces, robot-to-suit interfaces, and human-robot interfaces. These technologies have been demonstrated in space operations, but are not routinely used. Incorporating them into robotic systems will enhance performance. Other areas still in the early stages of development include: self-assembling and self-configuration features, common human-systems interfaces, and marsupial robot interfaces. The common theme in all of these technologies is the well-defined and well-implemented interfaces, which include modularity and commonality principles, resulting in unprecedented flexibility for robotic systems, allowing them to react to changing environments with increased versatility.

Technical Capability Objectives and Challenges

Modularity, commonality, and interfaces objectives include increasing the flexibility of robotic systems, such as cooperating heterogeneous robots and common human-robot interfaces. Desired technical capabilities include modular and common interfaces to allow for changes in operations and services in the field. Challenges include reconciling heterogeneity with modularity and commonality, as well as balancing flexibility with the extra mass and complexity that would ensue.

Benefits of Technology

Modular robotic interfaces allow robots and their components to be interoperable, making their servicing easier. More importantly, the interfaces enable new design approaches and systems configurations, which increase flexibility and responsiveness of robotic systems. Combining multiple redundant assets into a larger system will be achievable with modular and common interfaces; all required commodities could also be easily transferred across these interfaces through smart connector systems. Power, propellants, data, consumables, and structural loads can be shared, resulting in a more robust system, although there will be a mass penalty incurred for the extra interface hardware. Common human-to-robot system interfaces that are easy to use and widely accepted, such as wearable controls, will allow more intuitive and familiar control of the robot by the human with increased productivity, reduced training time, and reduced errors.

Table 39. TA 4.7.1 Technology Candidates – not in priority order

TA	Technology Name	Description
4.7.1.1	Refueling Interfaces	Provide multiple smart quick disconnect (QD) couplings that are rated for high pressure and cryogenic fluids in a plate-mounted configuration for transferring commodities.
4.7.1.2	Modular Serviceable Interfaces	Provide standardized and interoperable interfaces among disparate robots and payloads. These interfaces can be modular and smart, allowing for structural, mechanical, electrical, fluid, and pneumatic interactions.

Table 39. TA 4.7.1 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
4.7.1.3	Self-Assembling and Configuration Features	Provide modular bi-directional interfaces that allow multiple configurations of robotic assembling elements.
4.7.1.4	Marsupial Robot Interfaces	Provide docking and replenishing interfaces for a small daughter robot at a mother robot. Marsupial robotics is an active field of research, allowing for new forms of cooperative robotics.

TA 4.7.2 Verification and Validation of Complex Adaptive Systems

To be truly adaptive, a robotic or autonomous system must be able to seamlessly verify and validate that all of the original system requirements are being adequately met so that subsequent system performance will not be compromised. Human-rated systems require the highest level of V&V to ensure human safety and reliability. In addition, crew self-sufficiency is required as space exploration evolves further away from mission control on Earth. Systems beyond cis-lunar space must be able to function without intervention from mission control, because of the inherent communication latencies.

Robotic re-assembly and re-configuration will require automated V&V when a robot or system undergoes a change. For systems to rapidly react and adapt, such changes have to be seamless and may no longer be apparent to the user. An associated issue is that V&V is a rigorous process that is well-suited to stable configurations, for which all possible logic paths can be identified and examined a priori. However, for adaptable systems, new V&V methods have to be developed to allow systems engineering of more versatile adaptive robotic systems. Legacy systems, which cannot easily be changed, often experience additional difficulties and costs from V&V after the system configuration has changed. The potential for unintended consequences after a change requires rigorous V&V to avoid an unacceptable risk of failure.

Currently, complex adaptive systems are part of an active research topic seeking to evolve systems to be versatile, flexible, resilient, dependable, robust, energy efficient, recoverable, customizable, configurable, and self-optimizing by adapting to changing operational contexts, environments, or system characteristics. In space, these adaptive systems are being used in robotic spacecraft and surface exploration rovers to reduce the number of commands that must be sent and to allow greater mission success through flexible operations.

Technical Capability Objectives and Challenges

Objectives for V&V of complex adaptive systems include seamless, automated V&V, allowing system changes on demand. System verification will be a new challenge for human-rated spacecraft bound for deep space. New V&V approaches, techniques, and in-flight re-verification may be necessary following a repair. Similar approaches will need to be developed to verify a robotic system that was assembled on-orbit using the self-replicating or reconfigurable approaches described above.

Benefits of Technology

By using structured and configuration-controlled systems engineering methods, V&V can be automated with sensors and software so that a robotic system can self-certify for use after an executed configuration change. This will be game changing, since new systems' concepts of operations will be enabled without time consuming and costly V&V efforts that are largely done manually today.

Table 40. TA 4.7.2 Technology Candidates – not in priority order

TA	Technology Name	Description
4.7.2.1	Verification and Validation of Complex Adaptive Systems	Provides pre-flight verification and validation to the level necessary for human safety and reliability and for systems to allow crew independence; provides in-flight verification and validation following in-the-field system re-configuration.

TA 4.7.3 Robot Modeling and Simulation

With the recent exponential increase in computing power, modeling and simulation have become more viable and useful in the systems engineering process. Synthesis and trade studies are now possible and provide many new options for optimizing and predicting solutions' efficacy.

Technical Capability Objectives and Challenges

Robot modeling and simulation objectives include software tools to assist in synthesis, trade studies, and optimization of complex robotic and autonomous systems. They also include the ability to preview and optimize operations using concurrent dynamic simulation of alternative control options. End-to-end, holistic systems modeling and simulation is a key technology for the advanced systems engineering that will be required for autonomous robotic systems. As the complexity of the system increases due to the dramatic increase in possible use cases, only computer models can deal with the large number of permutations. Alternatively, new methods can be employed using autonomous algorithms that are rule-based or use other intelligent algorithm approaches. These also require sophisticated and powerful computer models and simulations for a comprehensive systems design and configuration. The computational cost of simulating complex dynamic systems remains a challenge.

Subsystems like multi-physics dynamic simulation, modeling of contact dynamics, and granular materials terra-mechanics can also predict robot subsystems' behavior and performance. These interactions with the local environment create inputs to the end-to-end systems behavior model.

Benefits of Technology

A benefit of system models is that through iterative design and synthesis, trade studies, and performance analysis, the system can be tested and optimized virtually. The highest-fidelity system will then need extensive physical testing to establish a good reference for modeling and simulation. This results in superior engineering, as well as savings to cost and time. When using model-based design, the results can be used to control the robotic system, resulting in increased efficiencies and a reduction in production-related errors. Modeling and simulation also enables optimization of actions given the state of the system and environment prior to execution.

Table 41. TA 4.7.3 Technology Candidates – not in priority order

TA	Technology Name	Description
4.7.3.1	End-to-End Systems Modeling	Provides complete computer systems modeling of functions and interfaces with applicable Concepts of Operations. This includes co-operative robotics with humans in-situ, for example, including human factors assessments.
4.7.3.2	Modeling of Contact Dynamics	Understanding of forces/torques generated on objects and platforms through mobility or manipulation.
4.7.3.3	Dynamic Simulation	Provides high-fidelity multi-physics simulations of robot dynamics and its interactions with the environment.
4.7.3.4	Granular Media Simulation	Models interaction between physical systems and granular materials.

TA 4.7.4 Robot Software

Robot software provides architectures, frameworks, and advances in software to enable the realization of intelligent robots and autonomous systems from component technologies. Robotic and autonomous systems software embodies intelligence and therefore plays a critical role in realizing the autonomous capabilities mentioned in previous sections.

Technical Capability Objectives and Challenges

Robot software objectives include providing architectures, frameworks, design patterns, and advances in software to enable the realization of intelligent robots and autonomous systems from component technologies, and providing standardized interfaces and messages. Challenges include managing overall software complexity, striking the right balance between flexibility and complexity, and addressing heterogeneity of hardware. Software reusability, extendibility, maintainability, flexibility, and efficiency are important features for realizing autonomous capabilities. Moreover, software development can be very costly and requires the proper levels of management to ensure the product is successful.

Benefits of Technology

Robot software will continue to play an increasingly important role in all future NASA missions and will be especially critical for robotic and autonomous systems. Proper architecting, design, and implementation of software would help maintain steady progress toward achieving more intelligent systems for space missions.

Table 42. TA 4.7.4 Technology Candidates – not in priority order

TA	Technology Name	Description
4.7.4.1	Robotic Architecture and Frameworks	Provide software frameworks for the integration and validation of new technologies.
4.7.4.2	Standardized Messaging Protocols	Provide standard protocols for sharing information among multiple assets, including ground control stations.
4.7.4.3	Model-Based Robotic Software	Consistent representation of models within a system through its lifecycle (from design, through implementation and in operations).

TA 4.7.5 Safety and Trust

Traditionally, robots have been isolated from human operators in controlled environments, such as a perimeter cage, to minimize disturbances and keep them from inflicting harm on humans. However, future systems will increasingly require close engagement between humans and machines. This includes technologies for safe operation of robotic vehicles by crew, safety of crew around autonomous vehicles and manipulators, and crew working side-by-side with robotic assistants and interacting with them physically. The ability of humans to adjust the autonomy level of machines is especially important for cooperative planetary exploration between astronauts and robots. Safety, trust, and proximity operation technologies are being developed that will increase confidence for humans that routinely or casually interact with robots. Systems are being developed that can learn to recognize human locations and actions so that evasive action or emergency stopping can occur automatically to protect the human. Terrestrial applications have been developed where robots and humans interact closely even in critical situations, such as telerobotic surgery.

Technical Capability Objectives and Challenges

The objective is to develop technologies that enable the safe operation of crew working with robotic platforms, including interacting with them physically. In high-proximity interactions, it is desirable to have systems that can measure and communicate the level of operator's safety and trust within the human-system. This capability already exists today, as shown by the Shuttle remote manipulator system (SRMS) arm when it positioned astronauts to various desired locations while strapped in by their feet. Similar robotic arm interactions are currently occurring on the ISS. The objective is for the crew to be able to work next to a robotic assistant, within a one-meter proximity in a controlled and safe manner, without being physically attached to it. It is also desired to have safety and trust technologies that enable crew and payload transportation using autonomous vehicles.

Benefits of Technology

Robots that work side-by-side with astronauts will massively amplify crew capabilities and productivity by assisting crew members during mobility, assembly, maintenance, inspection operations, and handling of hazardous materials. For example, an autonomous mobile system could persistently and cooperatively survey coolant lines on the ISS and identify the location of a coolant leak, and a robotic assistant could help change out the toxic-leaking ammonia coolant line valve with human supervision, but without putting the crew in harm's way. Crew members who are debilitated from the six-month journey to Mars can use robotic exercise countermeasures or augment their strength and dexterity with robotics at the Mars surface destination.

Table 43. TA 4.7.5 Technology Candidates – not in priority order

TA	Technology Name	Description
4.7.5.1	Safety, Trust, and Interfacing Proximity Operation Technologies	Enables human crew working side by side with robotic assistants and interacting physically.

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Appendix

Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ACARS	Aircraft Communications Addressing and Reporting System
AEGIS	Autonomous Exploration for Gathering Increased Science
AERCam	Autonomous EVA Robotic Camera
AI	Artificial Intelligence
API	Application Programming Interface
AR&D	Autonomous Rendezvous and Docking
ARC	Ames Research Center
ARINC	Aeronautical Radio, Incorporated
ARM	Asteroid Redirect Mission
ASTEP	Astrobiology Science Technology for Exploring Planets
ATHLETE	All Terrain Hex-Limbed Extra Terrestrial Explorer
AUV	Autonomous Underwater Vehicle
BEAM	Beacon-based Exception Analysis for Multi-missions
CAS	Capture Attach System
CASPER	Continuous Activity Scheduling Planning Execution and Replanning
CBM	Common Berthing Mechanism
CCD	Charge-Coupled Device
COTS	Commercial Off-The-Shelf
CW	Clohessy-Wiltshire
DEM	Discrete Element Modeling
DOF	Degrees Of Freedom
DRM	Design Reference Mission
DRO	Distant Retrograde Orbit
DSN	Deep Space Network
DTE	Direct To Earth
EDL	Entry, Descent, and Landing
EO1	Autonomous Spacecraft Experiment
EVA	ExtraVehicular Activity
FDIR	Fault Detection, Isolation, and Recovery
FOV	Field Of View
FPGA	Field Programmable Gate Array
GEO	GEostationary Orbit
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
GRACE	Gravity Recovery And Climate Experiment

GRAIL	Gravity Recovery And Interior Laboratory
GRC	Glenn Research Center
HD	High-Definition
HEOMD	Human Exploration and Operations Mission Directorate
HRI	Human-Robot Interfaces
HyDE	Hybrid Diagnostic Engine
IMS	Inductive Monitoring System
IMU	Inertial Measurement Unit
IPEX	Intelligent Payload EXperiment
IR	InfraRed
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IVA	IntraVehicular Activity
IVHM	Integrated Vehicle Health Management
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEE	Latching End Effector
LEM	Lunar Excursion Module
LEO	Low-Earth Orbit
LIDAR	LIght Detection And Ranging
LWIR	LongWave InfraRed
MER	Mars Exploration Rover
MMSEV	Multi-Mission Space Exploration Vehicle
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
OCAMS	Orbital Communication Adapter Modeling System
OCT	Office of the Chief Technologist
OPS	Operations Planning Software
OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security – Regolith Explorer
P2P	Peer-to-Peer
QD	Quick Disconnect
RAPID	Robot Application Programming Interface Delegate
RAT	Rock Abrasion Tool
R&D	Research and Development
RESOLVE	Regolith and Environment Science and Oxygen and Lunar Volatile Extraction
RF	Radio Frequency
ROV	Remotely Operated Vehicle
RWS	Robotics Workstation Software
S/C	SpaceCraft

SE	Systems Engineering
SEU	Single Event Upset
SHINE	Spacecraft Health INference Engine
SMD	Science Mission Directorate
SOA	State Of the Art
SPHERES	Synchronized Position Hold, Engage, Reorient Experimental Satellites
SRMS	Shuttle Remote Manipulator System
SS	Space Shuttle
SSRMS	Space Station Remote Manipulator System
STIP	Strategic Technology Investment Plan
STMD	Space Technology Mission Directorate
STS	Space Transportation System
SWaP	Size, Weight, and Power
TA	Technology Area
TABS	Technology Area Breakdown Structure
TDRSS	Tracking and Data Relay Satellite System
TIG	Time of IGnition
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
V&V	Verification and Validation
VDI	Virtual Dashboard Interface
VE	Virtual Environment
VEVI	Virtual Environment Vehicle Interface
VSLAM	Visual Simultaneous Localization And Mapping
VTOL	Vertical TakeOff and Landing
xGDS	Exploration Ground Data Systems

Abbreviations and Units

Abbreviation	Definition
%	Percent
°	Degrees
µG	Micro-gravity
µm	Micrometer
µrad	Microradian
A	Amps
C	Celsius
cm	Centimeter
CO_2	Carbon Dioxide
deg	Degrees
g	Grams
g/cc	Gram per Cubic Centimeter
hr	Hour
Hz	Hertz
J/cm^3	Joules per Cubic Centimeter
kg	Kilograms
km	Kilometers
kN-m	Kilonewton-meter
kPa	Kilopascal
kW	Kilowatt
L	Liters
LH_2	Liquid Hydrogen
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
m	Meters
m/h	Meters per Hour
m/s	Meters per Second
Mbps	Megabytes per Second
milli-g	Milli-gravity
mm	Millimeter
MPa	Megapascals
mrad	Milliradian
N	Newtons
N-m	Newton-meters
psi	Pounds per Square Inch
psig	Pounds per Square Inch Gauge
rad	Radians
RPM	Rotations Per Minute

Abbreviation	Definition
s	Seconds
V	Volts
VDC	Volts Direct Current
W	Watts

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Technology Candidate Snapshots

4.1 Sensing and Perception
4.1.1 3D Sensing

4.1.1.1 Three-Dimensional (3D) Range Imaging Sensors for Surface Mobility

TECHNOLOGY

Technology Description: Provide three-dimensional (3D) perception of environment with performance appropriate to surface mobility.

Technology Challenge: Achieving adequate frame rate, resolution, and field of view with a processor architecture that has low mass and power consumption with adequate radiation tolerance.

Technology State of the Art: Stereo vision implemented with a radiation-hard flight computer or radiation-tolerant field programmable gate array (FPGA). In low-power terrestrial systems, stereo vision implemented using commercial off-the-shelf (COTS) smartphone processor. Scanning and flash lidar range sensors.

Parameter, Value:

Frame rate: varies (0.1 frames/sec in space);

Angular resolution: 0.2 to 2 mrad/pixel;

Field of view: varies (18 to 120 degrees);

Size, weight, and power: varies (several kg including sensor and processor).

TRL

4

Technology Performance Goal: High-resolution range data produced at much higher frame rates with much smaller size, weight, and power than now possible.

Parameter, Value:

Frame rate: > 1 frames/sec;

Angular resolution: < 1 mrad/pixel;

Field of view: similar to current;

Size, weight, and power: < 100 grams including sensor and processor.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Miniaturization of processors for space applications, potentially by enabling use of commercial-grade electronics where appropriate.

CAPABILITY

Needed Capability: 3D terrain perception for surface mobility.

Capability Description: Provides 3D terrain perception adequate for mobility planning for surface vehicles.

Capability State of the Art: Stereo vision systems used on Mars Exploration Rover (MER) and Mars Science Laboratory (MSL) rovers. Sparse structured light range sensor used on Sojourner Mars rover for hazard detection and science target acquisition.

Parameter, Value:

Currently achieved with global shutter charge-coupled device (CCD) imagers with ~ 1024 x 1024 pixels. Currently available flight processors (for example RAD750 in MSL) allow computing 256 x 256 pixel range images in about 10 sec/frame.

Capability Performance Goal: Enable much faster average surface mobility traverse rate by reducing time required for hazard detection, while significantly reducing mass, power, and volume of the required flight processor, in a flight-qualifiable implementation.

Parameter, Value:

Frame rate: > 1 frames/sec;

Size, weight, and power: < 1 kg including sensors and processor.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.1 3D Sensing

4.1.1.2 Three-Dimensional (3D) Range Imaging Sensors for Above-Surface Mobility

TECHNOLOGY

Technology Description: Provide array of three-dimensional (3D) range data for above-surface mobility (see also TA 9).

Technology Challenge: Miniaturization and reduced power consumption.

Technology State of the Art: In mid-technology readiness level (TRL) terrestrial research and development (R&D), onboard 3D range image generation by automatic triangulation from image sequences acquired onboard, single-axis, scanning lidar range, and micro-scale, electronically beam-steered millimeter-wave radar.

Parameter, Value:

Mass: varies from a few grams to several hundred grams for terrestrial commerical off-the-shelf (COTS) sensors;

Maximum range: varies up to about 100 meters;

Range resolution: varies from about 1 cm to a few 10s of cm.

TRL 4

Technology Performance Goal: Enable safe above-surface mobility, especially while landing back to surface. Solutions must have high performance, low mass and power, and fault and radiation tolerance.

Parameter, Value:

Mass: varies with mission (10 grams to a few kg);

Maximum range: varies with mission (for example, a few 10s of meters to a few 100s of meters):

Range resolution: varies with mission (for example, 1 to 10 cm).

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Processor technology with very low size, weight, and power.

CAPABILITY

Needed Capability: 3D perception for autonomous navigation of above-surface vehicles.

Capability Description: Provides 3D perception adequate for safe operation during near-surface hovering or landing by aerial vehicles or free-flyers near small airless bodies, as well as to avoid collision with main spacecraft.

Capability State of the Art: None for above surface mobility; sensors for entry, descent, and landing (EDL) are related, though larger, and are TRL 8 (Jet Propulsion Laboratory (JPL) Lander Vision System -- see TA 9).

Parameter, Value:

Detect landing hazards on the order of 10 to 20 cm tall

Capability Performance Goal: Enable safe above-surface mobility, especially while landing back to surface. Solutions must have high performance, low mass and power, and fault and radiation tolerance. Resolution, maximum range, field of regard, frame rate, size, and power consumption requirements vary with mission type.

Parameter, Value:

Minimum range of < 1 m, maximum range of 10s of meters to 100s of meters, depending on application

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enhancing	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years

4.1 Sensing and Perception
4.1.1 3D Sensing

4.1.1.3 Three-Dimensional (3D) Range Imaging Sensors for Manipulation

TECHNOLOGY

Technology Description: Provide three-dimensional (3D) perception of environment with performance appropriate to manipulation and sample acquisition.

Technology Challenge: For Mars and the Moon, achieving very low mass and power consumption with a processor architecture that has adequate radiation tolerance. For Venus, obtaining adequate range data with a very compact, low-power sensor that only requires one aperture in the pressure vessel.

Technology State of the Art: Stereo vision performance using radiation-hard flight processor, radiation-tolerant field programmable gate array (FPGA) commercial off-the-shelf (COTS) smartphone processor. Dense structured light range sensor used for outdoor 3D model generation applications. Scanning or flash lidar range sensors.

Parameter, Value:	**TRL**
Curiosity rover: Maximum range: 5 meters; Range accuracy: approx. 2 cm; Angular resolution: approx. 2 mrad; Frame rate: approx. 0.1 Hz	4

Technology Performance Goal: For Mars: smaller, lighter, lower power. For Moon and small bodies: ability to operate in the dark, including shadows. For Venus: ability to operate with only one aperture in pressure vessel.

Parameter, Value:	**TRL**
Frame rate 1 Hz or more with reduced size, weight, and power.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Miniaturization of associated detector arrays and processors.

CAPABILITY

Needed Capability: 3D perception for sampling.

Capability Description: Provides 3D terrain perception adequate for planning sample acquisition.

Capability State of the Art: Stereo vision systems used on the Mars Exploration Rover (MER) and the Mars Science Laboratory (MSL) rover. Flash lidar for Origins Spectral Interpretation Resource Identification Security – Regolith Explorer (OSIRIS-REx), augmented with cameras.

Parameter, Value:

Mass, volume, spatial and range resolution (varies).

Capability Performance Goal: Reduce mass and power consumption to reduce size and cost. Operate in the dark for Lunar South Pole-Aitken Base Sample Return. Operate from inside a pressure vessel for Venus In-Situ Explorer, preferably looking through just one viewport. Operate from small above-surface vehicles for sample acquisition.

Parameter, Value:

Varies with mission, but typical is:

Frame rate: > 1 Hz;

Maximum range: 5 meters;

Range accuracy: approx. 2 cm;

Angular resolution: approx. 2 mrad

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enhancing	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	2 years

4.1 Sensing and Perception
4.1.1 3D Sensing

4.1.1.4 In-Situ Camera Geometric Calibration Diagnostics and Self-Calibration

TECHNOLOGY

Technology Description: Uses onboard algorithms to check camera geometric calibration and update calibration parameters in-situ.

Technology Challenge: Assuring adequate numerical conditioning and reliability of the algorithms.

Technology State of the Art: Online stereo camera self-calibration algorithms have been developed and validated in terrestrial applications.

Parameter, Value:
Epipolar misalignment: < 0.2 pixel

TRL
4

Technology Performance Goal: Automatic calibration of relative orientation of stereo cameras.

Parameter, Value:
Epipolar misalignment: 0.1 pixel

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Algorithm development and validation for space applications.

CAPABILITY

Needed Capability: In-situ camera geometric calibration diagnostics and self-calibration.

Capability Description: Assures quality of measurements provided by vision systems, such as range data from rover stereo vision systems, in the event that thermal or mechanical loads take the cameras out of geometric calibration.

Capability State of the Art: Laborious off-line process using downlinked images.

Parameter, Value:
Epipolar misalignment: approx. 0.2 pixel

Capability Performance Goal: Onboard, automatic calibration diagnostic that runs periodically and invokes self-calibration procedure as needed.

Parameter, Value:
Epipolar misalignment: 0.1 pixel

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.1 Vision-Based Aiding of Dead Reckoning for Navigation of Surface Vehicles

TECHNOLOGY

Technology Description: Uses onboard camera(s) or range sensor(s) to aid inertial and kinematic sensors for dead reckoning.

Technology Challenge: Processor miniaturization and power reduction while maintaining adequate fault tolerance.

Technology State of the Art: Stereo-vision-based visual odometry implemented in radiation-hard flight processor or radiant-tolerant field programmable gate array (FPGA)-based coprocessor. In terrestrial research and development, stereo vision-based visual odometry implemented in a smartphone processor; lidar-based visual odometry.

Parameter, Value:	TRL
Runtime of 10s of seconds per cycle on current flight computers.	4

Technology Performance Goal: Measurement updates frequent enough to keep vehicle safe in soft soil, with minimal burden on main flight processor.

Parameter, Value:	TRL
Runtime of < 1 second per cycle with smaller, lower power flight computers than currently used.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Progress on miniaturization and power reduction for flight computer.

CAPABILITY

Needed Capability: Position knowledge for surface vehicles relative to start of each traverse segment.

Capability Description: Estimates position of surface vehicles relative to position at the start of each traverse segment, or relative to last absolute position update.

Capability State of the Art: Stereo vision-based visual odometry for Mars Exploration Rover (MER) and the Mars Science Rover (MSL)

Parameter, Value:

Computing time per frame: approximately 40 sec.

Capability Performance Goal: Updates frequent enough to keep vehicle safe in soft soil, with minimal burden on main flight processor.

Parameter, Value:

Approx 1 Hz updates with power consumption of < 5 W.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.2 Map-Based Position Estimation for Navigation of Surface Vehicles

TECHNOLOGY

Technology Description: Automatically matches data from onboard cameras or range sensors to regional maps to provide vehicle position estimates in the map frame of reference.

Technology Challenge: Engineering sufficient robustness, fault detection, and redundancy to achieve required level of reliability.

Technology State of the Art: Automatic registration of diverse image and map types demonstrated in off-line experiments.

Parameter, Value: | **TRL**
Map-relative position error of about one map pixel width without human intervention; tested only with small data sets, so reliability is not characterized. | 4

Technology Performance Goal: Automatic, onboard registration of onboard data to mission map demonstrated with very high reliability.

Parameter, Value: | **TRL**
Position error: < one map pixel (for example, 30 cm), with > 99% reliability. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Algorithm development and validation.

CAPABILITY

Needed Capability: Absolute position knowledge for surface vehicles.

Capability Description: Position knowledge for surface vehicles relative to maps used for mission planning.

Capability State of the Art: People on mission operations team manually register images from Mars rovers to regional orthophotos created from orbital remote sensing.

Parameter, Value:
Map-relative position error of about one map pixel size (30 cm) with one human intervention required per position estimate.

Capability Performance Goal: Fully automatic, onboard absolute position estimation for surface vehicles.

Parameter, Value:
Map-relative position error of about one map pixel (for example, 30 cm) width without human intervention.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.3 Vision-Based Aiding of Dead Reckoning for Above-Surface Vehicles

TECHNOLOGY

Technology Description: Uses onboard camera(s) or range sensor(s) to aid inertial and kinematic sensors for navigation.

Technology Challenge: Achieving very low size, weight, and power with high accuracy and reliability, while providing adequate radiation tolerance for space missions.

Technology State of the Art: Vision-aided inertial navigation filter developed for New Millennium ST-9 mission, which was evaluated off-line with data from a sounding rocket flight. Real-time implementation of similar filters in smartphones for terrestrial applications.

Parameter, Value:
Position error: < 0.5% over 300 m;
Processor weight: 12 grams

TRL 4

Technology Performance Goal: Achieve performance comparable to current terrestrial research prototypes in a flight implementation.

Parameter, Value:
Position error: < 0.5% over 300 m;
Processor weight: 12 grams

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Miniaturization and power reduction of the necessary processor for a flight implementation.

CAPABILITY

Needed Capability: Position knowledge for above-surface vehicles relative to start of each flight segment.

Capability Description: Estimates position of above-surface vehicles relative to position at the start of each flight segment, or relative to last absolute position update.

Capability State of the Art: None

Parameter, Value:
Not applicable.

Capability Performance Goal: Relative navigation with error per command cycle that is on the order of the vehicle length or less.

Parameter, Value:
Position error: < 1% of distance travelled.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enabling	--	2029	2021	3 years

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.4 Map-Based Position Estimation for Navigation of Above-Surface Vehicles

TECHNOLOGY

Technology Description: Automatically matches data from onboard cameras to regional map images to provide vehicle position estimates in the map frame of reference.

Technology Challenge: Onboard matching of image data from onboard sensors to remote sensing data sets, where there may be significant differences in scale, lighting, or sensor type (for example, visible images vs. radar images).

Technology State of the Art: Automatic registration of diverse image and map types demonstrated in off-line experiments.

Parameter, Value: Map-relative position error of about one map pixel width without human intervention; tested only with small data sets, so reliability is not characterized.

TRL 4

Technology Performance Goal: Fully automatic, onboard operation.

Parameter, Value: Map matching for disparate sensor types with standard deviation of about 1 pixel relative to the map image and gross failure rate of about 0.1%.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Miniaturization and power reduction of the necessary processor and camera for a flight implementation.

CAPABILITY

Needed Capability: Absolute position estimation for above-surface vehicles.

Capability Description: Absolute position estimation for above-surface vehicles on Mars, Titan, Venus, and primitive bodies.

Capability State of the Art: Performed with aid of human operators in ground system using images downlinked from the spacecraft.

Parameter, Value: Position error: about 30 cm for Mars rovers.

Capability Performance Goal: Fully automatic, onboard operation.

Parameter, Value: Position error: varies with mission (< 1 meter).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enabling	--	2023	2020	4 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enabling	--	2029	2021	4 years

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.5 Radio Frequency (RF) Navigation Aiding for Above-Surface Vehicles

TECHNOLOGY

Technology Description: Provides range and bearing measurements between one vehicle and another when both are in-situ.

Technology Challenge: Achieving high accuracy with low-size, -weight, and -power flight hardware.

Technology State of the Art: Terrestrial ultra wide band radios and next-generation cellular phone technology provide range between nodes. NASA's Gravity Recovery and Climate Experiment (GRACE) mission measured inter-spacecraft range with micron accuracy for gravity science; that is far more accuracy than needed for the applications addressed here.

Parameter, Value:

Range error: 7 to 30 cm;

Maximum range: varies

TRL 6

Technology Performance Goal: Similar performance with similar size hardware in a flight qualifiable implementation.

Parameter, Value:

Maximum range: varies (100s of meters to 10s of km);

Minimum range: 1 to 10 meters;

Range error: varies (about 10 cm to a few meters).

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Low size, weight, and power (SWaP) adaptation of current commercial off-the-shelf (COTS) solutions for space qualifiability.

CAPABILITY

Needed Capability: Position knowledge relative to a main spacecraft for above-surface vehicles.

Capability Description: Position knowledge for an above-surface craft relative to a main spacecraft, where the main spacecraft could be a lander, rover, balloon, or orbiter.

Capability State of the Art: Very accurate, long-range radio ranging has been flown on the GRACE and Gravity Recovery and Interior Laboratory (GRAIL) missions.

Parameter, Value:

Centimeter-level accuracy for GRACE K-band ranging system.

Capability Performance Goal: Depends on mission and mission phase. Contributes to navigating surface craft to remote targets, as well as docking surface craft back to the main spacecraft.

Parameter, Value:

For reaching targets, max range of several kilometers with resolution of a few meters; for docking, min range of < 1 meter with error ≤ a few cm.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.6 Altimeter for Small Above-Surface Vehicles

TECHNOLOGY

Technology Description: Provides altitude for small above-surface vehicles.

Technology Challenge: Miniaturization; environmental survivability.

Technology State of the Art: Direct (pulsed) time of flight light detection and ranging (LIDAR), indirect (heterodyne detection) time of flight LIDAR, radar, ultrasonic, in a range of sizes with a range of performance specifications.

Parameter, Value:

Commerical off-the-shelf (COTS) sensor for terrestiral applications.

Systems:

Mass: 22 grams;

Max. range: 100 meters;

Range error: 20 cm;

Pulse repitition rate: up to 500 Hz

TRL

6

Technology Performance Goal: Varies with mission, but emphasizing lightweight for operation of CubeSat or smaller spacecraft within (for example) a few hundred meters of planetary surfaces.

Parameter, Value:

Mass: < 20 grams;

Altitude error: < 10 cm;

Pulse repetition rate: up to 10 Hz

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Electronics miniaturization/ integration and design for environmental survivability (radiation, thermal).

CAPABILITY

Needed Capability: Altitude knowledge.

Capability Description: Altitude knowledge for above-surface vehicles within a few meters to a few hundred meters above the surface, depending on the mission.

Capability State of the Art: Laser altimeter and guidance, navigation, and control (GN&C) light detection and ranging (LIDAR) for Origins Spectral Interpretation Resource Identification Security – Regolith Exlorer (OSIRIS-REx) mission (much larger than sought here).

Parameter, Value:

OSIRIS-REx: 7.5 km maximum range, 0.5 km minimum range, range accuracy 5-30 cm, range resolution 1 cm.

Capability Performance Goal: Smaller sensor suitable for integration into vehicle with total mass on the order of 1 to 10 kilograms.

Parameter, Value:

Mass: < 20 grams;

Altitude error: < 10 cm;

Pulse repetition rate: up to 10 Hz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	2 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	3 years

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.7 Manipulator State Estimation

TECHNOLOGY

Technology Description: Estimates position and orientation of manipulator end effector relative to a camera and range sensor on the body of the vehicle.

Technology Challenge: Maintaining adequate update rates with flight-qualifiable processors.

Technology State of the Art: Fusion of arm joint encoder measurements with visual tracking of fiducial marks on manipulators and end effectors is well-established in terrestrial systems.

Parameter, Value:
3D position error: 1 cm;
Update rate: > 100 Hz

TRL 6

Technology Performance Goal: Same performance as current terrestrial solution, running fully autonomously onboard.

Parameter, Value:
3D position error: 1 cm;
Update rate: > 100 Hz

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Low size, weight, and power (SWaP), high performance onboard computer.

CAPABILITY

Needed Capability: End effector state knowledge.

Capability Description: Knowledge of position and orientation of end effector relative to sensors on the body of the vehicle that are used for closed-loop control of manipulator motions.

Capability State of the Art: Done with aid of human operators in ground systems for the Mars Exploration Rover (MER) and the Mars Science Laboratory (MSL) rover, using downlinked images.

Parameter, Value:
Update rate: 1 per sol.

Capability Performance Goal: Fully automatic, onboard capability using onboard three-dimensional (3D) range sensor for improved accuracy and reliability.

Parameter, Value:
3D position error: 1 cm;
Update rate: > 100 Hz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.2 State Estimation

4.1.2.8 Manipulation Object State Estimation

TECHNOLOGY

Technology Description: Estimates position and orientation (pose) of an object to be manipulated or being manipulated.

Technology Challenge: Estimation with cameras and three-dimensional (3D) range sensors that have the dynamic range for harsh and varying lighting conditions.

Technology State of the Art: Vision system for Robonaut estimating object poses inside the International Space Station (ISS).

Parameter, Value:

Position error at 1 m range: < 2 cm;
Orientation error at 1 m range: < 5 degrees.
Lighting conditions: controlled.

TRL 4

Technology Performance Goal: Millimeter accuracy in real-time for object pose estimation in extravehicular activity (EVA) environment.

Parameter, Value:

Position error at 1 m range: < 1 mm;
Orientation error at 1 m range: < 3 degrees.
Lighting conditions: naturally varying conditions in space.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Object pose knowledge.

Capability Description: Millimeter accuracy in real-time for object pose estimation in extravehicular activity (EVA) environment.

Capability State of the Art: Vision system for Robonaut estimating object poses inside the ISS.

Parameter, Value:

Position error of 1% of range and 0.5 degrees in attitude.

Capability Performance Goal: Autonomous onboard object pose estimation, fusing data from camera(s), range sensor, and/or force, torque, and tactile sensors on the vehicle, for cases (1) before object has been contacted and (2) while object is being contacted by the vehicle.

Parameter, Value:

Varies with range, from centimeters at range of several meters, to millimeters at range of several centimeters.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.3 Onboard Mapping

4.1.3.1 Terrain Mapping for Surface Vehicles

TECHNOLOGY

Technology Description: Fuses data from three-dimensional (3D) range sensors and other sensors to create maps of terrain geometry near a surface vehicle and to infer terrain terra-mechanical properties that significantly affect trafficability.

Technology Challenge: Defining terramechanical quantities that are useful for trafficability analysis, that can be observed accurately and reliably with sensors suitable for flight; developing flight-qualifiable versions of such sensors; developing algorithms that can estimate these quantities accurately and reliably; and developing implementations of such algorithms that achieve adequate speed with small, low-power, flight-qualifiable processors.

Technology State of the Art: Terrestrial research and development prototype systems: terrain classification systems using multispectral images, thermal images, and image texture; and terrain learning systems that estimate slip, sinkage, roughness, and terramechanical terrain parameters from visual, odometric, and inertial measurements. For flight projects, slip prediction tables in ground operations systems generated from manual terrain classification and rover tilt-table experiments.

Parameter, Value:

Terrain type classification error rate: ~ 15%;

Slip prediction error: ~ 50% of wheel velocity;

Sinkage prediction error: Not available.

TRL

4

Technology Performance Goal: Automatic production of maps by ground system with trafficability estimates from orbital remote sensing, at resolution of orbital remote sensing instruments, over large areas. Automatic production of maps with trafficability estimates onboard from onboard sensors, at resolution comparable to size of vehicle-terrain contact patch, over areas of at least several vehicle body lengths.

Parameter, Value:

Terrain type classification error rate: ~ 5%;

Slip prediction error: ~ 25% of wheel velocity;

Sinkage prediction error: ~ 15% of wheel diameter.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development and integration of adequate onboard sensors; low size, weight, and power (SWaP), high performance onboard computer.

CAPABILITY

Needed Capability: Terrain mapping for surface vehicles.

Capability Description: Estimates a 2.5D map of terrain near a surface vehicle for purpose of motion planning and hazard avoidance.

Capability State of the Art: Mars Exploration Rover (MER) and Mars Science Laboratory (MSL) local geometric terrain maps built from range data computed onboard with stereo vision. Use of visual odometry on MER and MSL rovers to estimate wheel slip.

Parameter, Value:

Only models terrain geometry, not terramechanical characteristics.

Capability Performance Goal: Automatically estimate terramechanical properties that significantly affect trafficability and include these in the map; implementation can be split between ground and onboard.

Parameter, Value:

Terrain type classification error rate: ~ 5%;

Slip prediction error: ~ 25% of wheel velocity;

Sinkage prediction error: ~ 15% of wheel diameter

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.3 Onboard Mapping

4.1.3.2 Terrain Mapping for Above-Surface Vehicles

TECHNOLOGY

Technology Description: Fuses data from three-dimensional (3D) range sensors and other sensors to create map of terrain geometry beneath an above-surface vehicle and to infer terrain terra-mechanical properties that significantly affect safe landing (see also TA 9).

Technology Challenge: Miniaturization, reduced power consumption, and radiation and temperature tolerance of sensors and processors.

Technology State of the Art: Onboard terrain mapping systems for unmanned aerial vehicles (UAVs) on Earth, using combinations of images and lidar range sensors. NASA's Origins Spectral Interpretation Resource Identification Security – Regolith Explorer (OSIRIS-REx) mission will use a flash lidar that is relevant.

Parameter, Value:
Map cell resolution: varies
(a few centimeters to a few meters);
Map height resolution: varies
(a few centimeters)

TRL 6

Technology Performance Goal: Onboard terrain mapping with sensors and processors that together are less than a few kilograms, for some applications well under one kilogram.

Parameter, Value:
Map cell resolution: varies (a few centinmeters to a few meters);
Map height resolution: varies (< 1 centimeter to a few centimeters)

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Miniaturization of appropriate sensors; low size, weight, and power (SWaP); high performance flight computer.

CAPABILITY

Needed Capability: Terrain mapping for above-surface vehicles.

Capability Description: Estimates a 2.5D map of terrain beneath an above-surface vehicle for purpose of identifying safe landing sites and science targets for in-situ aerial missions.

Capability State of the Art: Has not been done onboard in space.

Parameter, Value:
Not applicable.

Capability Performance Goal: Autonomous, real-time, onboard terrain mapping for identifying safe landing sites and science targets for in-situ aerial missions.

Parameter, Value:
Map cell resolution: varies
(a few centimeters to a few meters);
Map height resolution: varies
(< 1 centimeter to a few centimeters).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enabling	--	2029	2021	5 years
Discovery: Discovery 14	Enabling	--	2023	2020	5 years

4.1 Sensing and Perception
4.1.3 Onboard Mapping

4.1.3.3 Landmark Mapping from Image Sequences and Other Navigation Data

TECHNOLOGY

Technology Description: Estimates the three-dimensional (3D) coordinates of a network of landmarks on a planetary surface, using observations of the landmarks in images and other navigation data to constrain the landmark locations.

Technology Challenge: Achieving sufficient speed with flight processors that are sufficiently small, low-power, and radiation tolerant.

Technology State of the Art: Visual simultaneous localization and mapping (VSLAM) algorithms for Earth applications.

Parameter, Value:
Landmark database size: varies (100s to 1,000s);
Update speed: varies (a few seconds or less per cycle).

TRL 4

Technology Performance Goal: Fully automatic, onboard landmark mapping that achieves suitable speed and accuracy with feasible flight processors.

Parameter, Value:
Landmark database size: varies (100s to 1,000s):
Update speed: varies (a few seconds or less per cycle).

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Low size, weight, and power (SWaP), high performance onboard computer.

CAPABILITY

Needed Capability: Landmark mapping.

Capability Description: Creates a map of a network of landmarks on a planetary surface to aid in subsequent position estimation of spacecraft by observing those landmarks.

Capability State of the Art: Bundle adjustment algorithms used by human operators in ground systems for the Mars Exploration Rover (MER) and the Mars Science Laboratory (MSL) rover to create maps of landmark networks and image tie points for mapping and localization.

Parameter, Value:
Vehicle position error in target body surface reference frame: a few meters or less;
Operator interventions per update: ≥1

Capability Performance Goal: Fully automatic, onboard operation to increase navigation accuracy of Mars rovers in long distance traverse (for example, 500 m/sol) and to increase navigation accuracy for above-surface vehicles.

Parameter, Value:
Vehicle position error in target body surface reference frame: a few meters or less;
Operator interventions per update: none.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.3 Onboard Mapping

4.1.3.4 Three-Dimensional (3D) Modeling from Multiple Observations

TECHNOLOGY

Technology Description: Estimates geometric of three-dimensional (3D) structures, such as the lava tubes, using observations from multiple images or 3D range images obtained from multiple vehicle locations.

Technology Challenge: Miniaturization and environmental qualifiability of sensors and processors.

Technology State of the Art: Automatic 3D indoor mapping with structured light sensors in emerging smartphones and tablets; NASA is adapting this to an experiment on the International Space Station (ISS). Automatic 3D mapping of underwater structures from sonar data for unmanned underwater vehicles.

Parameter, Value:
Map resolution: varies (for example, 10 cm/cell);
Map size: varies (for example, up to 100 x 100 meters);
Update rate: varies (for example, < 1 sec/frame)

TRL: 5

Technology Performance Goal: Automatic 3D mapping of structures such as the interior of lava tubes.

Parameter, Value:
Map resolution: 10 cm;
Map size: 50 x 50 meters;
Update rate: < 1 sec/frame

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Low size, weight, and power (SWaP), high performance onboard computing and on compact 3D sensors that can operate in the dark.

CAPABILITY

Needed Capability: 3D modeling of 3D structures.

Capability Description: Estimates a 3D model of objects with fully 3D structure, such as lava tubes on the Moon or Mars, as opposed to 2.5D structure, like typical terrain. Also germane in Earth science to mapping volcanic vent and to under ice missions in Arctic regions for monitoring water flows under glaciers in studying climate change. Also germane to in-space robotic servicing.

Capability State of the Art: None

Parameter, Value:
Not applicable.

Capability Performance Goal: Automatic, onboard 3D modeling of 3D structures.

Parameter, Value:
Map resolution: 10 cm;
Map size: 50 x 50 meters;
Update rate: < 1 sec/frame

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years

4.1 Sensing and Perception
4.1.4 Object, Event, and Activity Recognition

4.1.4.1 Natural Object Recognition

TECHNOLOGY

Technology Description: Recognizes natural objects from predefined classes using onboard sensors; the objects may be landmarks, obstacles, or scientifically-significant formations. (See also TA 4.5.8 Automated Data Analysis for Decision Making)

Technology Challenge: Developing adequate recognition algorithms; obtaining adequate training data for such algorithms; achieving adequate speed with suitable flight processors.

Technology State of the Art: Algorithms for recognizing specific classes of natural landmarks, for example, craters, rocks with specific spectral signatures, etc.

Parameter, Value:

Example: crater detection

Miss probability: varies (for example, < 5% for fresh craters, > 65% for all craters).

TRL

5

Technology Performance Goal: Automatically recognize a wider range of natural objects for a wider range of missions using suitable, flight-qualifiable sensors and processors.

Parameter, Value:

Miss probability: varies (for example, < 5% for all objects of interest).

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Algorithm development; adequate onboard sensors; low size, weight, and power (SWaP), high performance onboard computer.

CAPABILITY

Needed Capability: Natural object recognition.

Capability Description: Recognizes natural objects, for example items like craters, rocks, sand dunes, cryovolcanos, plumes, or surface material types, as potential landmarks, navigation hazards, or science targets.

Capability State of the Art:

Autonomous Exploration for Gathering Increased Science (AEGIS) automatic science targeting system on Mars rovers.

Parameter, Value:

Miss probability: varies by application;

False alarm rate: varies by application;

Run time: varies by application

Capability Performance Goal:

Automatically recognize a wider range of natural objects for a wider range of missions.

Parameter, Value:

Miss probability: varies (for example, < 5%);

False alarm rate: varies (for example, < 5% of all detections);

Run time: varies (for example, a few seconds/frame)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Discovery: Discovery 14	Enabling	--	2023	2020	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.4 Object, Event, and Activity Recognition

4.1.4.2 Human-Made Object Recognition

TECHNOLOGY

Technology Description: Recognizes man-made objects and estimates their position relative to the vehicle, using observations from images, range data, radio beacons, and/or other sources. (See also TA 4.6 Autonomous Rendezvous and Docking.)

Technology Challenge: Achieving adequate reliability over the necessary range of object distances, object orientations, and lighting conditions.

Technology State of the Art: Rendezvous and docking systems for space, using cameras and/or lidar. Terrestrial research and development object recognition systems using cameras and/or range sensors of various types.

Parameter, Value:
Maximum range: varies;
Pose estimation error: varies;
Missed detection rate: varies;
False alarm rate: varies

TRL 4

Technology Performance Goal: Ability to recognize sample caches automatically with onboard sensors and algorithms. Ability for surface craft to recognize main spacecraft.

Parameter, Value:
Maximum range: varies;
Pose estimation error: varies;
Missed detection rate: varies;
False alarm rate: varies

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Algorithm development; adequate onboard sensors; low size, weight, and power (SWaP), high performance onboard computer.

CAPABILITY

Needed Capability: Man-made object recognition.

Capability Description: Recognizes man-made objects.

Capability State of the Art: Detection of docking fixtures in automatic rendezvous and docking systems.

Parameter, Value:
Maximum range: varies;
Pose estimation error: varies;
Missed detection rate: varies;
False alarm rate: varies

Capability Performance Goal: Automatic, onboard recognition of sample caches for Mars Sample Return. Automatic, onboard recognition of various spacecraft structures for in-space robotic servicing. Automatic recognition of main spacecraft by surface craft returning from sorties.

Parameter, Value:
Maximum range: varies;
Pose estimation error: varies;
Missed detection rate: varies;
False alarm rate: varies

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.4 Object, Event, and Activity Recognition

4.1.4.3 Event Recognition

TECHNOLOGY

Technology Description: Automatically processes time sequence data to detect occurrence of natural events (for example, dust devils on Mars, comet outgassing, rainfall or cyrovolcanic emissions on Titan) and man-made events (for example, completing a manipulation operation).

Technology Challenge: Achieving adequate reliability over the necessary range of object distances, object orientations, and lighting conditions; achieving adequate speed with achievable flight processor performance.

Technology State of the Art: Algorithms for change detection using cameras on a stationary vehicle, observing natural phenomena, particularly clouds and dust devils.

Parameter, Value:
Missed detection rate: unknown;
False alarm rate: ~80%;
Location error: unknown;

TRL 4

Technology Performance Goal: Change detection from a moving vehicle, observing natural phenomena and spacecraft events.

Parameter, Value:
Missed detection rate: < 5%;
False alarm rate: < 5%;
Location error: < 5° direction to event;

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Algorithm development; low size, weight, and power (SWaP), high performance onboard computer; in some cases, adequate onboard sensors.

CAPABILITY

Needed Capability: Event recognition.

Capability Description: Automatically detects occurrence of events that are important to operation or safety.

Capability State of the Art: Automatic detection of clouds and dust devils onboard Mars rovers.

Parameter, Value:
Miss probability: unpublished;
False alarm rate: ~ 80% of all detections.

Capability Performance Goal: Extend capability to a wider set of events and missions, such as automatic, onboard detection of plumes on Europa, Enceladus, and Titan; onboard detection of volcanic events at Venus; onboard detection of outgassing events on comets.

Parameter, Value:
Miss probability: < 5% for all objects of interest;
False alarm rate: < 5% of all detections.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	4 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.5 Force and Tactile Sensing

4.1.5.1 Space-Qualifiable Force and Torque Sensors

TECHNOLOGY

Technology Description: Provide measurements of forces and torques for individual contacts in a space-qualifiable implementation.

Technology Challenge: Accuracy over wide temperature dynamic range.

Technology State of the Art: 6 degrees of freedom (DOF) force/torque sensors for intravehicular activity (IVA) (for example, Robonaut has demonstrated force/torque sensing on the International Space Station (ISS)). Two of these sensors were built with IVA/extravehicular activity (EVA) compatible materials. Technology readiness level (TRL) 3 for EVA; TRL 7 for IVA.

Parameter, Value:

These parameters are mission dependent

Max force

Max moment

Sensitivity %

Immunity to single event upsets (SEUs) and radiation effects

TRL 3

Technology Performance Goal: 6 DOF force/torque sensors with redundancy for robustness (for example redundant sensors on each channel or redundant channel)

Force/torque sensors that are qualifiable for microgravity and surface exploration environments.

Parameter, Value:

These parameters are mission dependent

Max force

Max moment

Sensitivity %

Immunity to SEU and radiation effects

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Force and torque sensors

Capability Description: Provide measurements of forces and torques for individual contacts.

Capability State of the Art: 6 DOF force/torque sensor flew in 1994 on Space Transportation System (STS)-62 as part of the Dexterous End Effector. Mars Exploration Rover (MER) had no force/torque sensing on their arms. Mars Science Laboratory (MSL) rover has a 3 DOF force sensor in its wrist.

Parameter, Value:

These parameters are mission dependent

Max force

Max moment

Sensitivity %

Immunity to SEU and radiation effects

Capability Performance Goal: 6 DOF force/torque sensor with redundant sensors on each channel, qualifiable for microgravity and surface exploration environments.

Parameter, Value:

These parameters are mission dependent

Max force

Max moment

Sensitivity %

Immunity to SEU and radiation effects

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.1 Sensing and Perception
4.1.5 Force and Tactile Sensing

4.1.5.2 Space-Qualifiable Tactile Sensors

TECHNOLOGY

Technology Description: Provide array measurements of normal and/or shear quantities (for example, displacements) over extended contact areas.

Technology Challenge: Electrical harnessing for all of the measurement channels; temperature and environmental qualifiability, for example, for polymeric materials typically used.

Technology State of the Art: Robonaut has force/torque sensors in the fingers and coarse tactile sensors in the limbs for collision detection; not designed for external environment. Mature tactile sensors exist for terrestrial applications, but in an implementation that is challenging to space-qualify, due to materials and harnessing issues.

Parameter, Value:
Minimum measurable force; maximum force, sensors/unit surface area (mission dependent).

TRL
4

Technology Performance Goal: Provide array measurements of normal and/or shear quantities (for example, displacements) over extended contact areas, in a space-qualifiable implementation that addresses the electrical harnessing issue of having many sensor channels in a small space.

Parameter, Value:
Mission dependent.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Tactile sensors.

Capability Description: Provide array measurements of normal and/or shear quantities (for example, displacements) over extended contact areas.

Capability State of the Art: Nothing has flown, except inside the International Space Station (ISS).

Parameter, Value:
Unavailable

Capability Performance Goal: Provide array measurements of normal and/or shear quantities (for example, displacements) over extended contact areas, in a space-qualifiable implementation that addresses the electrical harnessing issue of having many sensor channels in a small space.

Parameter, Value:
Mission dependent.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enabling	--	2029	2021	3 years

4.2 Mobility
4.2.1 Extreme-Terrain Mobility

4.2.1.1 Rappelling Mobility Systems

TECHNOLOGY

Technology Description: Provides self-mobility that can rappel down steep terrain and retract back using assistive tethers.

Technology Challenge: Challenges include both vertical and lateral mobility on steep or vertical surfaces, overhangs, and access to lava-tubes and skylights.

Technology State of the Art: Research rovers have demonstrated rappelling and retracting into/from volcanoes, cliff faces, steep slopes, and overhangs in terrestrial field tests across limited distances and under a limited number of field trials.

Parameter, Value: (TRL 4)

Slope angle: > 90° (including overhangs);
Slope length: 10s of meters;
Tether strength: 500 N tethers;
Tether abrasion resistance: limited to dozen excursions;
Tether management: limited progress for ones that pack into small volumes (< 10 liters) and sense tether tension;
Tether power/comm: 10s of W, 10 Mbps;
Anchor mass as fraction of total system mass;
Tether mass as a function of total system mass and total length;
Self-emplacement of anchor: (yes/no).

Technology Performance Goal: Ability to traverse to rappelling site and then reliably rappel and retract payloads on highly sloped and rocky terrain. Ability to self-anchor; provide power and communication over tether; and manage its tether across long traverses to prevent snagging and recovering from snagged tether. Smart tethers that can sense tether tension and geometry to assist in planning robot motions and assessing its stability. Increase rappelled system mass fraction and energy fraction/efficiency. Increase rappelling distance for a range of terrain compositions and terrain hazard densities

Parameter, Value: (TRL 6)

Rappelling distance: 2 km;
Rappelling speed: 1 m/s;
Rappelling mass to system mass: 1:2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Extreme-terrain access.

Capability Description: Provides access to extreme terrain topographies such as crater walls, fissures, canyons, gullies, and lava tubes through their skylights.

Capability State of the Art: None: state of the art mobility is limited to untethered non-rappelling rovers.

Parameter, Value:

Slope angle: < 25°;
Slope length: unlimited

Capability Performance Goal: Ability to repeatedly access sites that are deep in extreme terrain topographies such as kilometers down crater walls and survive for extended periods of time to acquire in-situ measurements and samples for science of resource utilization.

Parameter, Value:

Slope angle: > 90° (including overhangs);
Slope length: several kilometers;
Tether strength: 1000+ N;
Abrasion resistance: to allow tens of excursions; Tethers that pack into small volumes (< 10 liters) with ~100 W power with small losses and high data rates (> 100 Mbps).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.1 Extreme-Terrain Mobility

4.2.1.2 Climbing Mobility Systems

TECHNOLOGY

Technology Description: Provides self-mobility that can climb extreme terrain topographies without the aid of a tether.

Technology Challenge: Challenges include terrrain properties that are not known or only partially known a priori; upward (against gravity) mobility on steep or vertical surfaces and overhangs; access to lava-tubes, skylights, and so on.

Technology State of the Art: Climbing mobility demonstrated using limbed anchors in a lab environment.

Parameter, Value:
Demonstrated emplacement of anchors and climbing; demonstrated gripping and releasing of grips using micro-spine technology; demonstrated climbing on natural rock with > 90 degree slopes for limited distances and on limited rock types.

TRL 2

Technology Performance Goal: Small climbing mechanism mass as fraction of total system mass, as a function of total mass; climbing system power efficiency in climbing straight up. Terrain slope angle. Terrain composition. Hazard density.

Parameter, Value:
Climbing distance: 100s of meters;
Climbing speed: 0.5 m/s;
Climbing mechanism mass to system mass: 1:2

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Extreme-terrain access.

Capability Description: Provides access to extreme terrain topographies such as crater walls, fissures, gullies and lava tubes.

Capability State of the Art: None: state of the art mobility is limited to rovers that can climb low-grade slopes.

Parameter, Value:
Slope angle: < 25°;
Slope length: unlimited

Capability Performance Goal: Ability to repeatedly access sites that are deep in extreme terrain topographies such as steep mountain walls for extended periods of time to acquire in-situ measurements and samples for science of resource utilization. Mobility systems that are strong enough to scale such terrains without assistive tethers and in an efficient manner (multiples of the potential energy gain).

Parameter, Value:
Slope angle: > 90° (including overhangs);
Slope length: several kilometers;
Energy efficiency: > 1% compared to potential energy (mph) change.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.1 Extreme-Terrain Mobility

4.2.1.3 Soft/Friable Terrain Mobility Systems

TECHNOLOGY

Technology Description: Provides self-mobility that can traverse extremely soft or friable terrains on bodies with substantial gravity.

Technology Challenge: Terra-mechanical properties of the terrain or heavy mobility platforms that makes supporting the weight of the mobility system on that terrain very challenging.

Technology State of the Art: Tank treads for large surface area contact to reduce ground pressure for heavy vehicles.

Wheeled mobility platforms with multiple wheel pairs to reduce ground pressure. Wheeled platfoms with large wheels, such as inflatable wheels, to reduce ground pressures. Compliant flight-like wheels that maintain constant ground pressure. Very low ground pressure (~0.7 kPa or 0.1 psi) wheeled rover.

Parameter, Value:	TRL
Ground pressure, 7 kPa (1 psi)	2

Technology Performance Goal: Mobility across soft terrains with friable surfaces and ability to transition between hard and soft terrains; ability to traverse slope terrains with such compositions.

Parameter, Value:	TRL
Ground pressure, 0.7 kPa (0.1 psi)	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Extreme-terrain mobility.

Capability Description: Provide mobility across soft terrains such as fine powdered dunes and terrains of friable rocks (such as Venusian Tesserae terrain).

Capability State of the Art: Prior lunar rovers and present martian rovers use rigid wheels with ~7 kPa (~1 psi) ground pressure.

Parameter, Value:

For wheeled vehicles, wheel mass as fraction of total vehicle mass as function of ground pressure.

Capability Performance Goal: Mobility under very low ground-pressure.

Parameter, Value:

Mobility with ground pressure: < 0.7 kPa.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.2 Below-Surface Mobility

4.2.2.1 Subsurface Access Through Natural Cavities

TECHNOLOGY

Technology Description: Provides access to and across natural occurring subsurface cavities such as lava tubes and crevasses where resources such as sunlight and line-of-sight are very constrained.

Technology Challenge: Lack of direct sunlight and line-of-sight for communication; rocks and debris could easily get dislodged and pose a risk to mobility system; no a priori orbital maps or images of natural cavities, so terrain is largely unknown.

Technology State of the Art: Human teams have explored skylights, lava tubes, and cenotes on Earth. NASA Astrobiology Science Technology for Exploring Planets (ASTEP) program funded robotic cenote exploration in 2007.

Parameter, Value:	TRL
ASTEP cenote explorer was a submarine, but could not rappel into the hole by itself	4

Technology Performance Goal: Ability to enter, explore, and exit a natural cavity of hundreds of meters in depth/length below the surface. Ability to operate for multiple sols in such environments.

Parameter, Value:	TRL
Length of excursion: 100s of meters; Operational duration: tens of sols	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mobility through natural cavities.

Capability Description: Entering, moving through and exiting a natural cavity over multiple sols in the absence of sunlight and line-of-sight with other surface or orbital assets.

Capability State of the Art: No deployed planetary system had demonstrated mobility through a natural cavity (for example, “skylights” into lava tubes).

Parameter, Value:

Not applicable.

Capability Performance Goal: Ability to enter, explore, and exit a natural cavity of hundreds of meters in depth/length below the surface. Ability to operate for multiple sols in such environments.

Parameter, Value:

Mobility traverse length/depth: 100s m;

Ability to anchor at surface and rappel into deep.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

4.2 Mobility
4.2.2 Below-Surface Mobility

4.2.2.2 Subsurface Access Through Human-Made Holes

TECHNOLOGY

Technology Description: Provides mobility through narrow and deep human-made holes for in-situ measurements.

Technology Challenge: Transporting instruments, sampling devices, and samples through narrow (1-2 cm) diameter holes that may be hundreds of meters long requires traction mechanisms, sensing, and control.

Technology State of the Art: Commercial drilling companies offer well-logging services both for wireline sensors lowered into hole after drilling, or "logging while drilling" where sensors are integrated into drill string. Currently, these are not robotic systems.

Parameter, Value:	TRL
Downhole depth: 100s of meters.	9

Technology Performance Goal: Reduce the size, mass, and power of down-hole mobility system. The smallest current commercial well-logging technology is ~4 cm diameter. This needs to be reduced to 1-2 cm to meet mass and power constraints of planetary missions.

Parameter, Value:	TRL
Both excavation and sensing need to be reduced to 1-2 cm diameter: excavation at ~500 J/cm^3, for example, pulsed neutron sources with gamma ray spectroscopy, EM sounding, all with performance comparable to current industry practice	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Miniaturization of down-hole mobility and sensing systems.

Capability Description: Methods of moving down-hole and performing engineering and science sensing.

Capability State of the Art: No such system has been flown.

Parameter, Value:
Not applicable.

Capability Performance Goal: Complete suite of down-hole mobility and sensing systems 1-2 cm diameter.

Parameter, Value:
System diameter: < 2 cm diameter.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.2 Below-Surface Mobility

4.2.2.3 Burrowing Mobility

TECHNOLOGY

Technology Description: Provides platforms that can burrow deep into a planetary surface.

Technology Challenge: Access to up to tens of kilometers of depth by a system whose mass and power would meet the constraints of their corresponding flight mission.

Technology State of the Art: Robots that burrow underground without leaving a full-diameter open-hole to the surface are presently limited to near-surface operations; tunnel boring machines need cuttings removal.

Parameter, Value:	TRL
Burrowing depth: 1,000 m Burrowing diameter: > 1 m	9

Technology Performance Goal: Burrowing device that compacts most cuttings right behind the vehicle under substantial pressure to provide weight-on-bit for good cutting performance at front. Small open-hole (for example, a narrow tube on spool) to route excess cuttings/samples, power, and data transmission. Liquid carbon dioxide (CO_2) cuttings transport fluid from Mars atmosphere has ultra-low viscosity and so flows well through small tubes.

Parameter, Value:	TRL
Depth: 10,000 m; Diameter: 3-10 cm; Mass: 10 kg; Power: 150 W Able to excavate at ~500 J/cm^3, able to compact cuttings to ~90% of native density so that < 10% of cuttings need to be transported out (also used as science samples).	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Deep subsurface access to putative liquid water aquifers.

Capability Description: Devices that can access putative liquid water aquifer on Mars to search for extinct or extant life (for example, chirality of complex organic molecules).

Capability State of the Art: None

Parameter, Value:
Not applicable.

Capability Performance Goal: Low-mass and low-power deep subsurface access without needing large assets on the surface to conduct operations (difference between burrowing and deep drilling).

Parameter, Value:
~100 kg/~150W system that can reach 10 km depth in ~1 year and deliver fine sample particles to surface for analysis or sample return.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years

4.2 Mobility
4.2.2 Below-Surface Mobility

4.2.2.4 Long-Endurance Submerged Mobility

TECHNOLOGY

Technology Description: Provides under-liquid mobility for extended periods of time for in-situ observations.

Technology Challenge: Large moons of outer planets appear to have liquid-water oceans under ice caps where life could evolve; ice penetrators could release submarines to search for hydrothermal vents, which could power colonies of life.

Technology State of the Art: Autonomous underwater vehicles (AUV) that dive to depths of 1,000 meters and are designed for missions lasting many months and covering thousands of miles.

Parameter, Value:	TRL
Depth: 1,000 meters; Duration: months; Distance: thousands of miles	6

Technology Performance Goal: Under-ice AUVs that survive and operate at pressures greater than the deepest oceans on Earth; powered by radioisotopes, able to communicate with station at ice-deployment location which is tethered to surface.

Parameter, Value:	TRL
External Pressure: 500 MPa; Temperature: 0-150° C; Power: radioisotope-powered	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Under-liquid mobility.

Capability Description: Provides mobility through a liquid medium at high pressures.

Capability State of the Art: Remotely Operated Vehicles (ROVs) that are tethered to a vessel.

Parameter, Value:
Duration tethered.

Capability Performance Goal: Long-duration; low-cost and amenable to large number of units for larger area/volume coverage. Unconstrainted: for example, untethered, does not rely on manned vessel; self-powered and self-sustaining.

Parameter, Value:
Months to year durations.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	10 years

4.2 Mobility
4.2.3 Above-Surface Mobility

4.2.3.1 Ballistic Systems

TECHNOLOGY

Technology Description: Ballistic-lift systems provide mobility through ballistic hops and can be fired from a base, leap through self-actuation, or use periodic reaction (thrust). No atmospheric interaction is needed, although an atmosphere may or may not be present.

Technology Challenge: Useful ballistic robots are very challenging on Earth because of the relatively high surface gravity and so have been rarely implemented. A primitive example is the grappling hook. However, for lower-gravity environments, ballistic mobility becomes increasingly attractive, allowing tethered or untethered packages to be launched tens or hundreds of meters per hop. These will be challenging to research and validate on Earth without elaborate gravity offloading schemes and subscale testing.

Technology State of the Art: Although many technologies have been researched, ballistic-lift research to date has been performed on Earth, which has a relatively high gravitational attraction, so the state of the art are spring-actuated systems. On low-gravity bodies, relatively little energy is required to move significant distances, so slow moving actuators can be used instead of spring action. Springs and actuators allow energy to be stored over time and to be released in a short burst of high power that enables lighter, lower power systems. Examples include Grasshopper, Cricket, and Flea.

Parameter, Value:

Length of the hop: 10 m
Height of the hop: 5 m
Control authority: none during hop
Lifetime: many launches (> 10)
Energy/distance: ~10x theoretical minimum.

TRL: 4

Technology Performance Goal: These have the potential of navigating extremely difficult (rough, loose) terrain in an energy efficient manner, storing energy gathered over time and releasing it in a burst. For Asteroid Redirect Mission (ARM), ascend from a multi-hundred-meter asteroid surface with up to ~60 ton spacecraft and collected material (aka boulder). Must absorb descent contact (5-10 cm per sec) and provide an escape velocity on push-off on the order of 20 cm/sec. For Phobos, sub milli-g environments (860-190 µg) ability in a controlled manner send crewed vehicles on suborbital hops via mechanical energy only and recover a portion of that energy on landing.

Parameter, Value:

Crewed systems from 2-30 tons ranging from small leap-frogging exploration vehicle to entire habitat.
Energy/distance: ~3x theoretical minimum.
Length of the hop: 200 m
Attitude controlled during hop.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Precise navigation control.

CAPABILITY

Needed Capability: Large-distance mobility with precise control across rugged terrain.

Capability Description: Provides mobility to distant and difficult terrains potentially without the overhead of carrying fuel for propulsion or limitations associated with heavily requirements-constrained landing zones.

Capability State of the Art: There have been no successful space missions utilizing ballistic-lift (e.g., hopper) capabilities.

Parameter, Value:

Distance jumped: x height

Capability Performance Goal: Explore planetray surface without expending any energy other than mechanical. Use solar energy.

Parameter, Value:

Energy management: target body dependent
Distance/Mass ratio: target body dependent

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	4 years

4.2 Mobility
4.2.3 Above-Surface Mobility

4.2.3.2 Static-Lift Systems

TECHNOLOGY

Technology Description: Static lift systems are buoyant and provide mobility using the difference between the densities of the atmosphere and the vehicle's buoyant gas. Static-lift systems may be powered or unpowered. Examples are balloons (tethered and untethered aerostats), dirigibles, and hybrid lift.

Technology Challenge: Challenges in atmospheric vehicles include environmental compatibility of materials and avionics (e.g. hot deep atmosphere of Venus, cold atmosphere of Titan, and sulfuric acid clouds of Venus), light-weighting of power sources, avionics, communications, insturments, and structures, thermal control, buoyancy modulation systems, and lower power propulsion. For extraterrestrial applications, new environmental test chambers would be helpful to validate performance of prototypes under relevant planetary conditions.

Technology State of the Art: Tethered balloons (aerostats), free balloons, dirigibles (blimps and airships), and hybrid-systems are commonplace on Earth and represent the State-of-the-Art. They are typically helium-filled or use hot air for buoyancy. Helium is used because of safety concerns in an oxyden rich atmosphere, which is not a factor for extraterrestrial applications. On Earth, these systems are in production and used daily so they are at high TRL (~9). Propulsion systems are propeller-based. Dirigibles are excellent for endurance, but limited in speed, so they are a good fit for loitering missions, under calm conditions. The only extraterrestrial balloons were the two hellium superpressure balloons on the Soviet Vega missions that flew for 2 days in the clouds of Venus in 1985. Some technology development has occurred for Titan, Mars and advanced Venus balloons, with maturities ranging from TRL 1 to 5 depending on the specific concept.

Parameter, Value:	TRL
Endurance: 1 hr to ~ 2 years Speed: ~ 100 km/hr (self-propelled) Altitude: 0 to ~ 50 km	4

Technology Performance Goal: Performance goals are application dependent but generally include increasing altitude operation range, increasing flight duration, increasing payload mass and addressing environmental compatibility. Some applications require trajectory and/or altitude control via buoyancy modulation or propulsion; others merely drift with the prevailing winds. All concepts require automatic deployment and inflation upon arrival at the destination. Venus and Titan are the most attractive targets because of their thick atmospheres and constant cloud cover, but Mars and giant planet balloon concepts also exist and have utility.

Parameter, Value:	TRL
Endurance: months Speed: ~0 to ~ 3.6 km/hr (wind-driven, e.g. Titan) Altitude: 0 to 15 km (Titan); 0 to 65 km (Venus); 0-5 to km (Mars)	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mobility through the atmosphere of planetary bodies.

Capability Description: Mobility through the atmosphere of bodies with substantial gravity where atmosphere is dense enough to support airships. Static systems could act as data-gathering vehicles themselves and/or enable easier access to regions of interest for cooperative vehicles. Examples include free or powered aerobots for Venus and Titan; free aerobots for Mars (atmospheric density precludes powered aerobots on Mars using near-term technology). The capability desired is to be able to maneuver to specific sites of scientific interest, hover over that spot, and to drop tethered instruments or sampling devices onto the surface. Returning to a safe altitude, science results can be transmitted to Earth, cooling off (in the case of Venus), and the next science target objective can be planned.

Capability State of the Art: State of the art includes the above surface explorers: Deployed balloons in the Venusian atmosphere to study the atmosphere and the exposed surface of Venus. Titan and Venus are relevant space environments for static-lift systems due to their dense atmospheres.

Parameter, Value: Duration (time) aloft. Subject to outgassing, available onboard power, latitude control for significant winds that blow toward poles to stay in manageable equatorial region or atmosphere. Altitude control due to rapid changes to pressure and temperature.

Capability Performance Goal: Powered blimps are considered attractive in the relatively dense atmospheres of Venus and Saturn's moon Titan. Solar-heated balloons are frequently considered for Mars or the gas giants (where the atmospheres are mostly hydrogen and helium, so lighter gas can only be achieved by heating). Proposed static-lift missions include a Titan mission concept to send a dirigible towards the surface that lowers sensors around and into methane lakes searching for life. Airship concepts could also be deployed for long-term exploration of the Venusian atmosphere.

Parameter, Value: Duration (time) aloft. Precision navigation and landing, Altitude control due to rapid changes to pressure and temperature.

Payload: 10s of kg

Endurance: 1 Earth year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enabling	--	2023	2020	4 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enabling	--	2029	2021	4 years

4.2 Mobility
4.2.3 Above-Surface Mobility

4.2.3.3 Dynamic-Lift Systems

TECHNOLOGY

Technology Description: Dynamic-lift systems utilize vehicle motion through the atmosphere or atmosphere movement (wind) to generate lift, and may be powered or unpowered.

Technology Challenge: Challenges in dynamic-lift vehicles include environmental compatibility (extreme heat or cold, extremely high or low pressures (density), chemical (for example, sulfuric acid on Venus)), power collection and consumption, avionics, communications, and instruments.

Technology State of the Art: There is no state of the art for the space environment and these technologies remain untested.

Parameter, Value:
Not applicable.

TRL
None

Technology Performance Goal: Minimum-power mobility systems with control authority to land on designated targets.

Parameter, Value:
Flight duration: mission and target body dependent.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: An aircraft design and fabrication that can accommodate planetary atmospheres on the order of thousandths of that on Earth.

Capability Description: Mobility to increase our extraterrestrial exploration range with powered above-surface flight.

Capability State of the Art: Current capability concepts of dynamic lift mobility concepts include Mars Airplane and the solar-electric Venus Airplane (both untested).

Parameter, Value:
No flight system exists.

Capability Performance Goal: Kites are currently being investigated for power generation on Earth, and have potential for doing so on Mars as well. Depending on specific conditions, this could be more reliable and higher power than solar. While gliders may be single use, they may still be useful for space exploration as they don't need a power source if dropped during entry.

Parameter, Value:
In-flight duration: hours (for unpowered systems);
In-flight duration: days to weeks (for powered systems)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.2 Mobility
4.2.3 Above-Surface Mobility

4.2.3.4 Power-Lift Systems

TECHNOLOGY

Technology Description: Powered-lift systems, a critical enabler for vertical takeoff and landing (VTOL) capability, use thrust to overcome weight for lift. An advantage of powered lift systems is that they can be used in a range of atmospheric environments.

Technology Challenge: Challenges in powered-lift vehicles include environmental compatibility (extreme heat or cold, extremely high or low pressures (density), chemical (for example, sulfuric acid on Venus), etc.; power collection and consumption, avionics, communications, instruments, etc.; light-weighting of power sources, avionics, communications, instruments, engine reusability, controls, and autonomy. Powered-lift is the least efficient means of above surface mobility, making endurance, power, and energy the greatest challenges.

Technology State of the Art: The state of the art includes tethered, free rotor, and rocket thrust. Short duration autonomous flight and return to launch location with precision landing has been demonstrated in testing by commercial entities. The Apollo Lunar Excursion Module (LEM) demonstrated rocket thrust in manual operation.

Parameter, Value:

Precision landing, distance, time;

Effective specific impulse. ~300 s for systems using fuel/oxidizer mixtures. Aerodynamic systems (e.g. helicopters) have tremendous "effective specific impulse."

TRL

7

Technology Performance Goal:

Altitude.
Number of cycles.
Control authority.
Ability to descend/ascent from surface.
Precise destination control.
Duration of forward flight.
Control authority.
Lifetime.
Energy/distance.

Parameter, Value:

Seconds, minutes, meters, etc.
For Mars Hopper, effective specific impulse of 200 s
For Titan Helicopter, effective specific impulse of 2,000 s (lift force times duration per unit mass consumed)

TRL

4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Critical enabler for VTOL capability.

Capability Description: Mobility solution that takes advantage of access advantages of VTOL without sacrificing efficiency in forward flight.

Capability State of the Art: The LEM, an exception to the very low TRL of extraterrestrial platforms, demonstrated rocket thrust in manual operation. On Earth, many powered-lift robotic systems, such as quadcopters, have become mainstays and are rapidly finding uses in the civil and commercial sectors for surveillance, law-enforcement, marketing, and Earth science.

Parameter, Value:

Increased distance: hundreds of meters on Morpheus and Mighty Eagle.

Capability Performance Goal: Potential uses include jetpacks and thruster-powered vehicles. One potential mission is the Asteroid Redirect Mission "Option B" to lift a boulder off the surface of a large asteroid, which can be achieved with powered-lift alone, if hoppers are not included in the mission concept. In 2015, Origins Spectral Interpretation Resource Identification Security – Regolith Explorer (OSIRIS-REx) plans to descend and touch an asteroid with an arm using powered flight.

Parameter, Value:

Distance, mass, fuel consumption.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

4.2 Mobility
4.2.4 Small-Body and Microgravity Mobility

4.2.4.1 Free-Floating Robots

TECHNOLOGY

Technology Description: Provide self-positioning and self-orientation in microgravity for sensing and operations.

Technology Challenge: Inspection of spacecraft, as well as exploration of asteroids, requires robots that can maneuver effectively in microgravity, ensuring collision-free trajectories even as close-up observations are performed with occasional planned contact for docking and sampling.

Technology State of the Art: Mini autonomous extravehicular activity (EVA) robotic camera (AERCam), a free-flying spherical inspection robot capable of tele-operated maneuvering in the vicinity of a human spacecraft. It is slightly over one half the diameter of the AERCam that was flown in 1997 (see Capability SOA below).

Parameter, Value:

AERCam Sprint total delta-V capability: ~10 m/s;

Total mass: 16 kg;

Non-refuelable in-flight.

Mini-AERCam is 5 kg but still only ~10 m/s total delta-V.

TRL

6

Technology Performance Goal: Need total delta-V (> 100 m/s); need mass ~5 kg; need autonomous control and hazard avoidance; need in-space refueling.

Parameter, Value:

Total delta-V: > 100 m/s;

Total mass: < 5 kg;

Autonomous control and hazard avoidance;

Autonomous docking with refuel and recharging station.

TRL

7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Robot Navigation (4.2.6).

CAPABILITY

Needed Capability: Space asset inspection.

Capability Description: Provides non-contact (for example, visual) remote inspection of the health of space assets such as micrometeorite damage and leak detection.

Capability State of the Art: AERCam Sprint was flown in 1997 on STS 87.

Parameter, Value:

Delta V: 10 m/s;

Mass: 16 kg

Capability Performance Goal: Larger delta V, autonomous refueling (including docking), and autonomous hazard avoidance.

Parameter, Value:

Delta V: 100 m/s per refuel;

Mass: 5 kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	3 years
Exploring Other Worlds: Push	Enhancing	--	--	--	3 years

4.2 Mobility
4.2.4 Small-Body and Microgravity Mobility

4.2.4.2 Hopping/Tumbling Surface Robots

TECHNOLOGY

Technology Description: Provide mobility on the surface of small bodies with low-gravity using hopping and tumbling maneuvers.

Technology Challenge: Non-uniform gravity and varying gravity vector direction of small bodies; challenging rugged topography with surfaces covered with large rocky to ones covered with fine regolith. Controlled motions are very challenging given low-gravity. Microgravity mobility testing is very challenging with limited opportunities and limited durations of a microgravity environment, often with large uncertainties in the gravity levels.

Technology State of the Art: Prototype hopping and tumbling robots demonstrated in lab environments; in parabolic flight and in drop towers.

Parameter, Value:

Uncontrolled mobility.

TRL 4

Technology Performance Goal: Provide both large surface coverage and fine maneuverability around target sites. Mobility to reach designated sites on different parts of the body. Increase energy efficiency and lifetime of mobility system.

Parameter, Value:

Controlled mobility to designated targets to within 10% of traverse distance or a few meters for targets designated by a main spacecraft station-keeping at 1 kilometer.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small-body mobility.

Capability Description: Provides surface and low-altitude above surface mobility for small bodies.

Capability State of the Art: While several systems have been attempted, none succeeded to date.

Parameter, Value:

Not applicable.

Capability Performance Goal: Greater surface access and coverage. Longer-duration exploration campaigns. More controlled mobility to designated targets of interest to the science and human exploration programs.

Parameter, Value:

Surface coverage: 100s x 100s of m^2 of surface coverage;

Controlled mobility to designated targets to within 10% of traverse distance or a few meters for targets designated by a main spacecraft station-keeping at 1 km;

Lifetime: weeks to months.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years

4.2 Mobility
4.2.4 Small-Body and Microgravity Mobility

4.2.4.3 Anchoring Robots

TECHNOLOGY

Technology Description: Provide mobility on the surface of small bodies by anchoring and de-anchoring onto the surface.

Technology Challenge: Small bodies have surfaces with mix of regolith, gravel, and rock. Consumable-free exploration of such bodies relies on anchoring and de-anchoring to move around the surface. Anchoring also provides intimate contact enabling acoustic-seismic mapping and other interior sensing. Validation of such a capability is extremely challenging given the limitations of current test beds. Surface properties of small bodies are at best only partially known.

Technology State of the Art: NASA All Terrain Hex-Limbed Extra Terrestrial Explorer (ATHLETE) robot developed under human-robot systems project has demonstrated anchoring/de-anchoring for small bodies in terrestrial settings (Earth gravity; non-vacuum, ambient temperature).

Parameter, Value:

Pull-out force: > 50 N with anchors of mass ~1 kg for a 1,000 kg platform.

TRL 5

Technology Performance Goal: Demonstrate robust anchoring and de-anchoring on a range of terrain types (from soft regolith to hard surfaces) in microgravity. Validate capability in relevant environment.

Parameter, Value:

Pull-out force: > 50 N,
Anchor mass: < 1 kg for rock and < 10 kg for regolith, for a 1,000 kg platform (this would scale for smaller platforms).

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Mobility Components (Terrain Adhesion 4.2.8.3).

CAPABILITY

Needed Capability: Small-body surface operations.

Capability Description: Provides ability to anchor in support of mobility, sensing (for example, seismometry), sample acquisition, and asset manipulation.

Capability State of the Art: None has been flown.

Parameter, Value:

Not applicable.

Capability Performance Goal: Strong, lightweight, reusable anchors for soft and hard surfaces.

Parameter, Value:

Pull-out force: > 50 N;
Anchor mass: < 1 kg for rock and < 10 kg for regolith,
for a 1,000 kg platform (this would scale for smaller platforms).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years

4.2 Mobility
4.2.4 Small-Body and Microgravity Mobility

4.2.4.4 Wheeled/Tracked/Hybrid Robots

TECHNOLOGY

Technology Description: Provide mobility on the surface using wheels, tracks, limbs, or a hybrid of these.

Technology Challenge: Low-mass, low-power mobility over extreme surfaces such as soft regolith, steep slopes, and dense rock fields, which may require hybrids of more conventional mobility systems such as wheels, tracks, and limbs.

Technology State of the Art: All Terrain Hex-Limbed Extra Terrestrial Explorer (ATHLETE) rover developed under NASA Human-Robot Systems project demonstrated hybrid wheel/limb rover that achieves power-efficient wheeled roving over ~97% of terrain with highly capable limbed mobility (mostly to extricate itself) from remaining 3%. Demonstrations were in both Earth and reduced-gravity (gravity offloading), but no vacuum/thermal extremes.

Parameter, Value:	TRL
Kilogram of mobility mass per N of payload weight to reach 99% of Moon/Mars surface: 0.075 kg/N	5

Technology Performance Goal: Low power and low mass to reach > 99% of lunar or Mars surface, without requiring extreme wheel sizes or similar systems that are massive, bulky, hard to stow and deploy, and prone to damage.

Parameter, Value:	TRL
Kilogram of mobility mass per N of payload weight to reach 99% of Moon/Mars surface: 0.075 kg/N	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Need capability to move with good power efficiency (< 15% average specific resistance) over > 99% of lunar and Mars terrain, carrying large payloads.

Capability Description: Hybrids of wheels and limbs or tracks and limbs can provide power-efficient mobility with extreme terrain access.

Capability State of the Art: NASA ATHLETE rover developed under the Space Technology Mission Directorate (STMD) Human Robot Systems project.

Parameter, Value:

< 15% average specific resistance;

~0.075 kg/N mobility mass to payload weight.

Capability Performance Goal: 12% average specific resistance; < 0.06 kg/N mobility mass to payload weight.

Parameter, Value:

12% average specific resistance;

< 0.06 kg/N mobility mass to payload weight.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.2 Mobility
4.2.5 Surface Mobility

4.2.5.1 Mobility Subsystem for Crewed Surface Transport

TECHNOLOGY

Technology Description: Self-transports a payload system, including a crew in a pressurized cabin, on planetary surfaces with acceptable safety and reliability.

Technology Challenge: Challenges for surface rovers are mobility on natural terrains reducing the mobility mass fraction of the total mobile mass, along with power and thermal challenges. Tires, suspension, docking, communication, control, sensing, and cabin technology challenges (TA 7) are significant.

Technology State of the Art: Multi-wheeled vehicles with active suspension such as Multi Mission Space Exploration Vehicle (MMSEV) and All Terrain Hex-Limbed Extra Terrestrial Explorer (ATHLETE).

Parameter, Value:	TRL
Mobility mass fraction: 20% (mass of mobility mechanism/total mass) for large payloads.	4

Technology Performance Goal: Reduce mass fraction for a crew rover that is capable of operating on both the lunar and Martian environment, as well as survive launch on an unmanned rocket, transit environment to the Moon and Mars, and the landing on either planet.

Parameter, Value:	TRL
Mass fraction: Range: 400 km; Speed: 20 km/h; Mass: 3,000 kg; Payload: 2,000 kg; Hill Climb: 35 deg; Life: 3,600 days	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Crew rover to explore Mars and the Moon.

Capability Description: Exploration of Mars and the Moon using a Crew Rover.

Capability State of the Art: Apollo Lunar Rover.

Parameter, Value:

Range: 30 km;
Speed: 20 km/h;
Mass: 4,400 kg;
Payload: 500 kg; Hill
Climb: 35 deg;
Life: 3 days

Capability Performance Goal: Reduce mass fraction for a crew rover that is capable of operating on both lunar and Martian environments.

Parameter, Value:

Mass fraction:
Range: 400 km;
Speed: 20 km/h;
Mass: 3,000 kg;
Payload: 2,000 kg;
Hill Climb: 35 deg;
Life: 3,600 days

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	6 years

4.2 Mobility
4.2.5 Surface Mobility

4.2.5.2 Mobility System For Uncrewed Surface Transport

TECHNOLOGY

Technology Description: Self-transports small and large payloads to designated target areas on planetary surfaces, potentially at relatively high speeds.

Technology Challenge: Fast transport of payloads across uneven rocky surfaces with long mission durations. Technology challenges include energy storage, wheels, suspension (including active), highly-dense power for actuation, and wheels on legs concepts.

Technology State of the Art: Rocker-bogie wheeled mobility for rough terrains. Alternative mobility that included tri-wheeled rovers with large inflatable wheels and spherical rovers that are wind-driven or driven through internal actuation.

Parameter, Value:

For rocker bogie wheeled platforms:

Traverses rocks of a 1.5 wheel diameters. Pulls out of holes.

TRL
9

Technology Performance Goal: Faster traverses with larger payloads.

Parameter, Value:

Range: 500 km;

Speed: 500 m/h;

Payload: 90 kg;

Slope angle: 30°;

Duration: 10 years

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fast surface transport.

Capability Description: Fast traverse and transport of large payloads.

Capability State of the Art: Slow mobility (both mechanical and autonomous).

Parameter, Value:

Range: 50 km;

Speed: 100 m/h;

Payload: 90 kg;

Slope angle: 30°;

Duration: 10 years

Capability Performance Goal: Orders-of-magnitude faster traverse with larger payloads.

Parameter, Value:

Range: 500 km;

Speed:500 m/h;

Payload: 90 kg;

Slope angle: 30°;

Duration: 10 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.6 Robot Navigation

4.2.6.1 Adaptive Autonomous Surface Navigation

TECHNOLOGY

Technology Description: Assesses hazards for a given mobility platform using multi-sensory inputs, rapidly plans and executes motions to avoid such hazards, and adapts models based on prior experience.

Technology Challenge: Assessment of navigation performance under a range of terrain and lighting conditions. Incorporation of higher fidelity models of mobility in traversability assessment and motion planning with limited onboard computation. Assessment of broader range of terrain hazards (geometric and terramechanical hazards) with limited sensing and onboard computation. Online navigation parameter and algorithm tuning based on traverse experience.

Technology State of the Art: Global Positioning System (GPS)-aided navigation at 10s of km/hour in urban and rough terrains with GPS.

Parameter, Value:

Reliability: false positive and negative in terms of detecting and avoiding hazards.

TRL: 6

Technology Performance Goal: Assessment of hazards based on high-fidelity vehicle models; motion planning based on such models; assessment of negative obstacles; terrain hazards; thinking while driving.

Parameter, Value:

Traverse speed: > 100 m/hr;

Reliability: 6 sigma

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous surface traversing.

Capability Description: Uses onboard sensing to autonomously traverse long distances by detecting, avoiding, and learning from terrain hazards.

Capability State of the Art: Geometric-based hazard detection of positive (above surface) obstacles.

Parameter, Value:

Speed: 20 m/hr;

Low obstacle density: < 5%

Capability Performance Goal: Highly reliable, well-characterized and fast autonomous traverse in benign planetary terrain; supports various surface mobility platforms, adapts models and parameters based on prior experience; adapts computation based on hazard density.

Parameter, Value:

Traverse speed: > 200 m/hr;

Obstacle density: < 10%;

Adaptable to different mobility designs,

Adaptable computation based on terrain,

Learns from prior experience.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.6 Robot Navigation

4.2.6.2 Autonomous Navigation for Tethered Systems

TECHNOLOGY

Technology Description: Uses multi-sensory inputs to assess traversability for rappelling tethered systems, plans and executes motions to avoid such hazards, and adapts models based on prior experience.

Technology Challenge: Challenges include hazard assessment for extreme terrain mobility platforms; tethered route management across long traverses; surface mobility dynamics with and against gravity; terrain mapping of large topological transitions.

Technology State of the Art: Teleoperation of tethered platform based on assessments from onboard sensors for terrestrial applications. Technology readiness level (TRL) 6 for tele-operated systems; TRL 1 for autonomy navigation.

Parameter, Value:	TRL
Reliability: safe routes for tethered platforms; false positive and negative in terms of assessing and avoiding hazards.	6

Technology Performance Goal: Assessment of hazards based on terrain topography, platform dynamics, gravity, and tether geometry.

Parameter, Value:	TRL
Tethered traverse distance: kms; Reliability: 6 sigma	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Extreme terrain navigation.

Capability Description: Uses onboard sensing to autonomously rappel down sloped and rocky terrains.

Capability State of the Art: Geometric-based hazard detection of positive (above surface) obstacles.

Parameter, Value:

Slopes: < 15 degs;

Rock density: < 5%

Capability Performance Goal: Safe autonomous traverses of tethered platforms that allows access to steep and high sinkage terrains with risk of platform entrapment or tether entanglement.

Parameter, Value:

Slope: up to vertical;

Rock/boulder density: 50%;

Learns from prior experience

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.6 Robot Navigation

4.2.6.3 Low-Altitude Above-Surface Navigation

TECHNOLOGY

Technology Description: Uses multi-sensory input to autonomously control above-surface platforms to traverse to designated locales and avoid mountainous terrain.

Technology Challenge: Data rich, computationally-intensive sensing and perception and motion planning on power- and computation-limited flight processors. Vision-based localization and mapping in dynamic closed control.

Technology State of the Art: Navigation of aerial vehicles in urban environment including obstacle detection and avoidance.

Parameter, Value: Real-time hazard avoidance not operational at this time; expected to be available on other government agency systems within a few years.

TRL 4

Technology Performance Goal: Fast terrain mapping, obstacle detection, and motion planning on limited computation flight proecessors.

Parameter, Value: Ability to fly short hops (~excursions tens of seconds to minutes depending on target body) with 99% reliability for hazard avoidance and safe landing.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Above-surface navigation.

Capability Description: Provides controlled traverses to designated locales.

Capability State of the Art: None.

Parameter, Value: Not applicable.

Capability Performance Goal: Energy-efficient controlled mobility above planetary surfaces.

Parameter, Value:
Fly speed: > 1 km/hr;
Traverse distance: 10s of km
Hazard avoidance: 99%
Landing location accuracy: 2 m

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Earth Venture Suborbital	Enabling	--	On-going	--	5 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	5 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years

4.2 Mobility
4.2.6 Robot Navigation

4.2.6.4 Below-Surface Navigation

TECHNOLOGY

Technology Description: Provides self-sensing and self-perception of the surface environment and then self-selection of optimal routes to achieve sub-surface traverse goals.

Technology Challenge: Energy-constrained, potentially mass and volume constraint mobility, with no line-of-sight for communication and orbital information; no sunlight.

Technology State of the Art: Underwater surface navigation for government application.

Parameter, Value:

Mission duration: 10s of hours

TRL: 5

Technology Performance Goal: Use of limited available sensed data to direct a below-surface mobility platform. Technology solutions would differ depending on whether platform is under-ice melting probe, under-liquid (submersible) platforms, or a skylight explorer.

Parameter, Value:

Operation duration without intervention (communication cycle): multi-sol;

Waypoint positional accuracy: 10% of traverse depth.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Below-surface mobility.

Capability Description: Ability to reach waypoints below surface using sensory limited information and limited communication cycles.

Capability State of the Art: None

Parameter, Value:

Not applicable.

Capability Performance Goal: Ability to reach designated waypoints with a given accuracy.

Parameter, Value:

Below-surface positional accuracy: 10% of traverse depth and lateral distance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years

4.2 Mobility
4.2.6 Robot Navigation

4.2.6.5 Small-Body/Microgravity Navigation

TECHNOLOGY

Technology Description: Provides self-assessment of hazards in microgravity with motion planning and execution for hazard avoidance.

Technology Challenge: Mobility in microgravity can easily generate platform gyrations making perception, mapping, motion planning, and control very challenging.

Technology State of the Art: Limited visual based pose estimation during hopping traverses.

Parameter, Value: Traverse distance: few meters.

TRL 3

Technology Performance Goal: Traverse to remotely designated targets.

Parameter, Value: Traverse accuracy: 20% of traverse distance.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small-body/microgravity navigation.

Capability Description: Provides self-assessment of hazards in microgravity with motion planning and execution for hazard avoidance.

Capability State of the Art: None

Parameter, Value: Not applicable.

Capability Performance Goal: Traverse to designated remotely designated targets.

Parameter, Value: Traverse accuracy: 20% of traverse distance.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years

4.2 Mobility
4.2.7 Collaborative Mobility

4.2.7.1 Collaborative Mobility Algorithms

TECHNOLOGY

Technology Description: Provides algorithms that control and coordinate the mobility of a group of planetary platforms to achieve a higher-level objective that cannot be performed by a single platform.

Technology Challenge: Requires force/torque sensing for cooperation.

Technology State of the Art: Homogeneous and heterogeneous groups of robots need to be able to cooperate to perform tasks with low-bandwidth, or in an emergency, with no intercommunications.

Parameter, Value:	TRL
Load-sharing demonstrated, even without communications.	4

Technology Performance Goal: Coordinated handling and transportation of loads (for example, habitats).

Parameter, Value:	TRL
Load: > 2 times capacity of each robot; Separation between coordinated vehicles; Physical cooperation vs. cooperative activities.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Hierarchical control with and without intercommunications.

Capability Description: Homogeneous and heterogeneous groups of robots need to be able to cooperate to perform tasks with low-bandwidth, or in an emergency, no intercommunications.

Capability State of the Art: None in space.

Parameter, Value:
Not applicable.

Capability Performance Goal: Coordinated handling and transportation of loads (for example, habitats).

Parameter, Value:
Load: > 2 times capacity of each robot;
Separation between coordinated vehicles;
Physical cooperation vs. cooperative activities.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years

4.2 Mobility
4.2.8 Mobility Components

4.2.8.1 Wheels for Planetary Surfaces

TECHNOLOGY

Technology Description: Provides wheels that survive the thermal and other environmental challenges, have compliance with near-constant ground pressure over contact patch, and allow appropriate grousers to be included.

Technology Challenge: Design light wheels for the environment, which may require utilizing non-traditional materials.

Technology State of the Art: Pneumatic wheels are mature terrestrial technology with uniform ground pressure; commercial companies have worked with NASA on compliant wheels suitable for planetary environments. Apollo wheels are still the state of the art.

Parameter, Value:	TRL
Wheel load capacity: ~650 N/kg.	4

Technology Performance Goal: Increase wheel load capacity per unit mass. Design lunar and Martian worthy wheels for use on the NASA Space Exploration Vehicle and conduct environmental test on wheels that have expected load rating of anticipated vehicles.

Parameter, Value:	TRL
20% improved performance over Apollo wheels (wheel load capacity per unit mass) with greater than 1,000 km of useful life.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Wheel for large lunar and Mars rover that travels at dynamic speeds.

Capability Description: Wheels capable of being used on lunar and Martian crewed rovers.

Capability State of the Art: Mars Exploration Rover (MER)/Mars Science Laboratory (MSL) wheels are machined from single billet of aluminum – not compliant; Apollo Lunar Rover wheels were woven grid of music wire with titanium cleats – were compliant.

Parameter, Value:

Compliant Apollo wheels were 5.4 kg and 41 cm in diameter to carry 3,500 N max load; diameter scales like 1/2 power of load, mass scales like 3/2 power of load (constant ground pressure 1 psi).

Capability Performance Goal: Reduce overall mobility mass by reducing the mass of the wheels for lunar and Martian rovers.

Parameter, Value:

20% improved performance over Apollo wheels (wheel load capacity per unit mass).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.8 Mobility Components

4.2.8.2 Actuators for Mobile Robots

TECHNOLOGY

Technology Description: Provide light-weight, extreme environment-capable actuators and actuator components (motors, bearings, gears, gearboxes, positoin sensors, brakes, electronics and lubricants) that generate high torque at low speed and high speed at low torque (multi-speed gearbox, solid-state analogs of traditional "series-wound" motors, advanced motor controller for permanent magnet motors, etc.).

Technology Challenge: Large range of torque and speed using a robust, long-life, small and lightweight actuator. Uncrewed planetary rovers need a stall rim thrust equal to 50% the weight of the vehicle in local gravity, and an operating rim thrust equal to ~2% the weight of the vehicle at cruise speed. This 25:1 ratio is poorly matched to small motors with high-ratio single-speed gearheads.

Technology State of the Art: For power-constrained space applications, actuator state of the art results in very slow moving rovers ~5-10 cm/s due to their large gear ratios that are necessary to meet the stall rim requirement. Terrestrial vehicles use multi-speed transmissions to addess this issue. Electric vehicles can operate without a multi- or variable-speed transmission if the motor is relatively large.

Parameter, Value:

State of the art is open-frame motor and gear component sets that are integrated into the output structure for a given application.
Parameter values vary depending on application.
For example, for uncrewed martian rover that use electromagnetic actuators
(1W-1000W):
Specific Power: ~200 W/kg (motor)
Specific Torque: 300–400 N-m/kg (for harmonic or planetary gearhead)
Speed: ~1.5 RPM (at rim thrust equal to 2% of vehicle weight)
Ambient temperature range:
-60 °C – +60 °C
Lifetime performance:
~10^8 revolutions.

TRL: 9

Technology Performance Goal: Increase specific power, specific torque, speed and lifetime of actuators. Improve matching between low and high speed load conditions.

Parameter, Value:

Specific Torque: 500+ N-m/kg
Specific Power: 300+ W/kg
Speed: ~15 RPM (at rim thrust equal to 2% of vehicle weight)
Ambient temperature range:
-180 °C – +100 °C
Lifetime performance:
~10^8+ revolutions.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Actuators for a wide range of planetary mobility applications.

Capability Description: Actuators that can support a range of planetary mobility applications from wheeled surface rovers (drive wheels, steering wheels, suspension articulation) to propeller-based above-surface platforms to below surface applications. Some applications apply to crewed and uncrewed platforms.

Capability State of the Art: Varies depending on application. For example, for wheeled rover, state of the art is high torque actuators that result in slow cruise rover speeds of 5 cm/s.

Parameter, Value:

Varies based on application
Specific Torque
Specific Power
Ambient temperature range
Lifetime performance

Capability Performance Goal: Varies depending on application. Increase specific power, specific torque, speed, and lifetime for lunar and Martian crewed rovers. Improve matching between low and high speed load conditions.

Parameter, Value:

Varies based on application
Specific Torque
Specific Power
Ambient temperature range
Lifetime performance

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.8 Mobility Components

4.2.8.3 Terrain Adhesion

TECHNOLOGY

Technology Description: Provides mobility aids for rolling, crawling or flying platforms traction, adhesion, or anchoring (including their reverse operation) to different terrain types.

Technology Challenge: Challenges include a priori unknown or partially known terrain properties, substantial holding forces and torques in multiple direction, repeated applications over extended periods of time and under changing environmental conditions.

Technology State of the Art: Anchors for hard rock and regolith; omnidirectional anchoring mechanisms using micro-spines on certain types of natural rocks; and gecko-adhesives with hold forces in one direction and release in another.

Parameter, Value:

Omnidirectional microspine anchors that can withstand 150 N holding forces on certain types of natural rocks;

Two-level gecko-adhesives that can hold 2 N loads and accommodate misalignments.

TRL

5

Technology Performance Goal: Increase holding strength in multiple directions and increase the durability (lifetime and number of cycles) these adhesion mechanisms can repeatedly support.

Parameter, Value:

Holding strength:

Surface types: rock and regolith;

Number of adhesion and removal cycles: > 1,000s

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Terrain adhesion.

Capability Description: Provides adhesion to a range of terrain types for mobility and in-situ measurements.

Capability State of the Art: None used in operational space missions.

Parameter, Value:

Mass of feet as fraction of total system mass supported on vertical surface in 1-g field.

Capability Performance Goal: Reliable anchors for a range of surfaces that can be repeatedly gripped and released with holding strengths to support mobility across a range of surfaces for multi-sol operations.

Parameter, Value:

Holding strength: to support mobility platform weight with margin;

Surface types: rock and regolith;

Number of adhesion and removal cycles: > 1,000s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.2 Mobility
4.2.8 Mobility Components

4.2.8.4 Sensing Terra-Mechanical Properties

TECHNOLOGY

Technology Description: Provides stand-off or contact sensing of properties, such as load-bearing strength, friability, and anchor strength verification.

Technology Challenge: Terrains are largely heterogeneous and terrain properties have a wide range of values. Measuring terrain properties is challenging in terrestrial setting and even more so in space. Developing, testing, and integrating worthy sensors into Martian and lunar missions is a challenge.

Technology State of the Art: Ground penetrating radar has been used to look-ahead at the dielectric/density profiles in the terrain, which is used as a proxy for regolith density and strength.

Parameter, Value:

Sensing and look-ahead (few meters) warning of extremely low load-bearing strength (< 7 kPa or 1 psi) or extremely low coefficient of friction (< 0.1).

TRL 3

Technology Performance Goal: Enable stand-off sensing distance with sufficient accuracy of soil cohesion and friction angle measurements to enable prediction of traversability. Ground-penetrating radar or similar look-ahead method for estimating surface and subsurface material loadbearing and frictional properties.

Parameter, Value:

Stand-off sensing distance: > braking distance, which is a function of speed;

Accuracy of soil cohesion and friction angle measurements.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Terrain sink hazard assessment.

Capability Description: Provides ability to predict hazardous terrain to prevent entrapments or failures due to sinkage, thus ensuring safety of the mobility or surface asset.

Capability State of the Art: Operational space missions do not have this capability onboard. However, regolith parameters are estimated on the ground, based on data from multiple observations by onboard sensors (for example, cameras).

Parameter, Value:

Accurary of load bearing strength: > 30%;

Accuracy of shear strength: > 30%;

Distance between sensor and terrain: sensors do not currently exist;

Sensor system mass and power: sensors do not currently exist.

Capability Performance Goal: Enable look-ahead estimation of loadbearing strength and shear strength.

Parameter, Value:

Accurary of load bearing strength: < 10% (in particular for load bearing strengths < 7 kpa or 1 psi);

Accuracy of shear strength: < 10%;

Distance between sensor and terrain: ~5-10 m (for vehicles that move at few km/hour);

Sensor system mass and power: < 1 kg.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.1 Manipulator Components

4.3.1.1 Actuators

TECHNOLOGY

Technology Description: Generates forces and torque to create motion of a robot.

Technology Challenge: Challenges include combination of torque and speed, fine sensing and environmental extremes.

Technology State of the Art: Actuator selection driven by torque speed performance requirements, cycloidal gear trains and custom planetary gear trains are being explored for performance enhancement. Magnetic, capacitive, and optical position sensing technologies are being explored. Transverse flux motors are being investigated as well.

Parameter, Value:

Increases of specific torque to 150 N-m/kg are possible with cycloidal gear trains. Custom planetary gear trains offer path to increased efficiency without incurring mass increases. Improved position sensing technologies provide a path to higher position and force resolution targets. Transverse flux motors offer increased torque density with less gearing.

TRL
3

Technology Performance Goal: Pursue increases in specific torque, speed, and resolution of force and position sensing, and radiation tolerance.

Parameter, Value:

Specific Torque: 500 N-m/kg;
Speed: 3.6 rad/s;
Position Resolution: 0.0001 rad;
Force Resolution: 0.001 N-m;
Life: 10 years;
Radiation Dose: 1,000 Gray;
Minimum Temperature: -40° C

TRL
5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Actuator design and modeling tools, improved absolute position sensing.

Capability Description: Modeling design tools enable proper selection of actuator components to optimize performance for torque, speed, force resolution, and temperature range. Improvements in absolute position sensing are required to meet higher resolution and radiation tolerance.

Capability State of the Art: Actuators used as leg joints for Robonaut 2 on the International Space Station (ISS).

Parameter, Value:

Specific Torque: 100 N-m/kg;
Speed: 1.2 rad/s;
Position Resolution: 0.001 rad;
Force Resolution: 0.01 N-m;
Life: 5 years;
Radiation Dose: 60 Gray;
Minimum Temperature: -20° C

Capability Performance Goal: Higher servo bandwidth, torque density and strength to weight ratio.

Parameter, Value:

Specific Torque: 1000 N-m/kg;
Speed: 6.3 rad/s;
Position Resolution: 0.0001 rad;
Force Resolution: 0.001 N-m;
Life: 10 years;
Radiation Dose: 1000 Gray;
Minimum Temperature: -100° C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.1 Manipulator Components

4.3.1.2 Lightweight Structures

TECHNOLOGY

Technology Description: Provide structures developed from lightweight materials for robotic arm designs.

Technology Challenge: Challenges include lightweight materials that can receive fasteners without adding additional features with more weight and failure modes.

Technology State of the Art: Structural members constructed from carbon fiber are widely used for achieving optimized mass solutions. Advanced composites are also being explored.

Parameter, Value:	TRL
Carbon fiber properties.	3

Technology Performance Goal: Pursue increases in specific strength, reduced creep, and increased rigidity.

Parameter, Value:	TRL
Specific Strength: 2,000 kN-m/kg; Creep: 0.001%; Rigidity: 50 Mpa	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced structural materials and modeling techniques.

Capability Description: Structural members built with composites or lightweight metals that provide maximum strength with minimum weight. Modeling techniques allow better use of different materials to address loads requirements.

Capability State of the Art: Phoenix robotic arm used on Mars.

Parameter, Value:
Specific Strength: 700 kN-m/kg;
Creep: 0.1%;
Rigidity: 10 Mpa

Capability Performance Goal: Higher strength and stiffness robot structures.

Parameter, Value:
Specific Strength: 2,000 kN-m/kg;
Creep: 0.01%;
Rigidity: 15 Mpa

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.1 Manipulator Components

4.3.1.3 Motor Controllers

TECHNOLOGY

Technology Description: Provide control and power electronics and intelligence to run an actuator to meet performance requirements.

Technology Challenge: Challenges include combination of torque and speed, fine sensing, and environmental extremes.

Technology State of the Art: Silicon carbide and gallium nitride for power processing units can provide more power processing in a smaller form factor. Cell phone power processing requirements are driving these technologies.

Parameter, Value:

Silicon carbide technologies provide path to increased power capability; Gallium nitride technologies provide path to reduced volume.

TRL: 3

Technology Performance Goal: Pursue increases in current handling, voltage, peak power, and processing capability and radiation tolerance.

Parameter, Value:

Continuous Current: 60 A;
Peak Current: 120 A;
Voltage: 360 V;
Servo Rate: 10 kHz;
Radiation Dose: 1,000 Gray

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Integrated power electronics and motor control module.

Capability Description: More efficient power electronics and processor capability to enable operations with minimum required power draw for actuator control.

Capability State of the Art: Robonaut motor controllers incorporate intelligent actuation to reduce computational burden on main robot computer, which also reduces power consumption.

Parameter, Value:

Continuous Current: 30 A;
Peak Current: 60 A;
Voltage: 120 V;
Servo Rate: 5 kHz;
Radiation Dose: 60 Gray

Capability Performance Goal: Embedded motor controllers able to sink more power in extreme space environments with greater channel count and processing power.

Parameter, Value:

Continuous Current: 60 A;
Peak Current: 120 A;
Voltage: 3,600 V;
Servo Rate: 10 kHz;
Radiation Dose: 1,000 Gray

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.1 Manipulator Components

4.3.1.4 Manipulator Concepts

TECHNOLOGY

Technology Description: Provide new manipulator concepts with improved kinematic configuration (serial, parallel, hybrids), dynamic performance (structural stiffness), packaging efficiency, and payload to mass ratio.

Technology Challenge: Improved payload to mass ratio. Compactly stowable manipulators able to reach into constrained spaces and provide long reach. Improved motor placement for improved dynamics and enhanced mechanical advantage.

Technology State of the Art: Space Station Remote Manipulator System (SSRMS).

Parameter, Value:

Mass handling capacity to manipulator mass ratio: 64:1;

Speed of operations: 0.37 m/s (unloaded), 0.02 m/s (loaded); Stowable volume to manipulator reach: 75 m^3: 17.6 m

TRL 6

Technology Performance Goal: Increase in mass handling capacity to manipulator mass, increase in speed of operation, and reduction in package volume to manipulator reach.

Parameter, Value:

Mass handling capacity to manipulator mass ratio: 200:1;

Speed of operations: 2 m/s (unloaded), 0.5 m/s (loaded);

Stowable volume to manipulator reach: 3x improvement

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Lightweight structures and mechanisms.

CAPABILITY

Needed Capability: Manipulators with high-mass-handling capacity and dexterity to access constrained spaces.

Capability Description: Low-mass low-volume manipulators with long reach and articulation to access constrained space for inspection, docking/berthing, satellite servicing, sample acquisition, in-space assembly, payload offloading, and positioning. Concepts for collaboration between multiple long-reach manipulators.

Capability State of the Art: SSRMS and Shuttle Remote Manipulator System (SRMS) gear-driven long-reach robotic manipulators.

Parameter, Value:

Mass handling capacity to manipulator mass ratio: 64:1;

Speed of operations: 0.37 m/s (unloaded), 0.02 m/s (loaded);

Stowable volume to manipulator reach: 75 m^3: 17.6 m

Capability Performance Goal: Equivalent SSRMS and SRMS performance with: increase in mass handling capacity to manipulator mass, increase in speed of operation, and reduction in package volume to manipulator reach.

Parameter, Value:

Mass handling capacity to manipulator mass ratio: 200:1;

Speed of operations: 2 m/s (unloaded), 0.5 m/s (loaded);

Stowable volume to manipulator reach: 3x improvement

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years

4.3 Manipulation
4.3.2 Dexterous Manipulation

4.3.2.1 Dexterous Manipulator Arms

TECHNOLOGY

Technology Description: Provide handling, positioning, and controlling of objects and interfaces on spacecraft, equipment, tools, and natural objects.

Technology Challenge: Challenges include integrated tactile perception, force control, grasping reflexes, grasp learning, tool use, and autonomous object manipulation.

Technology State of the Art: Hybrid force position control strategies and force impedance control strategies support advances in force and position control. Trajectory monitoring allows crew members to stop the robot with minimal contact. Technology readiness level (TRL) 5 for integrated tactile force control, grasp learning, and autonomous object manipulation; TRL 9 for position control.

Parameter, Value:	TRL
Arm Degree of Freedom: 7; Number of Arms: 4; Reach: 0.6 m; Strength: 100 N; Position Resolution: 0.0001 m; Force Resolution: 0.001 N; Speed: 1 m/s; Life: 5 years; Radiation dose: 60 Gray; Minimum Temperature: -20° C	5

Technology Performance Goal: Advanced model-based multi-modal control systems, which address integrated tactile perception, force control, grasping reflexes, grasp learning, tool use, and autonomous object manipulation. Manipulator hardware architectures, which address integrated tactile perception, force control, grasping reflexes, grasp learning, tool use, and autonomous object manipulation.

Parameter, Value:	TRL
Arm Degress of Freedom: 7; Number of Arms: 4; Reach: 0.6 m; Strength: 200 N; Position Resolution: 0.00001 m; Force Resolution: 0.0001 N; Speed: 2 m/s; Life: 10 years; Radiation dose: 1,000 Gray; Minimum Temperature: -200° C	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced model-based multi-modal control systems, advanced actuator stack.

Capability Description: Develop advanced model-based arm compliance control strategies for safe operations around equipment and humans. Develop advanced model based control strategies for accurate position and force control for impulse and sustained high torque applications.

Capability State of the Art: Robonaut 2 dexterous manipulator arms use control algorithms for gravity compensation and inertia compensation for rigid body dynamics.

Parameter, Value:

Arm Degree of Freedom: 7;
Number of Arms: 4;
Reach: 0.6 m;
Strength: 100 N;
Position Resolution: 0.0001 m;
Force Resolution: 0.001 N;
Speed: 1 m/s;
Life: 5 years;
Radiation dose: 60 Gray;
Minimum Temperature: -20° C

Capability Performance Goal: Robot arms able to handle objects and tools with dexterity, strength and speed that exceeds human performance.

Parameter, Value:

Arm Degree of Freedom: 7;
Number of Arms: 4;
Reach: 0.6 m;
Strength: 200 N;
Position Resolution: 0.00001 m;
Force Resolution: 0.0001 N;
Speed: 2 m/s;
Life: 10 years;
Radiation dose: 10,000 Gray;
Minimum Temperature: -200° C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	4 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.2 Dexterous Manipulation

4.3.2.2 Dexterous Manipulator End Effectors

TECHNOLOGY

Technology Description: Provide an ability to reliably grasp diverse objects, swap tools, and actuate interfaces.

Technology Challenge: Challenges include fine sensing in cold, abrasive, and radiated environment.

Technology State of the Art: Tactile arrays using large surface area force contact sensing structures. Piezoceramic designs and capacitive designs are being explored. Additive manufacturing techniques using metals to grow high specific strength structures. Visual, infrared and LIDAR sensing techniques are being explored for pre-grasp sensing.

Parameter, Value:

Grip Strength: 20 N per finger;
Tactile force resolution: 0.1 N;
Life: 5 years;
Radiation dose: 60 Gray;
Minimum Temperature: -20° C;
Sensel size for sensor array: 1 mm^2;
Overload sensor strength: 200 N

TRL 3

Technology Performance Goal: Advanced dexterous manipulator end effector sensing and actuation to address challenges of fine sensing in cold, abrasive, and radiated environment. Advanced materials provide low distal mass to enable high strength performance. Pre-grasp sensing provides advanced control techniques in a cluttered environment.

Parameter, Value:

Number of fingers: 5;
Maximum object diameter: 20 cm;
Grip Strength: 50 N per finger;
Tactile force resolution: 0.001 N;
Life: 10 years;
Radiation dose: 1,000 Gray;
Minimum Temperature: -200° C

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced dexterous manipulator end effector sensing, actuation, and materials.

Capability Description: Robust and high-resolution sensor arrays within the hand/fingers. Multiple surfaces, contact anywhere on the hand. High strength, low mass materials. High specific power actuators (< 50 W), miniaturized computing networks within the forearm, pre-grasp sensing.

Capability State of the Art: Robonaut 2 on the International Space Station (ISS) has five fingered dexterous hands, which provides an ability to reliably grasp diverse objects, swap tools, and actuate interfaces.

Parameter, Value:

Number of fingers: 5;
Maximum object diameter: 20 cm;
Grip Strength: 20 N per finger;
Tactile force resolution: 0.1 N;
Life: 5 years;
Radiation dose: 60 Gray;
Minimum Temperature: -20° C

Capability Performance Goal: Robots able to handle objects and tools with the dexterity that exceeds human performance.

Parameter, Value:

Number of fingers: 5;
Maximum object diameter: 20 cm;
Grip Strength: 50 N per finger;
Tactile force resolution: 0.01 N;
Life: 10 years;
Radiation dose: 1,000 Gray;
Minimum Temperature: -200° C

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.4 Mobile Manipulation

4.3.4.1 Mobile Manipulation

TECHNOLOGY

Technology Description: Provides a manipulation capability across a large work region.

Technology Challenge: Challenges include coordinated motion, force control across the engine system, and fusion of localization with force control.

Technology State of the Art: Manipulation while roving is a tested technology, both in analog and laboratory environments. More maturation needed. Robonaut 2 on the ISS is driving manipulation while climbing.

Parameter, Value:
Range: 10 km;
Speed: 0.1 m/s;
Arm Payload: 1 kg;
Arm Degrees of Freedom: 7;
Base Degrees of Freedom: 2

TRL
4

Technology Performance Goal: Mature manipulation while roving (manipulators moving while roving); prove technology of manipulation while climbing; extend in-space manipulator workspaces by extending the mobility range of their mobile base (e.g. the self-extending of the truss that moves the manipulator base).

Parameter, Value:
Range: 1,000 km;
Speed: 1 m/s.;
Arm Payload: 10 kg;
Arm Degrees of Freedom: 7;
Base Degrees of Freedom: 6

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Manipulation of objects by a robot while in motion.

Capability Description: Robots should be capable of handling tools, objects, etc. while also moving about their environments (for example, Robonaut 2 holding extravehicular activity (EVA) platform while climbing handrails on station; Centaur 2 carrying payloads while roving on surface).

Capability State of the Art: Mars Exploration Rover (MER) arm operations, Mars Science Laboratory (MSL) arm operations, Centaur robot in Meteor Crater Desert Research and Technology Studies (D-RATS) field test (2010).

Parameter, Value:
Range: 10 km;
Speed: 0.1 m/s;
Arm Payload: 1 kg;
Arm Degrees of Freedom: 7;
Base Degrees of Freedom: 2

Capability Performance Goal: Reliable and efficient manipulation of objects; autonomous capability of robot to perform tasks that require simultaneous manipulation of some object together with mobility in an environment.

Parameter, Value:
Range: 1,000 km;
Speed: 1 m/s.;
Arm Payload: 10 kg;
Arm Degrees of Freedom: 7;
Base Degrees of Freedom: 6

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.5 Collaborative Manipulation

4.3.5.1 Collaborative Manipulation

TECHNOLOGY

Technology Description: Provides a teamed approach for multiple robots or teams of humans and robots working with objects, equipment, or samples.

Technology Challenge: Challenges include a wide array of human interaction modalities superimposed on a force control problem, multi-point contact problems, and safety.

Technology State of the Art: Coordinated manipulation between humans and robots and between multiple robots has been demonstrated in laboratory environments.

Parameter, Value:
Force Resolution: 0.1 N;
Position Resolution: 0.01 m;
Reach: 2 m

TRL 3

Technology Performance Goal: Reliable and efficient manipulation of objects between human/robot teams and between multi-robot teams, not limited to pair teams.

Parameter, Value:
Force Resolution: 0.01 N;
Position Resolution: 0.001 m;
Reach: 2 m

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Multi-robot and human/robot object handling to accomplish large scale operations.

Capability Description: Robotic assistance to human for handling large, flexible and dangerous objects. Multiple robotic platforms (such as All Terrain Hex-Limbed Extra Terrestrial Explorer (ATHLETE)) combining efforts to pick up and translate large objects, too big for a single robot or human to translate.

Capability State of the Art: Space Station Remote Manipulator System (SSRMS) operations with an astronaut at the end of the arm.

Parameter, Value:
Force Resolution: 0.1 N;
Position Resolution: 0.01 m;
Reach: 2 m

Capability Performance Goal: Intelligent robot-robot and robot-human interaction to accomplish object translation tasks.

Parameter, Value:
Force Resolution: 0.01 N;
Position Resolution: 0.001 m;
Reach: 2 m

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.1 Robotic Drilling

TECHNOLOGY

Technology Description: Drills into natural materials to place sensors, extract cuttings, or produce core samples.

Technology Challenge: Challenges include dry drilling, sample conveyance, and cleanliness/contamination. This also includes low-power autonomous operation with high reliability.

Technology State of the Art: Drilling is a well known technology on Earth where drilling mud can be used for lubrication and cooling. In space, the vacuum prohibits terrestrial methods and hence dry drilling is necessary. Technology readiness level (TRL) 9 for manually operated drills and TRL 5 for automated drilling.

Parameter, Value:

Manual drilling during Apollo was ~2.5 m deep, but robotic drilling in a space mission has only achieved 5-10 cm of depth. The goal for the Resource Prospector Mission is 1 m depth robotic drilling.

TRL 5

Technology Performance Goal: Robotic system capable of assembling drill strings autonomously and acquiring samples at medium depths.

Parameter, Value:

Depth: 0.1-1 m;
Diameter: 0.01-0.02 m

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sample acquisition or emplacement of sensors (for example, heat flow probes, seismometers, etc.).

Capability Description: Acquire sub surface samples for characterization to determine usefulness for ISRU and determine the presence of microbial life. Emplace scientific measurement sensors.

Capability State of the Art: Rock Abrasion Tool (RAT) on Mars Exploration Rover (MER). Shallow drilling on Mars Exploration Laboratory (MSL).

Parameter, Value:

MSL Drill Depth: 0.63 inch (1.6 centimeters) in diameter and about 2.6 inches (6.5 centimeters) deep.

Capability Performance Goal: Robotically drill holes on-demand to multiple meters of depth for sample acquisition and instrument emplacement.

Parameter, Value:

Muti-use drill capable of drilling from 0.1-1 m in depth.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.2 Deep Robotic Drilling

TECHNOLOGY

Technology Description: Provides hundreds of meters of drilling into natural materials to extract subsurface regolith, cuttings, or volatile samples, to collect small core samples, or to emplace sensors for exploration.

Technology Challenge: Deep robotic drilling in space requires low-power, low-mass, dry drilling, and the automated assembly and operation of drill rods without getting stuck, which is a complex operation. Dry drilling is necessary because no lubrication in the form of drilling mud is available in space. Retrieving samples from asteroid drilling requires a method to capture samples as they are brought to surface before they 'float away.' Curation and conveyance of samples is also challenging because of Planetary Protection, designated Zones of Minimum Biological Risk, and risk of "special region" contaminants migrating to crewed areas and vice versa (see TA 7).

Technology State of the Art: Deep drilling in space with robotic assembly and autonomous operations does not exist for space missions today. This technology is in the lab development stages at technology readiness level (TRL) 4. Deep-sea autonomous robotic drilling is a mature technology in use today at TRL 9.

Parameter, Value:	TRL
Drilling rates: ~8-15 cm/hour (in sandstone) while expending 60 W of electrical power (~20 W mechanical) in a laboratory; Drilling depth: up 2.2 m in rock.	4

Technology Performance Goal: Automated low-power, low-mass, deep dry drilling with sample collection from such depths.

Parameter, Value:	TRL
Depth: 1-300 m; Diameter: 0.01-0.02 m	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: 7.1.2.5 Cutting tools for cold/hard regolith and/or rock/metal; 7.1.2.6 Long-life or self-renewing/repairing cutting edges.

CAPABILITY

Needed Capability: Mars, asteroid, and comet deep drilling.

Capability Description: Extract regolith, cuttings, or volatiles from subsurface depths on bodies with substantial gravity and bodies with reduced gravity to asess potential for in-situ resource utilization (ISRU) or for bio-signatures (for example, drill through confining layers to aquifer on Mars); emplace sensors (for example, heat flow probes, seismometers) for science measurements exploration on Mars, asteroids, comets or other planetary bodies.

Capability State of the Art: On Earth, large high-power underwater autonomous drilling systems are being developed for the oil and gas industry (for example, Deep Drilling Systems). For space, no deep robotic drilling has been demonstrated to date, however, small (kitchen-size appliance) low-power deep Mars drill prototypes have been developed.

Parameter, Value:

Tested a second-generation prototype at Johnson Space Center (JSC) and in the high Canadian Arctic.

Mars InSight will go to depth of up to 5 m in 2016 but is not sample return.

Depth: 10-100 m;

Diameter: 0.01-0.02 m

Capability Performance Goal: Long-life, controlled deep drilling that can break through hard and confining layers (for example, drilling through bedrock to access aquifers on Mars), creating a stable small diamter bore hole. Deploy drill integrated sensors to track bit position and environmental conditions; low mass casing optional.

Parameter, Value:

Drill rate: > 0.8 m/sol;

Drill depths: 0.1 to 300 m (for subsurface ice may be shallower);

Hole diameter: 4 cm (stable bore hole);

System Mass: ~1,000 kg;

Operational lifetime: 4 years;

Other features: multi-use drill

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.3 Surface/Shallow Robotic Sample Acquisition

TECHNOLOGY

Technology Description: Provides smart sample acquisition devices for robotically picking up surface rocks and loose surface dust or regolith up to 3 centimeters in depth.

Technology Challenge: Challenges include ensuring that the appropriate size sample has been captured, sample conveyance, and cleanliness and contamination. This also includes low-power autonomous operation with high reliability.

Technology State of the Art: Lunar Surveyor and Mars Phoenix class robot arm with scoop is state of the art. Simple scoops as end effectors on robotic arms. Some sieving and dynamic vibration used to enhance flow. Technology readiness level (TRL) 9 for ground-in-loop and TRL 5 for smart sampling.

Parameter, Value:

Depth: 0.03 m;

Sample size 0.01 kg to 0.1 kg;

Rocks from pebbles to 0.1 m diameter;

Low digging forces in regolith of bulk density 1.4 g/cc and less.

TRL

5

Technology Performance Goal: Autonomous regolith acquisition with smart size sorting and beneficiation capabilities.

Parameter, Value:

Depth: 0.03 m;

Sample size 0.01 kg to 0.1 kg;

Rocks from pebbles to 0.1 m diameter; Low digging forces in regolith of bulk density 1.4 g/cc and less.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Surface/shallow robotic sample acquisition.

Capability Description: Provides smart sample acquisition for picking up surface rocks and loose surface dust/regolith up to 3 centimeters in depth.

Capability State of the Art: Surface Scoops, rakes, pneumatic nozzles and dozer blades mounted on robotic mobility devices.

Parameter, Value:

Depth: 0.03 m;

Sample size 0.01 kg to 0.1 kg;

Rocks from pebbles to 0.1 m diameter;

Low digging forces in regolith of bulk density 1.4 g/cc and less.

Capability Performance Goal: Robotic Surface sample acquisition with automated size sorting and beneficiation.

Parameter, Value:

Depth: 0.03 m;

Sample size 0.01 kg to 0.1 kg;

Rocks from pebbles to 0.1 m diameter;

Low digging forces in regolith of bulk density 1.4 g/cc and less;

Additional smart size sorting and beneficiation capabilities.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.4 Subsurface Robotic Sample Acquisition

TECHNOLOGY

Technology Description: Provides smart sample acquisition devices for collecting regolith and volatiles up to 1 meter in depth.

Technology Challenge: Core sampling drills on planetary surfaces are prone to get stuck due to the dry drilling and thermal conditions where the drill may bind with the surrounding regolith in the bore hole. Extracting the core from the drill is also a difficult challenge.

Technology State of the Art: Coring drills are used primarily to access 1 meter in depth.

Parameter, Value:
0.01 m diameter core sample from 1 m depth.

TRL
6

Technology Performance Goal: Autonomous drill with predictive fault detection. Innovative non-drilling methods such as pneumatic jets, moles, and expanding gases.

Parameter, Value:
0.02 kg – 1 kg sample from 1 m depth.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sub surface robotic sample acquisition.

Capability Description: Smart sample acquisition devices for collecting regolith and volatiles up to 1 meter depth.

Capability State of the Art: Small samples are acquired primarily by the use of coring drills and auger systems.

Parameter, Value:
Depth: 1 m;
Diameter: 0.1 m – 0.2 m

Capability Performance Goal: Acquire a regolith sample from 1 m demo including volatiles if present.

Parameter, Value:
0.01 m diameter core sample from 1 m depth.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.5 Sample Handling

TECHNOLOGY

Technology Description: Provides a means to move, transfer, or modify samples that have been acquired, loading them into instruments or packaging systems.

Technology Challenge: Robot must be able to load sample into specialized containment systems for sample return.

Technology State of the Art: Samples have been acquired and transferred robotically on Mars and the Moon. Beneficiation and crushing have not been attempted. Sieving can have problems in low gravity.

Parameter, Value:
0.2 kg sample handling on robotic arms approximately 2-3 m long have been achieved in space on planetary surfaces (Moon, Mars).

TRL 9

Technology Performance Goal: Autonomously reach and move sample to return capsule for packaging and encapsulation.

Parameter, Value:
Sample mass: 1 kg;
Reach: 2 m

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Transfer acquired regolith samples to instruments on a lander spacecraft.

Capability Description: Delivery of a sample for analysis and characterization of in-situ regolith.

Capability State of the Art: Mars Viking, Mars Phoenix Arm, Mars Exploration Rover (MER), Mars Science Laboratory (MSL), and Lunar Sample Return.

Parameter, Value:
Mars Viking Sample Mass: unknown;
Mars Phoenix Sample mass: 0.2 kg and ice shavings from rasp;
Phoenix Reach: 2.35 m;
MSL Sample Mass: 10s of grams

Capability Performance Goal: Autonomously handle more sophisticated samples (core) and beneficiate or crush them for introduction into an instrument.

Parameter, Value:
Sample mass of 0.2 kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.6 Regolith/Volatiles Sample Handling and Transfer

TECHNOLOGY

Technology Description: Provides a system that contains and transfers regolith and rock samples to the end user or instrument for characterization. Special sealing and verification methods may be required, in cases of volatiles to prevent sublimation losses, and in the case of solids for planetary protection reasons.

Technology Challenge: Highly dependent on the target body regolith which is unknown except for Apollo and some Mars data. The challenge is to dig 1 meter deep and then acquire volatiles and samples without losing or contaminating samples/volatiles, while maintaining their integrity and planetary protection compliance.

Technology State of the Art: Origins Spectral Interpretation Resource Identification Security – Regolith Explorer (OSIRIS-REx) scheduled to launch in 2018 with a sample return container for Earth return. Mars 2020 is planning to cache Mars regolith samples for future return to Earth. Some work has been done to develop sealed sample containers for Mars Sample Return.

Parameter, Value:

80 grams robotic regolith sample (OSIRIS-REx). The goal of the Mars 2020 mission is to acquire up to 28 rock/regolith samples and 3 blanks (with ability to replace 6 cores) or 34 rock/regolith samples and 3 blanks, and cache these for the future return mission. Total sample size is ~.5 kg.

TRL: 6

Technology Performance Goal: Acquire diverse regolith/volatiles samples and seal in a container, and verify containment (Mars only).

Parameter, Value:

100 kg (sample return to Earth or In-Situ Characterization).

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Preservation of sample integrity for sample return missions.

Capability Description: A capability that would prevent the loss via submilation of volatile samples. Sealed containers that do not allow volatile loss via sublimation and ensure planetary protection compliance.

Capability State of the Art: Apollo sample boxes were sealed with knife edge indium seal.

Hayabusa Asteroid sample return.

OSIRIS-REx asteroid sample return.

Stardust Mission.

Parameter, Value:

80 grams robotic regolith sample (OSIRIS-REx), 382 kg crew collection (Apollo).

Capability Performance Goal: Regolith acquisition including volatiles in an autonomous robotic method with sample caching in a sealed canister or delivery to a sealed instrument for analysis.

Parameter, Value:

Each regolith/volatile sample: ≥ 0.01 kg;

Multiple samples;

Caching capability for transport to Earth or in-situ instrument.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.3 Manipulation
4.3.6 Sample Acquisition and Handling

4.3.6.7 Robotic Excavation

TECHNOLOGY

Technology Description: Provides a means to remove surface regolith materials, either to expose lower strata or to deliver excavated bulk material for other use.

Technology Challenge: Robots will need to operate for many hours where solar energy is not available, work in the dark, be reliable, avoid getting trapped, or other hazards with autonomous skills.

Technology State of the Art: Small scoops on the end of robotic arms. Larger terrestrial prototypes have been demonstrated as a proof of concept for automated excavation and grading to build a landing pad and blast protection berms.

Parameter, Value:

Robotic landers: excavate to a depth of 0.5 m as in Bulk regolith operations; Manipulate 1,000's kg of regolith.

TRL 4

Technology Performance Goal: Excavation for Lunar Sample Return. Excavation to deliver in-situ resource utlization (ISRU) materials. Excavation to modify landing or habitation zone. Excavation to modify habitat shielding.

Parameter, Value:

1 kg at a depth of 20 cm;
100 kg at a depth of 1 m;
1,000 kg at a depth of 5 m;
10,000 kg at a depth of 1 m

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Robotic regolith operations.

Capability Description: Manipulate bulk regolith via excavation, hauling, and dumping to provide useful regolith operations for construction or exposing strata for science or ISRU value.

Capability State of the Art: Lunar Surveyor Scoop, Mars Viking Scoop, Mars Phoenix Scoop.

Parameter, Value:

Sample mass: 0.2-0.3 kg;
Depth: 20 cm

Capability Performance Goal: Excavate bulk regolith to expose lower strata.

Parameter, Value:

Expose sub surface regolith to a depth of 1 m.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.3 Manipulation
4.3.7 Grappling

4.3.7.1 Grappling

TECHNOLOGY

Technology Description: Provides robots that can grapple objects and free-flying spacecraft using surface features, then berthing them to the robot's spacecraft through a rigidized interface.

Technology Challenge: Grappling asteroids and natural objects, and any objects in dynamic spin or free drift.

Technology State of the Art: Advanced ground control techniques being investigated for Space Station Remote Manipulator System (SSRMS) operations. Advanced vision and control systems being evaluated for enhancing situational awareness and control of large objects.

Parameter, Value:	TRL
Object Mass: 20,000 kg; Object Speed: 0.1 m/s; Reach: 17 m	3

Technology Performance Goal: Increase vision and control system capabilities to handle larger structures for assembly of on-orbit spacecraft for future human exploration missions to near-Earth objects (NEOs), near-Earth asteroids (NEAs), and planetary bodies.

Parameter, Value:	TRL
Object Mass: 1,000,000 kg Object Speed: 1 m/s; Reach: 17 m	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Grappling object and free-flying spacecraft.

Capability Description: Improved vision systems, contact sensing systems, robust control systems to accommodate challenging arm configurations, and ground control operations.

Capability State of the Art: The SSRMS is a 7-joint robot used to move and position crew, payloads, and modules around the International Space Station (ISS).

Parameter, Value:

Object Mass: 20,000 kg;

Object Speed: 0.1 m/s;

Reach: 17 m

Capability Performance Goal: Capture of natural objects (for example, NEAs) and berthing with human-made objects (for example, space assets).

Parameter, Value:

For NEAs:

Rotational velocity: < 0.5 RPM;

Relative speed: 0.1 m/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years

4.4 Human-System Interaction
4.4.1 Multi-Modal Interaction

4.4.1.1 Virtual Environment (VE)

TECHNOLOGY

Technology Description: Immersive, interactive, virtual image displays enhanced by non-visual display modalities (auditory, haptic, etc.).

Technology Challenge: Challenges include enabling the operator to effectively utilize multiple sensory modes (to perceive system state, understand the remote environment, and issue commands) and mitigating the negative impacts of virtual environment (VE) implementation (spatial display distortions, system latency, and display resolution).

Technology State of the Art: VE research prototypes have been used to monitor and remotely operate numerous robots in analog field tests. NASA Ames: Virtual Environment Vehicle Interface (VEVI), Virtual Dashboard Interface (VDI), Viz, VERVE. JPL Operations Planning Software (OPS) Lab VE systems.

Parameter, Value:	TRL
Use of VE tools with data from NASA robotic missions: 10%.	5

Technology Performance Goal: Enable user to perceive system state and/or remote environment with higher performance (accuracy, speed, etc.) and/or with less effort (workload, fatigue, training, etc.) than with conventional operator interfaces.

Parameter, Value:	TRL
Use of VE tools with data from NASA robotic missions: 100%.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: System and environment display.

Capability Description: A synthetic environment that facilitates user perception and a sense of presence with a complex system or a remote site/environment. VEs typically employ interactive 3D computer graphics, immersive displays, head/body tracking, etc.

Capability State of the Art: Not currently used for flight missions.

Parameter, Value: Use of VE tools by ground control: 10%.

Capability Performance Goal: System capable of providing an effective sense of “presence” for a complex planetary surface mission.

Parameter, Value: Use of VE tools by ground control and crew: 100%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.4 Human-System Interaction
4.4.1 Multi-Modal Interaction

4.4.1.2 Multi-Modal Dialogue

TECHNOLOGY

Technology Description: Rich communication between humans and robots that incorporates natural language, gesturing, spatial dialogue, etc.

Technology Challenge: Challenges include achieving human-paced interaction, ensuring accuracy of recognition (speech, gesture, etc.), adapting dialogue (to user, situation/context, bandwidth, etc.), and supporting graceful degradation.

Technology State of the Art: Research systems have demonstrated multi-modal dialogue between single humans and small numbers of robots. NASA Peer-to-Peer Human-Robot Interaction (P2P-HRI) project.

Parameter, Value:	TRL
Number of simultaneous modes: 3	4

Technology Performance Goal: Enable user to interact (provide commands, monitor task execution, and resolve problems) with a robot with higher performance (accuracy, speed, etc.) and/or with less effort (workload, fatigue, training, etc.) than conventional operator interfaces.

Parameter, Value:	TRL
Workload reduction: 50% Training time reduction: 50% Error rate reduction: 50%	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Natural human-robot communication.

Capability Description: Software system that enables a user to communicate with an autonomous system (software agent, robot, etc.) in a human-like manner.

Capability State of the Art: Not currently used for flight missions.

Parameter, Value:
Command success rate: 50%

Capability Performance Goal: System capable of providing transparent human-robot dialogue for proximal and remote interaction.

Parameter, Value:
Command success rate: 90%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	7 years

4.4 Human-System Interaction
4.4.3 Proximate Interaction

4.4.3.1 Robot-to-Suit Interfaces

TECHNOLOGY

Technology Description: Enables suited astronaut to attach and directly interact with a robotic system.

Technology Challenge: Challenges include effective mating and de-mating in vacuum and dusty environments and effective control of robotic systems attached to the suit by the crew member.

Technology State of the Art: Current extravehicular activity (EVA) suits do not possess required interfaces for robotic augmentation, and a clean sheet design would most likely be required. NASA is developing an EVA Grasp Assist Device for use with gloves. Quick disconnect interfaces are available for breathing air recharge. Some research systems have begun addressing interfacing to complex robots with autonomous control modes.

Parameter, Value:	TRL
Number of robots supported by suit interface (modularity): 1	4

Technology Performance Goal: Enable suited crew to rapidly attach to and safely operate a variety of robot systems (mobility, manipulation, exoskeleton, etc.) with little (or no) training. Enhance or augment suited crew capability (e.g., increased force).

Parameter, Value:	TRL
Number of robots supported by suit interface (modularity): 3	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Verification and validation (V&V) of robot to suit interfaces in motion based test system such as Johnson Space Center (JSC) Air Bearing Floor, Jetpack Mobility Platform, Robotic Mobility Platform.

CAPABILITY

Needed Capability: Physical human-robot teaming will enhance crew performance, health, and safety.

Capability Description: Hardware and software interfaces that allow a suited astronaut to efficiently, rapidly, and productively work with an intermittently attached robotic system (for example, robotic jetpack). Integrated robotic mechanisms in the EVA suit will provide augmented bio-mechanics, thus canceling the limiting effects of the pressurized garment and joint restrictions.

Capability State of the Art: Flight systems have largely been limited to using simple mechanical and operator interfaces to manually control robots. Simplified Aid for EVA Rescue is a self-contained maneuvering unit worn by astronauts like a backpack. The system relies on small nitrogen-jet thrusters for astronaut controlled flight.

Parameter, Value:

Time required to mate/demate from the robotic system: system dependent.

Operator performance metrics (task times, workload, work efficiency index, etc.).

Capability Performance Goal: Interactive in-situ enhanced EVA by crew, safely working with multiple heterogeneous robots. Crew communicate directly with robots through advanced interfaces and support systems such as smart skins. Increased EVA duration.

Parameter, Value:

EVA Duration: 8 hour EVA;

Time required for mate/demate: 50% reduction;

Operator performance metrics:

50% reduction in task times

50% increase in overall efficiency

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

4.4 Human-System Interaction
4.4.3 Proximate Interaction

4.4.3.2 Intent Recognition and Reaction

TECHNOLOGY

Technology Description: Enables autonomous system to detect, recognize, and/or react to human intent.

Technology Challenge: Challenges include developing systems to recognize user activity, gaze (direction, target, etc.), gestures (affect, deictic, and iconic), speech, and other elements as indicators of implicit operator intent, behavioral models capable of predicting future operator actions, and planning systems capable of responding appropriately.

Technology State of the Art: Research systems have demonstrated rudimentary capacity to recognize human activity and intent, particularly for a well-defined and structured task performance.

Parameter, Value:
Recognition accuracy (simple tasks): 50%
Recognition accuracy (complex sequence): 30%

TRL 4

Technology Performance Goal: Recognize intent of astronaut engaged in proximal joint human-robot task performance. Recognize intent of user performing teleoperation of a remote robot in the presence of short delays.

Parameter, Value:
Recognition accuracy (simple tasks): 90%
Recognition accuracy (complex sequence): 90%

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Natural human-robot communication.

Capability Description: Software that enables an autonomous system to perceive and act upon human intent. This may require detection and interpretation of dialogue, gaze, gestures, activity (structured and unstructured task performance). This may also require construction and maintenance of user (or role) specific behavior models.

Capability State of the Art: Not currently used for flight missions.

Parameter, Value:
Percent of activities robustly recognized: 0%

Capability Performance Goal: A system capable of robustly and transparently recognizing user (particularly flight crew) intent, determining appropriate response, and responding in a timely and effective manner.

Parameter, Value:
Percent of activities robustly recognized: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

4.4 Human-System Interaction
4.4.3 Proximate Interaction

4.4.3.3 Feedback Displays for Proximate Interaction

TECHNOLOGY

Technology Description: Enables user to receive feedback (status, information, etc.) and to monitor activity or intent of autonomous system.

Technology Challenge: Challenges include adapting feedback display design principles and methods to NASA mission environments (aircraft, spacecraft, habitats, extravehicular activity (EVA)), operational constraints (training, crew availability, etc.), system control modes (autonomy level, interaction/intervention duration), and implementation restrictions (for example, hardware and software that can be certified for flight missions).

Technology State of the Art: Research systems have demonstrated proof-of-concept with a variety of signaling and communication methods for proximal interaction between humans and autonomous systems. Significant research and development in human-computer interaction and industrial design has been performed for consumer products.

Parameter, Value:

Bits of information (light array): 3

Effective distance: 5 m

TRL: 5

Technology Performance Goal: Feedback methods and systems that can provide effective (accurate, rapid, high usability) signaling and communication between humans and autonomous systems in physical proximity.

Parameter, Value:

Training time: 5 min

Communication error rate: 10%

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Proximal signaling and communication.

Capability Description: Display methods that enable an autonomous system to signal and communicate with a human in physical proximity. These methods may include visual mechanisms (light arrays, point lights, text readouts, graphical interfaces), body language (movement, gestures, etc.), auditory feedback (synthesize speech, sounds), and force displays (haptics, tactile).

Capability State of the Art: Not currently used for flight missions.

Parameter, Value:

Not applicable.

Capability Performance Goal: Feedback displays that support effective communication of system state (subsystem health, errors, faults), goals (movement intentions, control mode, etc.) and high-level indications (task progress, information/intervention need, etc.).

Parameter, Value:

Information speed (communication efficacy);

Fidelity (level of abstraction and representation); Accuracy;

Bandwidth required;

Persistency (long-term information);

Continuity (how often can feedback be provided);

Proximity (how close must a user be for communication).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

4.4 Human-System Interaction
4.4.5 Distributed Collaboration and Coordination

4.4.5.1 Interaction Architecture

TECHNOLOGY

Technology Description: Provides software framework that facilitates coordination, communication, and collaboration between humans and autonomous systems (including robots and software agents).

Technology Challenge: Challenges include enabling humans and autonomous systems to communicate (conversing about goals, abilities, plans, and achievements) and to collaborate (jointly solving problems).

Technology State of the Art: Research systems have demonstrated interaction architecture between small groups of humans and robots. NASA Peer-to-Peer Human-Robotic Interfaces (P2P-HRI) project.

Parameter, Value:

Number of agents performing joint task: 10

Human-agent ratio: 3:1

TRL 4

Technology Performance Goal: Support distributed human (ground control teams and flight crews) and autonomous systems (software agents, robots, etc.). Incorporate standards-based services and protocols.

Parameter, Value:

Control modes supported: 5

Human-agent ratio: 10:1

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Human-system operations support.

Capability Description: Support for human-system coordination, communication, and collaboration. An interaction architecture may include methods for resource and task allocation and delegation, trading/sharing of control, dialogue management, and data distribution.

Capability State of the Art: Not currently used for flight missions.

Parameter, Value:

Not applicable

Capability Performance Goal: System capable of multi-agent (human, autonomous software, robot, etc.) interaction and interoperation.

Parameter, Value:

Control modes supported: 5

Number of agents performing joint task: 20

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

4.4 Human-System Interaction
4.4.5 Distributed Collaboration and Coordination

4.4.5.2 In-Line Performance Metrics

TECHNOLOGY

Technology Description: Provides software that continually assesses the operational efficiency, task performance, and/or effort of a human-system team (individual or joint).

Technology Challenge: Challenges include developing appropriate (descriptive and powerful) metrics, designing reusable software framework for in-line processing and assessment of telemetry and historical data, and automatically reporting on performance at different levels of abstraction to different users (flight director, subsystem engineer, etc.).

Technology State of the Art: Research systems have demonstrated proof-of-concept for a variety of applications (mobile robot site surveys, mobile robot scouting, etc.). However, the accuracy, robustness, and long-term performance of these systems under flight conditions have not been proven.

Parameter, Value:

Monitoring delay: 10 sec

Accuracy: 50%

TRL 4

Technology Performance Goal: Automatically and continuously produce accurate assessment of operational efficiency, task performance, and/or effort using a variety of metrics. Assessments should be performed at a variety of abstraction levels, over a range of time spans (including real-time), and support ground control decision process.

Parameter, Value:

Monitoring delay: 1 sec

Accuracy: 90%

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Human-system operations support.

Capability Description: Improved situational awareness and more effective system operation by providing continuous assessment of operational efficiency, task performance, and/or effort. Performance metrics may focus on subsystems, individual elements (human, robot, etc.), or joint team.

Capability State of the Art: Not currently used for flight missions.

Parameter, Value:

Not applicable

Capability Performance Goal: System capable of automatically processing telemetry and making comparisons of actual verses planned performance.

Parameter, Value:

Monitoring delay: 1 sec

Accuracy: 90%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.4 Human-System Interaction
4.4.5 Distributed Collaboration and Coordination

4.4.5.3 Notification and Summarization

TECHNOLOGY

Technology Description: Provides software that facilitates human-system operations by providing automated notification and summarization of key events or activities, system state, and operational data.

Technology Challenge: Challenges include developing algorithms for event detection (real-time and post-processing of telemetry), methods for summarization (narrative, graphical, etc.), and techniques for delivering/displaying notifications and summaries.

Technology State of the Art: Research systems have demonstrated proof-of-concept for a variety of applications (water plant management, mobile robot site surveys, etc.). However, the robustness and performance of these systems under flight conditions and over long durations have not been proven. Technology readiness level (TRL) 9 for terrestrial applications such as train systems, airline industry, unmanned aerial vehicles, and traffic systems.

Parameter, Value:

False positive rate: 50%
False negative rate: 30%
Workload (Bedford): 6
Types of users supported: 1

TRL 4

Technology Performance Goal: Enable different users and stakeholders to receive notifications and summaries that are customized to the user's role, time-varying needs/interests, and time-varying capacity to handle.

Parameter, Value:

False positive rate: 10%
False negative rate: 10%
Workload (Bedford): 2
Types of users supported: 10

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Human-system operations support.

Capability Description: Improved situational awareness and more effective system operation by providing automated notification (via a variety of delivery/display methods) and summarization (at several levels) of system events (task progress, faults, alarms), system state (current, changes, trends), and operational data (for example, instrument data).

Capability State of the Art: Not currently used for flight missions.

Parameter, Value:

Not applicable.

Capability Performance Goal: System capable of automatically detecting key events, generating appropriate notifications, and producing informative summaries from telemetry streams. The system should tailor notification and summarization to different user roles (flight director, system engineer, etc.).

Parameter, Value:

False positive rate: 10%
False negative rate: 10%
Workload (Bedford): 2
Types of users supported: 10

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.4 Human-System Interaction
4.4.8 Remote Interaction

4.4.8.1 Direct Teleoperation

TECHNOLOGY

Technology Description: Provides a system for performing manual control of a remote platform.

Technology Challenge: Challenges include mitigating the effects of latency on manual control, facilitating operator situational awareness, minimizing bandwidth requirements, and minimizing performance variation due to operator differences (proficiency, training, fatigue, etc.).

Technology State of the Art: Research teleoperation systems have demonstrated efficient and effective control of humanoid robots.

Parameter, Value:

28 degree-of-freedom system controlled across a bandwidth limited network (less than 1 Mbps) in the presence of short (< 1 sec) delay.

TRL: 4

Technology Performance Goal: Directly teleoperate Robonaut 2 (42 degrees-of-freedom) on the ISS from Earth via Tracking and Data Relay Satellite System (TDRSS). Directly teleoperate a planetary rover on Earth in unstructured natural terrain from the ISS via TDRSS.

Parameter, Value:

Latency: 10 sec with 50% jitter

Bandwidth: 50 Kbps to 1 Mbps

Training time: 1 hr

Operator performance variation: 20%

TRL: 8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Remote system operation.

Capability Description: Control method that enables operation of a remote system without autonomy. Manual control of telerobots is typically performed using control modes such as rate, position, or automated trajectory.

Capability State of the Art: The Space Station Remote Manipulator System is teleoperated by astronauts using the Robotic Work Station (RWS) inside the International Space Station (ISS). The RWS provides multiple camera views, hand controllers, and coordinated frame displays.

Parameter, Value:

Operator workstation requirements (input devices, user interface displays, data communication and storage, etc.). Operator performance metrics (workload, work efficiency index, task times, etc).

Degrees of Freedom: 28

Capability Performance Goal: Manually control complex remote systems across a space communications link in the presence of short (< 1 sec) delay.

Parameter, Value:

Latency: 10 sec with 50% jitter

Bandwidth: 50 Kbps to 1 Mbps

Training time: 1 hour

Operator performance variation: 20%

Degrees of Freedom: 42

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

4.4 Human-System Interaction
4.4.8 Remote Interaction

4.4.8.2 Supervisory Control

TECHNOLOGY

Technology Description: Provides a system for performing supervised control of a remote platform.

Technology Challenge: Challenges include facilitating operator situational awareness, minimizing bandwidth requirements, and providing effective decision support tools (including summarization, notification, and in-line performance metrics).

Technology State of the Art: Supervisory control with interactive monitoring has been demonstrated with research robots during numerous analog field tests.

Parameter, Value:

K-10 planetary rover has been remotely operated on Devon Island (Canada) using interactive supervisory control and satellite communications (500 kbps) from NASA Ames Research Center (ARC).

TRL

5

Technology Performance Goal: Remotely operate a planetary rover on the Moon using supervisory control and "Direct To Earth" (DTE) communications.

Parameter, Value:

Latency (lunar): 10 sec with 50% jitter

Bandwidth (lunar): 50 Kbps to 1 Mbps

Training time: 1 hr

Mean-time between intervention: 10 min

TRL

9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Remote system operation.

Capability Description: Control method to operate a remote system that has some level of autonomy. Supervisory control of telerobots is typically performed using command sequencing or task level commanding.

Capability State of the Art: The Mars Exploration Rovers are remotely operated on Mars by an Earth-based ground control team using a large suite of tactical operations tools.

Parameter, Value:

Operator workstation requirements (input devices, user interface displays, data communication and storage, etc.). Operator performance metrics (workload, work efficiency index, task times, etc.).

Capability Performance Goal: Perform supervisory control with interactive monitoring of complex remote systems across a variety of space communications links.

Parameter, Value:

Latency (lunar): 10 sec with 50% jitter

Bandwidth (lunar): 50 Kbps to 1 Mbps

Training time: 1 hr

Mean-time between intervention: 10 min

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.4 Human-System Interaction
4.4.8 Remote Interaction

4.4.8.3 Decision Support Tools for Remote Interaction

TECHNOLOGY

Technology Description: Provides systems that enable users to make informed reactive (including interruption), tactical, and/or strategic decisions for operating remote systems.

Technology Challenge: Challenges include making effective use of open standards and protocols, supporting interoperability, minimizing the effort and time required to support new functions and/or adapt to new missions, as well as enabling high usability (minimal training, workload, and barrier to use).

Technology State of the Art: Research systems have demonstrated proof-of-concept with flexible, interoperable ground data system frameworks applied to analog field experiments (simulated human and robot exploration missions).

Parameter, Value:

Exploration Ground Data Systems (xGDS) has been used for decision support with Desert Research and Technology Studies (RATS) and Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) in-situ resource utilization project.

TRL 5

Technology Performance Goal: Software that can provide effective and informed reactive, tactical, and strategic decision making during remote operations of human and robotic systems. Support high-tempo ground control operations for the 2019 Resource Prospector Mission.

Parameter, Value:

Number of users supported: 100

Types of users supported: 10

Training time: 1 hour

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Remote system operation.

Capability Description: Software that enables a user (or team of users) to better monitor system status, assess task progress, perceive the remote environment, and make informed operational decisions. These tools may include simulation, telemetry/data replay, feedback displays (auditory, force/haptics, 2D and 3D maps, 2D and 3D graphics), and groupware (for computer-supported collaborative work).

Capability State of the Art: Ground data systems used for remote operation of robotic spacecraft, landers, and rovers.

Parameter, Value:

Information speed (communication efficacy);

Fidelity (level of abstraction and representation);

Accuracy Bandwidth required;

Persistency (long-term information);

Continuity (how often can feedback be provided).

Capability Performance Goal: Decision support tools that enable smaller ground control teams to achieve the same (or better) performance as larger teams. Effort and time required to support a new mission or to adapt tools to support new mission function.

Parameter, Value:

Information speed (communication efficacy);

Fidelity (level of abstraction and representation);

Accuracy Bandwidth required;

Persistency (long-term information);

Continuity (how often can feedback be provided).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
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Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.1 System Health Management

4.5.1.1 Onboard Real-Time Fault Detection, Isolation, and Recovery (FDIR)

TECHNOLOGY

Technology Description: Onboard system (hardware and software) that continuously monitors and detects faults and failures in a spacecraft.

Technology Challenge: Computational cost, reliability, verification techniques, and validation are challenges.

Technology State of the Art: Model- and data-centric approaches that include adaptive modelling, reliability-based, statistics-based prognostic and diagnostic tools. Systems integrate both onboard and off-board data analysis and that adapt through learning. Systems that use data mining clustering techniques to isolate off-nominal interaction between parameters. Data-centric approaches include commercial products that are in test beds at various centers.

Parameter, Value:

Model-based approaches constantly verified healthy behavior – constant monitoring (% monitoring); can detect unanticipated faults; diagnoses both known faults and unanticipated faults.

Performance: processes 1,000s test results/second;

Accuracy: 75-85% without service history.

TRL: 4

Technology Performance Goal: Overall reliability: currently too many false positives and false negatives. Requires to be an integral part of the system architecture. For model-based approaches, need to ensure model correctness. For data-centric approaches, having sufficient data to identify nominal behavior. False negatives response time: percent anomalies autonomously detected relative to all anomalies.

Parameter, Value:

False positives: 1-3 σ;

False negatives: 1-3 σ;

Response time (time to criticality); Adaptable systems that learn from past experience;

Systems that scale with increased complexity;

Flexible systems that can be adapted to new missions or mission that undergo changes (extended mission as well); Computational Cost Performance: 1,000s tests/second.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Onboard diagnostics.

Capability Description: Provides software diagnostics for detecting, identifying, and isolating faults and failures at the component, subsystem, and the system levels as well as responding and recovering from such anomalous situations with the aid of onboard crew and ground support.

Capability State of the Art: Primarily monitor-and-respond system based on local system thresholds without knowledge of the state of the system.

Parameter, Value:

Static logic or procedures for detecting, isolating and recovering from faults;

Fault logic verified and validated through exhaustive testing;

Limited modeling of interactions among subsystems.

Capability Performance Goal: Real-time monitoring and analysis of onboard measurements. Dynamic thresholding based on models. Adaptable logic based on learned experience. FDIR for missions that can scale with increased complexity, increased communication latency, and with large uncertainties in our understanding of their destination environments.

Parameter, Value:

(Mission dependent – different for robotic vs. human missions)

False positives: 1-3 sigma;

False negatives: 1-3 sigma;

Response time (time to criticality).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	7 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	7 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	7 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	8 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enabling	--	--	2035	8 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enabling	--	--	2025	6 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.1 System Health Management

4.5.1.2 Ground-Based Fault Detection, Isolation, and Recovery (FDIR)

TECHNOLOGY

Technology Description: Algorithm development to isolate faults, analyze root causes, and recommend actions for recovery based on processing telemetry (bandwidth limited and time-delayed) using ground-based computational resources (including supercomputers).

Technology Challenge: Computational cost and reliability validation given probabilistic nature.

Technology State of the Art: Commercial product uses a diagnostic reasoner that adapts through learning. Used in test beds at various centers. NASA Ames Research Center (ARC) Inductive Monitoring System (IMS): uses data mining clustering technique to isolate off-nominal interaction between parameters. G2 is an AI expert system demonstrated on the ISS for payload monitoring. It is in use at some commercial satellite facilities for control of formation systems. NASA JPL Spacecraft Health Inference Engine (SHINE) is a high-speed expert system (stateless rule-based system) and inference engine for the diagnosis of spacecraft health.

NASA ARC Hybrid Diagnostic Engine (HyDE): general diagnostic system that uses models system models for monitoring and automatic fault diagnosis. Implemented on various systems.

Parameter, Value:

Diagnoses both known faults and unanticipated faults. Performance: processes 1,000s test results/second;

Accuracy: 75-85% without service history;

SHINE: executes ~500M rules/ second running on state of the art processor.

TRL
4

Technology Performance Goal: Adaptable diagnostic systems that learn from past experience;

Systems that scale with increased complexity;

Flexible systems that can be adapted to new missions or mission that undergo changes;

Parameter, Value:

Computational cost;

Performance: 1,000s tested/second; Accuracy: 99.9%.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ground-based diagnostics.

Capability Description: Provides ground-based software diagnostics for detecting, identifying, and isolating faults and failures both at the component and the system levels as well as responding and recovering from such anomalous situations.

Capability State of the Art: Custom ground-based tools that monitor and analyze spacecraft health. For some systems, that is done in real-time.

Parameter, Value:

Custom ground-tools;

Manually-generated fault trees and procedures.

Capability Performance Goal: Automated software for identification of off-nominal behavior to enable quicker corrective actions.

Parameter, Value:

Unmanned systems reliability: 3 sigma;

Manned systems reliability: 6 sigma;

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enabling	--	--	2035	4 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enabling	--	--	2025	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.1 System Health Management

4.5.1.3 Integrated Vehicle Health Management (IVHM)

TECHNOLOGY

Technology Description: Identifies trends based on telemetry and models that would predict impending failures and remaining useful life.

Technology Challenge: For spacecraft domain, the low numbers and highly customized types would make prediction models significantly more challenging than aircrafts. Validation given probabilistic nature.

Technology State of the Art: Uses maintenance information and physics based models to predict future failures.

Parameter, Value:

System- and configuration-dependent; Accuracy

TRL 4

Technology Performance Goal: Adaptable systems that learn from past experience.

Systems that scale with increased complexity. Flexible systems that can be adapted to new missions or mission that undergo changes;

Reduce the number of false positives and false negatives.

Parameter, Value:

Accuracy: 90%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Onboard/ground-based prognostic tools.

Capability Description: Uses maintenance telemetry and models to estimate remaining useful life and predict failures. Onboard has more access to sensor data with low latency but is computationally constrained. Ground-based has less access to sensor data with high latency but more computational resources.

Capability State of the Art: Monitors and anticipates failures based on exceed local thresholds. The use of Aeronautical Radio, Incorporated (ARINC) standards in aviation that enable IVHM. ACARS for communicating maintenance information between flight and ground crews. Health usage monitoring systems for helicopters.

Parameter, Value:

Reliability communication latency.

Communication bandwidth.

Capability Performance Goal: Automated software for identification of trends suggesting impending failures. Software recommends preventative corrective actions. Lead time for prognosis sufficient to provide corrective action to avoid transitioning into safe mode or catastrophic part failures.

Parameter, Value:

Unmanned systems reliability: 3 sigma;

Manned systems reliability: 6 sigma;

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	9 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enabling	--	--	2035	10 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enabling	--	--	2025	10 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.2 Activity Planning, Scheduling, and Execution

4.5.2.1 Onboard Real-Time Planning and Scheduling

TECHNOLOGY

Technology Description: Plans and schedules onboard activities while managing resources and preventing conflicts and violations of constraints.

Technology Challenge: Challenges include the computational complexity and ability to rapidly explore the optimization space, repair complex plans, more easily handle specialized constraints (for example, geometry), uncertainty, and develop verifiable command sequences with traceability to the initial activity requirements.

Technology State of the Art: Automated constrained-based planning and scheduling tools are used in several domains: manufacturing, production, and other domains. Online usage of automated planning and scheduling for spacecraft applications has had limited deployments for specific scenarios and instruments. Examples include: NASA Ames Research Center (ARC) Remote Agent; NASA Jet Propulsion Laboratory (JPL) Autonomous Sciencecraft Experiment (EO1), Intelligent Payload Experiment (IPEX), and Continuous Activity Scheduling Planning Execution and Replanning (CASPER).

Parameter, Value:	TRL
Computational time to generate or repair plans: varies based on application.	9

Technology Performance Goal: Scaling performance to more complex activities, goals, and constraints. Reducing computational cost and time for generating activities plans/sequences. Handling specialized constraints such as geometry, path planning, and complex power models, and interaction in a multi-agent environment. Verification and validation (V&V) of generated plans. Decrease response time from Remote agent (6 hours), Autonomous Sciencecraft (20 m), IPEX (1 m).

Parameter, Value:	TRL
2x improvement in time for generating plans, ability to handle optimization, and geometric constraints.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Automated planning and scheduling.

Capability Description: Plans and schedules activities to be executed onboard a spacecraft.

Capability State of the Art: Planning and sequencing is largely done on the ground and sequences are uploaded for onboard execution. Time-based sequences are generally used. Fixed sequence logic with pre-planned contingencies. Sequence failure results in aborting activity execution and calling home.

Parameter, Value:

Plans: manually generated.

Capability Performance Goal: Intelligent onboard re-planning of activities and corresponding execution based on real-time information about available resources and plan conflicts.

Parameter, Value:

Plans: automatically generatred onboard;

Reliability: 6 sigma;

Scalability: scales to support complete system's activities;

Computational time and memory footprint: amenable to embedded system usage

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 -2021	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	1 year
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	1 year
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	1 year
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	1 year
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	1 year
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	1 year
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	1 year
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enabling	--	--	2035	1 year
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enabling	--	--	2025	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.2 Activity Planning, Scheduling, and Execution

4.5.2.2 Ground-Based Mixed Initiative Planning and Scheduling

TECHNOLOGY

Technology Description: Provides on-ground planning and scheduling of activities for uploading, and preventing conflicts and violations of pre-defined constraints with or without human intervention (includes mixed initiative planning).

Technology Challenge: Challenges include generating verifiably optimal plans (for applications like the Deep Space Network (DSN)), as well as ensuring safe and correct plans. The computational complexity and ability to rapidly explore the optimization space, repair complex plans, and develop verifiable command sequences with traceability to the initial activity requirements are challenges.

Technology State of the Art: Automated constrained-based planning and scheduling tools are used in several domains: manufacturing, production, supply chain management, and other domains.

Parameter, Value:	TRL
Numerous applications (~ 20) but still small fraction of total missions; Adaptation and deployment requires very skilled teams and significant effort.	9

Technology Performance Goal: Scaling performance to more complex activities. Reducing computational cost and time for generating activities plans/sequences. Verification and validation (V&V) of generated plans.

Parameter, Value:	TRL
2x improvement in time for generating plans; Ability to handle complex, specialied constraints and resources (for example, geometry, path planning, complex power); Ability to handle both soft and hard constraints.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ground-based automated planning and scheduling.

Capability Description: Plans and schedules activities to be executed on the ground (for example, DSN communication links) or onboard a spacecraft.

Capability State of the Art: Planning and sequencing for most missions is largely done by humans on the ground. Selected complex missions are using automated planning: Hubble, Spitzer, DSN.

Parameter, Value:

Time/effort to manually generate plans/schedules; Quality metrics for plan (for example, science utilization); Time-based sequences are generally used;

Fixed sequence logic with pre-planned contingencies;

Centralized operation for plan generation.

Capability Performance Goal: Automated scheduling that can generate optimized plans to enhance human planning ability. Planning and scheduling that can leverage vast ground computational resources (centralized and distributed).

Parameter, Value:

Plan quality (optimization);

Ability to handle complex hard and soft constraints;

Ability to operate within a multi-agent environment;

Reliability;

Scalability;

2x improvement in time for generating plans.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years

4.5 System-Level Autonomy
4.5.2 Activity Planning, Scheduling, and Execution

4.5.2.3 Plan/Sequence/Schedule Verification Tools

TECHNOLOGY

Technology Description: Verifies the validity of plans, sequences, or schedules that are generated by automated and manual tools.

Technology Challenge: Flexibility of the plans make them harder to validate.

Technology State of the Art: There are some synergies between planning and scheduling and verification and validation (V&V), where techniques from both communities have been used interchangeably. Model checkers/Timed Game Automata have been used to verify flexible plans.

Parameter, Value:
Both planners and plans need verification.

TRL: 4

Technology Performance Goal: Improve scalability of the verification tools to support plans, sequences, and schedule of increased complexity. Increase reliability by reducing both false positives and false negatives.

Parameter, Value:
False positives;
False negatives.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Plan/schedule verification.

Capability Description: Provides an automated means to verify auto or manually generated plans/sequences.

Capability State of the Art: Custom tools for validating planned sequences.

Parameter, Value:
Verified time-based sequences.

Capability Performance Goal: Automated verification tool that increases the scheduling and planning accuracy. Core algorithms are scalable to different scheduling and planning platforms.

Parameter, Value:
False positives: 3 sigma
False negatives: 3 sigma

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 -2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.2 Activity Planning, Scheduling, and Execution

4.5.2.4 Onboard Executives

TECHNOLOGY

Technology Description: Executes and monitors the progress of activities generated by an automated or manual process and intervenes as necessary.

Technology Challenge: Flexibility, reliability, and scalability to more complex and realistic scenarios.

Technology State of the Art: Executive languages that represent activity plans and software engines for their execution.

Parameter, Value: Reliability > 3 sigma

TRL: 4

Technology Performance Goal: Ability to handle the complexities of more realisitic scenarios.

Parameter, Value: Reliability > 6 sigma

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Onboard activity execution.

Capability Description: Provides an automated means to execute auto- or manually-generated plans and sequences.

Capability State of the Art: Software for executing sequences is rule based with no ability to learn.

Parameter, Value: Reliability > 3 sigma

Capability Performance Goal: Goal-based execution of scheduled plans with feedback driven re-planning.

Parameter, Value: Reliability > 6 sigma

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.2 Activity Planning, Scheduling, and Execution

4.5.2.5 State Management

TECHNOLOGY

Technology Description: Provides an integrated management of system state between onboard assets and the ground systems.

Technology Challenge: The ability to reliably handle critical information in real time.

Technology State of the Art: State-centric systems that control and manage states and state histories and achieve goals (closed loop) rather than executing commands (open loop).

Parameter, Value:

Number of states: dozens

Types of states: simple

Operation duration: demonstration scenarios only (few hours)

TRL 5

Technology Performance Goal: To scale to more complex systems and scenarios with numerous states and to validate the reliable and efficient handling of critical information in real-time.

Parameter, Value:

Number of states: hundreds

Types of states: complex data types

Operation duration: life-time equivalent and scalable to entire systems.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: State management.

Capability Description: Provides an integrated system for managing system state between onboard assets and ground operations.

Capability State of the Art: State information is managed through sending low-level commands and receiving telemetry from sensors.

Parameter, Value:

Handling of system states: custom and varies for each subsystem.

Subsystem state relationship consistency: doesn't exist

Capability Performance Goal: State-aware monitor and control between flight assets and ground through the exchange of high-level states and constraints/goals on those states.

Parameter, Value:

System handling of states: ability to manage system state across subsystems and between onboard assets and ground.

Ability to access system state for more effective fault detection and isolation, and planning and exeuction.

Subsystem state relationship consistency: will be created (mandatory for system to be automated)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2021	2022	2015 - 2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Real-Time System-Wide Safety Assurance: An Integrated Safety Assurance System Enabling Continuous System-Wide Safety Monitoring	Enabling	--	--	2035	3 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enabling	--	--	2025	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.5 System-Level Autonomy
4.5.4 Multi-Agent Coordination

4.5.4.1 Multi-Agent Coordination

TECHNOLOGY

Technology Description: Provides an infrastructure for distributing autonomous functionalities across platforms.

Technology Challenge: Challenges due to the heterogeneity of the hardware and software tools that are interfaced. Challenges include verification and validation of the complex agent interactions, and the capability and management of agent system group goal direction.

Technology State of the Art: Multi-agent systems have been used for dynamic load balancing of networked systems.

Parameter, Value: (TRL 4)

Range of hardware and software systems that can be integrated: very limited;

Range of operations that can be performed: very limited.

Technology Performance Goal: Ability to support heterogeneous hardware and software applications.

Parameter, Value: (TRL 6)

System responsiveness;

System reliability.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Distributed operations and simulations.

Capability Description: Provides a capability to leverage computational resources on Earth and in space.

Capability State of the Art: Operations are largely centralized.

Parameter, Value:

Range of hardware and software systems that can be integrated: very limited;

Range of operations that can be performed: very limited.

Capability Performance Goal: Distributing system intelligence.

Parameter, Value: System responsiveness:

System reliability: > 3 sigma

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.5 System-Level Autonomy
4.5.8 Automated Data Analysis for Decision Making

4.5.8.1 Autonomous Decision Making

TECHNOLOGY

Technology Description: Analyzes large data sets with large uncertainties and conflicting information to provide timely operational decisions.

Technology Challenge: Making decisions based on heterogeneous data sets and partial models.

Technology State of the Art: Data mining algorithms.

Parameter, Value:
False positives;
False negatives.

TRL 2

Technology Performance Goal: Robustly analyze onboard telemetry against known models to make onboard decisions. Need to achieve a high level of reliability for consideration, in particular for mission critical operations.

Parameter, Value:
False positives: 6 sigma;
False negatives: 6 sigma.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous decision making.

Capability Description: Using spacecraft telemetry, analyzes large data sets with with large uncertainties and conflicting information to provide operational decisions.

Capability State of the Art: Decisions are largely done by operators on the ground using a set of custom diagnostic tools and human-driven analysis.

Parameter, Value:
Quality of service.

Capability Performance Goal: Ability to exceed human performance in addressing conflicting information in large data sets.

Parameter, Value:
False positives: 6 sigma;
False negatives: 6 sigma.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years
Enable Assured Machine Autonomy for Aviation: Initial Autonomy Applications	Enabling	--	--	2025	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.6 Autonomous Rendezvous and Docking
4.6.1 Relative Navigation Sensors

4.6.1.1 Three-Dimensional (3D) Imaging Sensor

TECHNOLOGY

Technology Description: Provides a three-dimensional (3D) image of a target over a large dynamic range (see TA 4.1.1. 3D Sensors).

Technology Challenge: Enhance the detector sensitivity, field of view, reliability, and performance. Reduce size of units and lower power.

Technology State of the Art: Flash Light Detection and Ranging (LIDAR): short-wavelength infrared focal plane array detector coupled with pulsed laser that measures return intensity and time of flight.

Parameter, Value:
Field of View: ±10º;
Resolution: 256 x 256;
Range: 2 m to 5 km;
Pixel array: 256 x 256;
Rng Accuracy: 0.02 m;
Bearing Accuracy: < 1.5 mrad/measurement;
Op range: 2 km to 1 m;
Volume: 10 L;
Mass: 10 kg;
Power: 30 W;
Field Regard: ±10º

TRL
7

Technology Performance Goal: Increase range resolution, reliability, performance, and reduce size.

Parameter, Value:
Pixel array: 256 x 256;
Rng Accuracy: 0.02 m;
Bearing Accuracy: < 1.5 mrad/measurement;
Op range: 2 km to 1 m;
Volume: 10 L;
Mass: 10 kg;
Power: 30 W;
Field Regard: ±10º

TRL
8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Focal plane array developments.

CAPABILITY

Needed Capability: Highly accurate ranging capability and 3D imaging capability.

Capability Description: Highly accurate ranging capability and 3D imaging capability.

Capability State of the Art: Flash LIDAR.

Parameter, Value:
Pixel array: 256 x 256;
Rng Accuracy: 0.45 m;
Bearing Accuracy: 8.7 mrad/measurement;
Op range: 5 km to 2 m;
Volume: 12 L.;
Mass: 10 kg;
Power: 40 W;
Field Regard: ±10º;
Ranging Accuracy: < 1 cm;
Operating Range: 5 km to < 1 m

Capability Performance Goal: Increase range resolution, field of view, reliability and performance. Reduce size and lower power.

Parameter, Value:
Rng Accuracy: 0.02 m;
Bearing Accuracy: < 1.5 mrad/measurement;
Op range: 2 km to 1m;
Volume: 10 L;
Mass: 10 kg;
Power: 30 W;
Field Regard: up to ±30º

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.6 Autonomous Rendezvous and Docking
4.6.1 Relative Navigation Sensors

4.6.1.2 Visible Camera

TECHNOLOGY

Technology Description: Provides radiation-tolerant, high-definition (HD) optical navigation sensors and star trackers with large dynamic range for light sensitivity to detect faint objects (target vehicle) and bright objects (Earth, Moon, etc.) in field of view.

Technology Challenge: Enhance detector sensitivity and dynamic range, and develop radiation tolerant HD imagers.

Technology State of the Art: Pressurized environments or short duration low-Earth orbit (LEO) missions.

Parameter, Value:

Focal Plane Array: ~2048 x 1536 pixels;

Field of view (FOV): 40 x 30 degrees

TRL

7

Technology Performance Goal: Long term deep space missions.

Parameter, Value:

Field Regard: 10º to 50º;

Resolution: 0.067 to 0.3366 mrad/pixel;

Mass: 3 kg;

Power: 5 W

TRL

8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Ability to operate in deep space environment for extended periods.

CAPABILITY

Needed Capability: Need visible cameras for both long-range acquisition of the target and close-up characterization of features for navigation.

Capability Description: Visible cameras with higher resolution and radiation tolerance for rendezvous and docking to accommodate deep space mission scenarios.

Capability State of the Art: Space-qualified visible cameras for LEO.

Parameter, Value:

Field Regard: 10º to 50º;

Resolution: 0.067 to 0.3366 mrad/pixel;

Mass: 5 kg;

Power: 10-15 W

Capability Performance Goal: Need higher resolution for targets with complex geometry.

Parameter, Value:

Rendezvous: < 8 μrad/pixel;

Proximity Operations: < 300 μrad/pixel

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.6 Autonomous Rendezvous and Docking
4.6.1 Relative Navigation Sensors

4.6.1.3 Longwave Infrared (LWIR) Camera

TECHNOLOGY

Technology Description: Provides relative navigation sensors with large dynamic range for thermal sensitivity to detect faint objects (target vehicle) and bright objects (Earth, Moon, etc.) in field of view.

Technology Challenge: Enhance detector sensitivity and dynamic range.

Technology State of the Art: 17 µm, small format array.	TRL	Technology Performance Goal: 12 µm, large format array.	TRL
Parameter, Value: Pixel array: 640 x 480; Resolution: 1.1 mrad/pixel.	5	**Parameter, Value:** Pixel array: 1280 x 960; or greater Resolution: 0.5 mrad/pixel.	8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Need higher-resolution focal plane arrays for longwave infrared (LWIR) cameras to perform deep-space missions.

Capability Description: Higher resolution LWIR cameras are needed to enable lighting-independent rendezvous and docking operations for deep-space missions.

Capability State of the Art: Low-fidelity LWIR cameras.	Capability Performance Goal: Need higher resolution to rendezvous and dock with future vehicles.
Parameter, Value: Pixel array: 640 x 480; Resolution: 1.1 mrad/pixel.	**Parameter, Value:** Pixel array: > 1000 x 1000; Resolution: < 300 µrad/pixel.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

4.6 Autonomous Rendezvous and Docking
4.6.2 GN&C Algorithms

4.6.2.1 Rendezvous Targeting

TECHNOLOGY

Technology Description: Delta-V and time of ignition (TIG) determination for long-range and medium-range rendezvous targeting (can be open-loop).

Technology Challenge: No experience performing autonomous rendezvous in non-central body gravity fields.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Algorithms to perform rendezvous targeting in low-Earth orbit (LEO).		**Technology Performance Goal:** Design targeting to accommodate low gravity field targets (asteroids, etc.).	
Parameter, Value: Demonstrated capability on a number of prototype systems and simulations.	7	**Parameter, Value:** Low gravity rendezvous targeting algorithms in non-central gravity fields.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Targeting algorithms for low gravity rendezvous.

Capability Description: Targeting algorithms for low gravity rendezvous burns.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Central-body (LEO) rendezvous scenarios.	**Capability Performance Goal:** Design targeting operations algorithms to accommodate low-gravity field targets (asteroids, etc.) where Clohessy-Wiltshire (CW) equations no longer hold.
Parameter, Value: Substantial gravity	**Parameter, Value:** Microgravity

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years

4.6 Autonomous Rendezvous and Docking
4.6.2 GN&C Algorithms

4.6.2.2 Proximity Operations/Capture/Docking Guidance

TECHNOLOGY

Technology Description: Delta-V and time of ignition (TIG) determination for proximity operations, capture, and docking, allowing for constraints and is in general closed loop.

Technology Challenge: No experience performing autonomous closed-loop guidance in non-central body gravity fields.

Technology State of the Art: Algorithms for performing LEO proximity operations, capture, and docking.

Parameter, Value: Demonstrated capability on a number of prototype systems and simulations.

TRL: 7

Technology Performance Goal: Low-gravity, closed-loop guidance algorithms in non-central gravity fields.

Parameter, Value: Demonstrated capability on a prototype system and simulation.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate:

CAPABILITY

Needed Capability: Need onboard, closed-loop guidance algorithms in non-central gravity fields.

Capability Description: Algorithms for performing closed-loop guidance in non-central gravity fields.

Capability State of the Art: Central-body (LEO) scenarios usually Clohessy-Wiltshire (CW)-based algorithms.

Parameter, Value: Substantial gravity

Capability Performance Goal: Design proximity operations algorithms to accommodate low-gravity field targets (asteroids, etc.) where CW equations no longer hold.

Parameter, Value: Microgravity

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years

4.6 Autonomous Rendezvous and Docking
4.6.3 Docking and Capture Mechanisms and Interface

4.6.3.1 Integrated Docking and Automated Rendezvous Systems Design

TECHNOLOGY

Technology Description: Assesses characteristics and performance of automated rendezvous and docking systems that results in lowest-integrated system mass and lowest life cycle and production cost.

Technology Challenge: Determine relationship between automated rendezvous system docking contact velocities and misalignments and resulting size and mass of docking system capture and docking load attenuation systems.

Technology State of the Art: Docking system capture and attenuation systems are sized to manual docking piloting capability of Orion and heritage vehicles, without consideration of potential contact velocity and misalignment reductions possible with fully automated rendezvous piloting systems.

Parameter, Value:	TRL
Docking mechanism mass and costs; Docking contact velocities and misalignments; Automated rendezvous system costs.	3

Technology Performance Goal: Determine optimum balance between automated rendezvous docking contact performance (contact velocities and misalignments) and docking mechanism capture and attenuation performance that results in the lowest-mass and lowest-cost combination of automated rendezvous system and docking system hardware.

Parameter, Value:	TRL
Docking mechanism mass and costs; Docking contact velocities and misalignments; Automated rendezvous system costs.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development of this technology is dependent on the advancement of the understanding of the docking contact piloting performance of automated rendezvous systems and the relationship between magnitude of contact velocities and misalignments and docking capture system dimensions and mass.

CAPABILITY

Needed Capability: Lowest-mass and lowest-cost combination of automated rendezvous system and docking system hardware that meets Exploration Design Reference Mission (DRM) docking needs.

Capability Description: Docking system(s) and automated rendezvous system(s) designed to work together, resulting in the lowest-mass and lowest-cost combination of automated rendezvous system and docking system hardware that meets Exploration DRM docking needs.

Capability State of the Art: Docking system capture and attenuation systems are sized to manual docking piloting capability of Orion and Commercial Crew Vehicles, without consideration of potential contact velocity and misalignment reductions possible with fully automated rendezvous piloting systems.

Parameter, Value:

Docking mechanism mass and costs;

Docking contact velocities and misalignments; Automated rendezvous system costs.

Capability Performance Goal: Determine optimum balance between automated rendezvous docking contact performance (contact velocities and misalignments) and docking mechanism capture and attenuation performance that results in the lowest-mass and lowest-cost combination of automated rendezvous system and docking system hardware.

Parameter, Value:

Docking mechanism mass and costs;

Docking contact velocities and misalignments; Automated rendezvous system costs.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years

4.6 Autonomous Rendezvous and Docking
4.6.3 Docking and Capture Mechanisms and Interface

4.6.3.2 Docking System for Exploration

TECHNOLOGY

Technology Description: Provides a docking mechanism or a family of mechanisms to meet the docking needs of all Crewed Design Reference Missions (DRMs) for the Human Exploration Operations Mission Directorate (HEOMD).

Technology Challenge: Providing a common and robust docking system with low-mass and low-contact loads and torques that has a high probability of capture for different classes and ranges of spacecraft mass properties.

Technology State of the Art: Flight-certified and in-development docking mechanisms for crewed missions in low-Earth orbit (LEO) environment.

Parameter, Value:

Mechanism mass: 300+ kg;

Allowable Docking Vehicle Masses: Mechanism-dependent, minimum capture mass: ~18,000 kg;

Based on Orion and heritage crew-piloted contact:

Docking Contact Velocity:

0.05 to 0.10 m/s;

Docking Contact Misalignments:

~4 deg, ~0.1 m;

Docking Contact and Attenuation Output Loads and Torques: 6,500 N, 2,800 N-m;

Operating Environment: LEO.

TRL

3

Technology Performance Goal: Develop a docking mechanism, or family of docking mechanisms, that uses common technologies and components.

Develop mechanisms suitable for automated rendezvous and proximity operations in LEO, deep space, lunar, and martian orbital environments.

Reduce docking system mass by 50% and docking contact loads and torques by 75% compared to SOA designs.

Parameter, Value:

Mechanism mass: 50% less than state of the art designs;

Allowable Docking Vehicle Masses:

~7,000 kg to 100,000+ kg;

Docking Contact Velocity and Misalignment Capture Envelope:

sized for automated rendezvous and proximity operations systems capabilities;

Docking Contact and Attenuation Output Loads and Torques:

75% lower than state of the art designs

Operating Environments: LEO orbit, deep space, lunar orbit and surface, Martian orbit and surface.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development of this technology is dependent on the development of docking requirements not limited by heritage system designs and standards, and advancement of docking attenuation system techniques and designs sized to the contact piloting capabilities of automated rendezvous and proximity operations systems. Verification and validation of docking system in motion based test system such as Johnson Space Center (JSC) 6 degrees of freedom (DOF) Dynamic Test System.

CAPABILITY

Needed Capability: Low-mass and low-contact force docking mechanisms.

Capability Description: A docking mechanism, or family of docking mechanisms that uses common technologies and components, has significantly lower mass than current docking mechanisms, and is appropriate for automated rendezvous and proximity operations in LEO, deep space, and lunar and martian environments.

Capability State of the Art: Flight-certified docking mechanisms for crewed missions in LEO environment.

Capability Performance Goal: Docking of vehicles with masses from ~7,000 kg to ~100,000+ kg, piloted by automated rendezvous and proximity operations systems, in LEO, deep space, and lunar and Mars orbital environments. Docking mechanisms need to have lowest-possible mass and lowest-possible docking output forces and torques while meeting HEOMD crewed mission operational and environmental requirements.

CAPABILITY - CONTINUED	
Parameter, Value: Mechanism mass: 300+ kg; Allowable Docking Vehicle Masses: Mechanism-dependent, minimum capture mass: ~18,000 kg; Docking Contact Velocity: 0.05 - 0.10 m/s; Docking Contact Misalignments: ~4 deg, ~0.1 m; Docking Contact and Attenuation Output Loads and Torques: 6,500 N, 2,800 N-m; Operating Environment: LEO.	**Parameter, Value:** Mechanism mass: 50% less than current SOA designs; Allowable Docking Vehicle Masses: ~7,000 kg to 100,000+ kg; Docking Contact Velocity and Misalignment Capture Envelope: sized per automated rendezvous and proximity operations systems capabilities; Docking Contact and Attenuation Output Loads and Torques: 75% lower than SOA designs; Operating Environments: LEO, deep space, lunar orbit and surface, Martian orbit and surface.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	4 years

4.7 Systems Engineering
4.7.1 Modularity, Commonality, and Interfaces

4.7.1.1 Refueling Interfaces

TECHNOLOGY

Technology Description: Provide multiple smart quick disconnect (QD) couplings that are rated for high pressure and cryogenic fluids in a plate-mounted configuration for transferring commodities.

Technology Challenge: Mitigate regolith dust on soft good seals inside QDs. Eliminating dust from fiber optics connectors to avoid attenuation of signal. Exclusion of dust and self-cleaning technologies are needed. Packaging of smart sensors in tight spaces inside a QD. Isolation of propellant fuel from propellant oxidizer to avoid combustion (typically achieved by separating interfaces). Lifetime of QDs is only in tens to hundreds of cycles; should be thousands.

Technology State of the Art: Manual mating or partially automated using industrial controls. Some robotic mating systems exist but are limited to mechanical interfaces.

Parameter, Value:

Automated mating within 5 minutes of starting. Self aligning to within 1 cm of a target on the flight plate and capable of +/- 1 degree mis-alignment without consequence. Latching with pneumatic or solenoid actuation. Self leak checking within 15 minutes after hard mate of the re-fueling interface.

TRL: 4

Technology Performance Goal: Six-degrees of freedom (DOF), self-positioning, self-aligning, smart coupling and latching system. Autonomous checkout and leak check of cryogenic propellants flowing through the QD couplings.

Parameter, Value:

Automated mating within 5 minutes of starting. Self aligning to within 1 cm of a target on the flight plate and capable of +/- 1 degree mis-alignment without consequence. Self latching for hard mate in an automated sequence after soft mate. Self leak checking within 15 minutes after hard mate of the re-fueling interface.

TRL: 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Transfer of commodities: cryogenic fluids, high pressure gases, power, data, and consumables.

Capability Description: Cryogenic fluids typically consist of propellants for propulsion or fuel cells. High pressure gases are used for purging and cold gas propulsion. Electric power is stored in chemical batteries for actuation and other system electrical needs. Data must be transferred for controls, diagnostics, and science purposes. Consumables are buffer gases or water for crew consumption.

Capability State of the Art: Current QD systems are manually cleaned and leak checked and mated or are partially automated. Seals in QD’s are subject to degradation from operational use and are easily damaged by contamination (such as regolith dust). QD lifetime is currently very limited due to environmental conditions and lack of dust protection.

Parameter, Value:

Cryogenic fluids transferred range in temperatures from liquid oxygen (LO_2) (-297° F, -183° C), to LN_2 (-321° F, -196° C) to liquid hydrogen (LH_2) (-423° F, - 253° C) and low pressures (20-35 psig typical). High pressure gases are typically ambient in temperature but can reach pressures as high as 5,000-6,000 psi. Power transfer occurs at the vehicle voltage (28-300 VDC) and can be in the kW range. Data can be transfered through fiber optic connectors for a high bandwidth capability. QD’s are currently manually checked and are not “smart.”

Capability Performance Goal: Automated mating of cryogenic re-fueling interfaces in a space environment. Positioning, alignment, actuation, mating and leak checks require no crew intervention. QD’s will be smart and have a self – leak checking capability with real time diagnostics during operations.

Parameter, Value:

Automated mating within 5 minutes of starting.

Self aligning to within 1 cm of a target on the flight plate and capable of +/- 1 degree mis-alignment without consequence.

Self leak checking within 15 minutes after hard mate of the re-fueling interface.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

4.7 Systems Engineering
4.7.1 Modularity, Commonality, and Interfaces

4.7.1.2 Modular Serviceable Interfaces

TECHNOLOGY

Technology Description: Standardized and interoperable interfaces among disparate robots and payloads. These interfaces can be modular and smart, allowing for structural, mechanical, electrical, fluid, and pneumatic interactions.

Technology Challenge: The technologies exist but adoption of an international standard faces organizational, political, and legacy issues that must be overcome.

Technology State of the Art: The technology for smart robotic modular end effector interfaces exits, but has not been commonly adopted or mandated. Some International Space Station (ISS) robotic end effector interfaces are modular.

Parameter, Value:	TRL
Structural grapple fixtures with power and data. Other government agency non-proprietary satellite-servicing interfaces (mechanical, electrical, etc.) that aimed to facilitate the development of an industry wide on-orbit servicing infrastructure.	5

Technology Performance Goal: Technology goal is to have an international standard interface that is serviceable and provides modularity between otherwise different robotic systems. Serviceability includes replenishing consumable commodities, transferring data and diagnostics, grappling, maintenance and repair procedures.

Parameter, Value:	TRL
Adoption of an International standard for robotic interfaces conducive to serviceability.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Standardized common, smart interfaces that allow modular approaches to serviceable interfaces.

Capability Description: Heterogeneous robots can link in a modular fashion due to standardized common serviceable interfaces.

Capability State of the Art: Today, most interfaces in space are not modular nor standardized. The NASA ISS grapple fixture is an example of a structural interface with an electrical connector and data transfer that enables robotic operations with different international payloads. Existing geostationary orbit (GEO) satellites do not have serviceable or standardized interfaces for grapelling, servicing or re-fueling. SOA is Line Replaceable Units (LRU) on ISS that require manual changeout and assembly. No international standard exists today for modular interfaces other than the international human spacecraft docking standard.

Parameter, Value:

Interface type: electrical (for power and data transfer)

Number of cycles: 10s of cycles

Standardized: no

Modular: no

Servicable: no

Provides structural support: few do.

Capability Performance Goal: Serviceable modular interfaces that can support on-orbit servicing using standardized interfaces for robotic operations. These interfaces should support autonomous docking and latching (i.e., without human intervention) and provide self-aligning and self-verifying capabilities with fault tolerance. These interfaces should also be capable of transferring mechanical, electrical and thermal loads between modules. This would eliminate the need for specialized robotic end effector tools, such as those used in the ISS Robotic Refueling Mission (RRM), which are complex. The goal is to enable a system that consists of multiple de-coupled subsystems, with the ability to reuse common modules across separate missions.

Parameter, Value:

Interface type: electrical (power and data), fluidic (cryogenic), gaseous (high pressure), and for consumables

Number of cycles: repeatable to 10,000 cycles without degradation in performance

Standardized: yes for various robot sizes/classes

Modular: yes

Serviceable: yes

Provides structural support: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	6 years

4.7 Systems Engineering
4.7.1 Modularity, Commonality, and Interfaces

4.7.1.3 Self-Assembling and Configuration Features

TECHNOLOGY

Technology Description: Provide modular bi-directional interfaces that allow multiple configurations of robotic assembling elements.

Technology Challenge: The ability to decompose it into a number of smaller robots for day-to-day operations could represent a significant reduction in total robotic mass. The associated reduction in the number of spare parts needed to recover from any fault could also be significant. These cost savings must be weighed against the increased complexity of each particular robot configuration relative to a single-purpose robot designed to perform the same task.

Technology State of the Art: Concepts and demonstrations exist in labs. One important reason existing flight robots exhibit a highly centralized, monolithic design is the need to protect the control electronics within a thermally controlled environment. Robots exhibiting a high degree of modularity will depend on emerging technologies for electronics that can operate directly in extreme temperature and radiation environments.

Parameter, Value:

Existing modular robots can be divided into two categories according to whether the primary actuator is rotational or prismatic. Interfaces have been developed but are all unique to each robot system.

TRL 4

Technology Performance Goal: Modular robotic systems offer potential advantages as versatile, fault-tolerant, cost-effective platforms for space exploration, but a sufficiently mature system is not yet available. The goal is to demonstrate a modular robot built from components with standard electromechanical interfaces, making it possible to assemble the components in a variety of ways to suit a variety of purposes.

Parameter, Value:

One robot system that can exist in more than one state of assembly and configuration without local human intervention, demonstrated in a space relevant environment.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Modular Serviceable Interfaces (4.7.1.2) are also the building blocks for reconfigurable and self-assembling, and even self-replicating, or self repairing robotic systems.

Capability Description: This capability allows two robotic systems to merge into one, or augment itself, via a modular interface that simplifies the number and type of interface connections (structural, power, data, commodities). It also allows a robot system to re-configure itself to perform a different function or task. This capability allows the robot to adapt to a changing environment or recover from damage. This capability is scaleable and can be applied to very small robotic modules or larger modules. Smaller sizes have a higher interface to module mass ratio, so these interfaces must be simple and minimal in smaller sizes.

Capability State of the Art: Current modular robotic systems are in the research stage in labs. The current monolithic design approach to robotics offers little room for reuse, adaptation, or maintenance on long-duration or open-ended missions. Adopting a modular design could address these needs, by allowing a single system mass to be reconfigured to suit each task and by reducing the number of spare parts required to achieve redundancy.

Parameter, Value:

Currently modular interfaces have been demonstrated, but only in the lab – not in space. Scale is a parameter that significantly influences the approach and design of modular robots.

Capability Performance Goal: Show the capability of a robot system to assemble itself and then re-configure itself into a new state to perform more than one useful function or task and/or recover from damage.

Parameter, Value:

One robot system that can exist in various states of assembly and configuration without local human intervention.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

4.7 Systems Engineering
4.7.1 Modularity, Commonality, and Interfaces

4.7.1.4 Marsupial Robot Interfaces

TECHNOLOGY

Technology Description: Provide docking and replenishing interfaces for a small daughter robot at a mother robot. Marsupial robotics is an active field of research, allowing for new forms of cooperative robotics.

Technology Challenge: Navigation and reliable coupling mating in a regolith dust environment. Multiple-robot operation.

Technology State of the Art: Marsupial robotics interfaces can be scaled-down versions of existing interface and docking systems.

Parameter, Value:

Reliable docking;

Consumables transfer;

Quick disconnect couplings.

TRL: 5

Technology Performance Goal: Integrate common marsupial robot interfaces to heterogeneous robots so that an overall increase in system efficiency can occur. For example, re-charging of marsupial daughter electrical power batteries at waypoints may prove beneficial to the system while allowing for increased mission flexibility.

Parameter, Value:

Reliable docking;

Consumables transfer;

Quick disconnect couplings;

Dust tolerance and mitigation;

Thermal shelter at mother robot; Systems efficiency and reliability for a given task.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: The ability for heterogeneous robots to mutually support each other's onboard resources.

Capability Description: Marsupial relationships formed among heterogeneous robots to provide functionality beyond what either robot could deliver individually.

Capability State of the Art: Spacecraft landers deliver robotic vehicles to other planetary surfaces and support them until they depart, and can continue to support as a sample cache, communication relay or other useful functions. International agency's Philae lander and Hayabusa MASCOT are examples of current marsupial spacecraft that are one-time deployed from the main spacecraft to a target body where future interaction does not involve physical contact with the main spacecraft.

Parameter, Value:

Distance between supported platforms: 10s of meters;

Rapid, energy efficient transport to target area; Protection during transport and retrieval;

Shelter from environmental conditions;

Power recharge, battery/fuel swapping;

Communication: wireless line-of-sight.

Capability Performance Goal: Replenishing interfaces for small daughter platforms from a more resources rich parent platform for power, data, thermal and other consumble resources. Enable communications between mother and daughters without the need for line of sight. Provide reliable interfaces for autonomous docking and commodity transfer capability.

Parameter, Value:

Distance between supported platforms: 10s of kilometers (for power sharing, communication in extreme environments and for mechanical support)

Communication: high-bandwidth without line-of-sight.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

4.7 Systems Engineering
4.7.2 Verification and Validation of Complex Adaptive Systems

4.7.2.1 Verification and Validation of Complex Adaptive Systems

TECHNOLOGY

Technology Description: Provides pre-flight verification and validation (V&V) to the level necessary for human safety and reliability and for systems to allow crew independence; provides in-flight V&V following in-the-field system re-configuration.

Technology Challenge: Validation and verification of a changing or evolving system and automated validation and verification on demand.

Technology State of the Art: Current methods explicitly depend on standards, regulations, processes and rigorous examination of the integrated system.

Parameter, Value:

Type of V&V support: highly customized software and hardware for low-complexity or well-modeled robotic and autonomous systems in a well-modeled environment;

In-flight or in-situ V&V: no

TRL 9

Technology Performance Goal: Automated V&V for robotic systems that are operating in dynamic and changing environments.

Parameter, Value:

Type of V&V support: automated hardware and software tools that handle complex systems with numerous configurations and can handle large environmental and operational uncertainties in poorly-modeled environments;

In-situ V&V: yes

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: New V&V methods that can be implemented real time with automated software.

CAPABILITY

Needed Capability: Verification and validation of complex autonomous and robotic systems.

Capability Description: Hardware and software that allow the systematic verification and validation of autonomous and robotic systems during development and in the field (in-situ). Such systems have to reason about large environmental uncertainties, ensure the integrity of the robotic or autonomous system, and ensure the safe operation as it works side-by-side with humans. They may also be reconfigured or re-assembled to allow crew self-sufficiency.

Capability State of the Art: Customized and extensive (costly and time-consuming) human-supervised testing for a handful of fixed system configurations. More sophisticated, complex, and dynamic system configuration and systems are often precluded in the design phase due to the complexities of V&V.

Parameter, Value:

Type of V&V support: highly customized software and hardware for low-complexity or well-modeled robotic and autonomous systems in a well-modeled environment;

In-flight or in-situ V&V: no

Capability Performance Goal: Reduce customization and expand automation of V&V approaches. Enable in-flight real-time V&V for highly reconfigurable systems, in particular, for those that will be working side-by-side with humans.

Parameter, Value:

Type of V&V support: automated hardware and software tools that handle complex systems with numerous configurations and can handle large environmental and operational uncertainties in poorly modeled environments;

In-situ V&V: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	12 years

4.7 Systems Engineering
4.7.3 Robot Modeling and Simulation

4.7.3.1 End-to-End Systems Modeling

TECHNOLOGY

Technology Description: Provides complete computer systems modeling of functions and interfaces with applicable Concepts of Operations. This includes co-operative robotics with humans in-situ, for example, including human factors assessments.

Technology Challenge: Modeling complex heterogeneous robotic systems that vary their concept of operations by adapting to the local environment and co-operating with humans and robots.

Technology State of the Art: Older technologies are mostly system specific solutions. New technologies are more generic and adaptable to modeling variations in robotic configurations. They support applications in a wider range of space environments but are still limited to traditional human/machine interface.

Parameter, Value:
Number of robots;
Number of interfaces;
Human interaction;
Environment;
Concept of Operations.

TRL
3

Technology Performance Goal: Future technologies will be more generic and readily adaptable to modeling variations in mission concept and robotic capabilities. They will support application in a wide range of space environments and support new technologies to bridge the human/machine interface. This will enable more effective and efficient use of robotic systems to support coordinated complex operations for more challenging human space exploration destinations.

Parameter, Value:
Number of robots;
Number of interfaces;
Human interaction;
Environment;
Concept of Operations.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Integrated space-based robotic systems modeling.

Capability Description: Provides a capability to model the integrated end-to-end dynamics, operations, and performance of robotic systems used to support human spaceflight. This will specifically entail the modeling of robotic mechanisms behavior in a variety of space exploration environments with particular emphasis on human-robotic interaction.

Capability State of the Art: The Space Shuttle used a human operated robotic arm for a variety of operations, including satellite deployment and retrieval, astronaut positioning and space structure assembly. The robotic systems on the International Space Station (ISS) provide a similar role. Each of these programs developed a collection of detailed task-specific simulations for design, analysis, training, and operations. While components of the tools are generic, the tools themselves are very specific to the robotic system.

Parameter, Value:
Number of robots;
Number of interfaces;
Human interaction;
Environment;
Concept of Operations.

Capability Performance Goal: This kind of capability was used throughout the life of the Space Shuttle and is currently used on the ISS. It is a critical capability in planning effective and safe robotic operations in a human spaceflight environment.

Parameter, Value:
Number of robots;
Number of interfaces;
Human interaction;
Environment;
Concept of Operations.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years

4.7 Systems Engineering
4.7.3 Robot Modeling and Simulation

4.7.3.2 Modeling of Contact Dynamics

TECHNOLOGY

Technology Description: Understanding of forces/torques generated on objects and platforms through mobility or manipulation.

Technology Challenge: Challenges include soil terra-mechanics, object mating, tools shifting in a robot's grasp, modeling disconnect mechanisms, and multi-point contact problems. Currently, interaction with granular materials is difficult to predict accurately and requires lab measurements fo geo-technical properties of the regolith and empirical characterization equations.

Technology State of the Art: Older contact dynamics modeling technologies are primarily based on specific system equation development (for example, Common Berthing Mechanism (CBM) ring petal surfaces, Ready to Latch Indicators, duckhead bumpers) that required long-duration development and extensive verification and validation (V&V) against hardware test data. Recent developments are more efficient in that they are based off of processing graphics models to configure input data for a contact dynamics algorithmic engine. Graphics based contact dynamics modeling is less labor intensive than previous efforts but still require development of the source graphics models (that is, using engineering drawings). Geometric primitives must also be taken into consideration during development.

Parameter, Value:

Force calculation resolution (edge on edge, flat on flat, rod on cam) 0.01 N;

Number of types of surfaces being contacted 1-5;

Conservation of momentum to within 0.1 N.

TRL 6

Technology Performance Goal: Enable more effective and efficient preflight modeling and analysis for safer robotic system operations, leveraging graphical models currently used in engineering analysis and training scene generators.

Provide ability to react to contact dynamics with an un-coperative and dynamically changing surface such as regolith, which is being manipulated by robotic excavators and/or site preparation robotic equipment.

Accommodate the dynamics of robots immersed in liquids such as oceans on moons in the Jovian system.

Parameter, Value:

Number of contacts: 3;

Number of limbs: 2;

Time Step: 0.001 s;

Object Rigidity: < 1 N/m;

Force calculation resolution (edge on edge, flat on flat, rod on cam) 0.001 N;

Number of types of surfaces being contacted: 10-50;

Conservation of momentum to within 0.001 N.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Efficient modeling of contact dynamics.

Capability Description: Computationally-efficient model-based algorithms for computing and predicting contact dynamics for a range of robotic mobility and manipulation applications. These may leverage graphics models, discrete element models (DEM), real time finite element analysis (FEA).

Capability State of the Art: Contact dynamics are used to model grapples (for example, Space Station Remote Manipulator System (SSRMS) Latching End Effector (LEE) to Grapple Fixture) for payload maneuvering operations or International Space Station (ISS) visiting vehicle capture/release operations. Contact dynamics modeling also come into play for manipulator berthing/unberthing payloads to/from numerous ISS mechanisms (for example, Common Berthing Mechanisms (CBMs), Capture Attach Systems (CASs), etc.). This is required for relocation of modules on the ISS.

Terra-mechanical models are largely empirical and do not currently capture the fidelity of the interaction of robotic components (such as wheels or legs) with regolith granular materials.

Capability Performance Goal: Enhance efficency and fidelity of algorithms that compute contact dynamics for future spacecraft for planning effective and safe robotic operations in a human spaceflight environment.

Provide predictive, real time modeling based on sensor inputs that will allow robotic platform to move across different media (traverse across surfaces, handle dynamically changing environments, move through liquid oceans, and so forth).

CAPABILITY - CONTINUED	
Parameter, Value: Number of contacts: 1; Number of limbs: 1; Time Step: 0.1 s; Object Rigidity: Inf Force calculation resolution (edge on edge, flat on flat, rod on cam) 0.01N; Number of types of surfaces being contacted: 1-5; Conservation of momentum to within 0.1 N. Fidelity of terramechanical models: low with errors in the tens of percentages based on empirical data (depending on terrain and object geometries) Lab testing needed for anchor analysis methods.	**Parameter, Value:** Force calculation resolution (edge on edge, flat on flat, rod on cam) 0.01 N; Number of types of surfaces being contacted: 1-5; Conservation of momentum to within 0.1 N. Fidelity of terramechanical models: medium to capture different phenoma of contact interaction.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

4.7 Systems Engineering
4.7.3 Robot Modeling and Simulation

4.7.3.3 Dynamic Simulation

TECHNOLOGY

Technology Description: Provides high-fidelity multi-physics simulations of robot dynamics and its interaction with the environment.

Technology Challenge: Challenges include: seamlessly integrating simultaneous spatial and temporal dynamics scales; modeling multiple vehicles with multi-body components interacting with the environment; and modeling complex environment.

Technology State of the Art: Simulation of in-space free-floating robotic systems; simulation of wheeled and legged surface vehicles with low-fidelity wheel-terrain models.

Parameter, Value:

Performance per system and environment complexity: real-time for single vehicle.

TRL: 5

Technology Performance Goal: Autonomous vehicle systems management of autonomous rendezvous and docking (AR&D). Extravehicular activity (EVA) Mission Kit. Orion grapple arm and docking system. Relative navigation. Mobile habilitation. Human in the loop.

Parameter, Value:

Performance per system and environment complexity: real-time for multiple vehicles in higher fidelity environments.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Modeling and simulation of entire mission phases.

Capability Description: Provides modeling and simulation to examine systems trades and assess system performance to inform the actual design.

Capability State of the Art: Modeling and simulation of small mission segments. Limited spatial and temporal scales.

Parameter, Value:

Single rigid body spacecraft or robotic vehicle with simple interaction with environment.

Capability Performance Goal: Multiple flexible multi-body vehicles interacting with space, air, ground, or water guidance, navigation, and control (GN&C) functions integrated with physical system behavior, environmental models, complex interaction with environment.

Parameter, Value:

Multiple vehicles;

Multiple subsystem functions;

Multiple mission phases;

Multiple spatial scales of operation;

Multiple temporal scales of dynamic response.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	7 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	7 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	7 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

4.7 Systems Engineering
4.7.3 Robot Modeling and Simulation

4.7.3.4 Granular Media Simulation

TECHNOLOGY

Technology Description: Models interaction between physical systems and granular materials.

Technology Challenge: Research efforts needed to a) reduce uncertainty in characterization of terrains, b) develop analogous simulants for laboratory testing, and c) understand the interactions between sampling systems and the terrain in presence of the multi-physics environmental effects (for example solid-fluid, solid-gas physics). Discrete Element Modeling (DEM) requires massive computing capacity to model billions of granular particles.

Technology State of the Art: Granular-material simulants exist for lunar regolith, but higher-fidelity simulants are required for Mars and asteroids. Mutli-physics in a planteray environment and asteroids has limited fidelity. DEM is limited to very small quantities of granular materials due to high computing power that is needed.

Parameter, Value:	**TRL**
Particle geometry: primarily spherical Computational cost: high	4

Technology Performance Goal: Reduce uncertainty in characterization of terrains; develop analogous simulants for laboratory testing, and understand the interactions between sampling systems and the terrain in presence of the multi-physics environmental effects (for example solid-fluid, solid-gas physics). Robotics low-gravity body anchoring systems, drills, sample containment and manipulation, surface mobility and guidance, navigation, and control (GN&C) computer modeling of the interaction of wheels and/or manipulation end effectors with granular materials such as planetary surface regolith.

Parameter, Value:	**TRL**
Particle geometry: polyhydral geometries Computational cost: medium	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Modeling terramechanics, modeling regolith excavation, and sub-surface access Discrete Event Modeling Test Beds for empirical data anchoring.

Capability Description: Provides high-fidelity models of the behavior of granular materials under gravity environmental conditions.

Capability State of the Art: Computer modeling of the interaction of wheels and/or manipulation end effectors with granular materials such as planetary surface regolith.

Parameter, Value:

Compaction level: low

Homogeneous regolith (single or dual particle sizes);

Slow soil engagement speeds;

Rolling contact.

Capability Performance Goal: Support for a wider range of interactions between physical systems and granular material (for example, wheeled rover, hopper footpad, anchor, or penetrator). Multiphasic soil (soil mixed with ice). Static and dynamic interaction well understood.

Parameter, Value:

Compaction level: high

Heterogeneous regolith with multiple particle sizes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	5 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.7 Systems Engineering
4.7.4 Robot Software

4.7.4.1 Robotic Architecture and Frameworks

TECHNOLOGY

Technology Description: Software frameworks for integration and validation of new technologies.

Technology Challenge: Scalability of frameworks and managing complexity associated with multi-mission systems with different deployment configurations. Integration of software modules that are independently developed by multiple institutions or groups. Evaluation of the effectiveness of various frameworks for a space environment.

Technology State of the Art: Ability to integrate multiple technologies and deploy on heterogeneous platforms. Enables validation and comparison of competing technologies of same capability.

Parameter, Value:

Scalability Interoperability;
Run-time efficiency;
Maintainability;
Flexibility;
Integration complexity for research grade software: low

TRL
6

Technology Performance Goal: Ability to flight qualify frameworks that are designed for multiple robotics missions and are extensible for design variations. Provide support for interoperability, reusability, and maintainability of the software and framework.

Parameter, Value:

Scalability Interoperability;
Run-time efficiency;
Maintainability;
Flexibility;
Integration complexity for flight software: low

TRL
9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Interoperable robot software.

Capability Description: Ability to effectively integrate technology advances from multiple institutions in an efficient and cost effective manner for maturation, validation, and deployment on multiple missions.Software framework that facilitates development and testing of “loosely coupled, highly cohesive” systems, which includes: (1) a well-defined “Application Programming Interface” (API) for module interaction; and (2) data distribution middleware to connect modules.The framework would support multiple languages and platforms; (2) integration of highly diverse functional modules; (3) heterogeneous communications patterns for data distribution (query and response, publish and subscribe, sequenced messaging, etc.); and (4) operational flexibility (terrestrial prototypes to flight systems, proximate and remote interaction, remote operations with variable bandwidth, latency, etc.

Capability State of the Art: No standardized robot software framework exists for flight missions.

Mars Exploration Rover (MER)/Mars Science Laboratory (MSL) software architecture have some commonality in their framework.

Remote robot operation prototype software tested on International Space Station (ISS) payload experiments (NASA Robot Application Programming Interface Delegate (RAPID)).

Parameter, Value:

Quasi-static motions and interactions with environment;

Requires re-implementation of algorithms using safety critical practices.

Capability Performance Goal: Dynamic motions and interactions of multiple assets (coordinated mobility; mobile manipulation). Consistent data representation across robotics subdomains. Provides system-level safety critical functionality without requiring the re-implementation of algorithms.

Supports robot development across the full technology readiness level (TRL) range: from terrestrial prototype to flight systems.

Parameter, Value:

Reduction in integration cost and deployment time.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

4.7 Systems Engineering
4.7.4 Robot Software

4.7.4.2 Standardized Messaging Protocols

TECHNOLOGY

Technology Description: Standard protocols for sharing information among multiple assets, including ground control stations.

Technology Challenge: A standardized protocol representation that can support heterogeneous robotic capabilities that may not be known a priori. Distributed aperture telescopes need to be able to effectively communicate between the spacecraft in formation in order to coordinate focusing movements.

Technology State of the Art: Messaging standards for controlling and coordinating operations of multiple heterogeneous platforms.

Parameter, Value:
Scalable interfaces;
Flexible interfaces;
Rich interfaces.

TRL: 6

Technology Performance Goal: Ability to control heterogeneous robotics assets using standardized protocol messaging.

Parameter, Value:
Interoperability;
Flexibility;
Extensibility.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Interoperable robot software.

Capability Description: Provides ability to effectively communicate among multiple assets including ground control stations.

Capability State of the Art: None

Parameter, Value:
Not applicable.

Capability Performance Goal: Standard message protocols and interfaces to command and monitor robotic assets). Consistent data representation across robotics systems.

Parameter, Value:
Scalable interfaces;
Flexible interfaces;
Rich interfaces;
Supports time-delayed communication.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

4.7 Systems Engineering
4.7.4 Robot Software

4.7.4.3 Model-Based Robotic Software

TECHNOLOGY

Technology Description: Consistent representation of models within a system through its lifecycle (from design, through implementation and in operations).

Technology Challenge: Heterogeneous nature of robot software models.

Technology State of the Art: Unified state-based representation for spacecraft systems (for example, Mission Data System).

Robot development software is not traceable to actual operations.

Parameter, Value:

Adoption for flight systems.

TRL 5

Technology Performance Goal: Develop model-based algorithms to enable autonomous operation of spacecraft.

Use the same spacecraft/robot system model to design test, verify, validate and operate the robot.

Parameter, Value:

Level of autonomy.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Autonomy technology advancements, sensors.

CAPABILITY

Needed Capability: Interoperable robotic models.

Capability Description: Consistent means to represent models and test with hardware in the loop prior to embedding throughout its life-cycle. Provides computationally-efficient and flexible algorithms to allow extensibility. Graphic user interfaces that allow system representation, interface definition, interaction modeling and modular code generation and testing.

Capability State of the Art: Primarily customized models are used. Recent mission such as Lunar Atmosphere and Dust Environment Explorer (LADEE) adopted a model-based robot software.

Parameter, Value:

Consistent use of model throughout system life-cycle: no

Consistent representation of model among subsystems: no

Interoperable model among flight systems and between flight and ground systems: no

Allows automated V&V: no

Allows system health management: customized.

Capability Performance Goal: Increase consistency within and among flight systems to enable greater use of autonomous capability.

Integrate one set of software systems throughout the entire life cycle of the robot. Gain large efficiencies and enable automated V&V and diagnostics through the use of a comprehensive systems model.

Mitigate legacy issues through model-based V&V of configuration changes and block upgrades.

Parameter, Value:

Consistent use of model throughout system life-cycle: yes

Consistent representation of model among subsystems: yes

Interoperable model among flight systems and between flight and ground systems: yes

Allows automated V&V: yes

Allows system health management: yes, generalized.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	5 years

4.7 Systems Engineering
4.7.5 Safety and Trust

4.7.5.1 Safety, Trust, and Interfacing Proximity Operation Technologies

TECHNOLOGY

Technology Description: Enables human crew working side by side with robotic assistants and interacting physically.

Technology Challenge: Integrated smart sensors and algorithms to detect human crew safety and trust, in particular crew working within 1 meter of the robot.

Technology State of the Art: Crew working in direct proximity to Robonaut 2 employing safety systems proven out on the ground and in orbit, Space Station Remote Manipulator System (SSRMS).

Parameter, Value:	TRL
Crew working next to limited functionality robots, tele-operated or simple tasks.	9

Technology Performance Goal: Crew working side by side with autonomous robots.

Parameter, Value:	TRL
≤1m proximity	5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Sensors and algorithms; crew testing.

CAPABILITY

Needed Capability: Safe operations for crew working next to autonomous robot assistants.

Capability Description: Safe operations.

Capability State of the Art: SSRMS and Robonaut 2.

Parameter, Value:
Robonaut 2;
Centaur;
SSRMS

Capability Performance Goal: Crew working side by side with autonomous robots.

Parameter, Value:
Less than 1 meter in proximity.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	7 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	7 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	8 years