AFRL's Integrated Systems Health Management Roadmap

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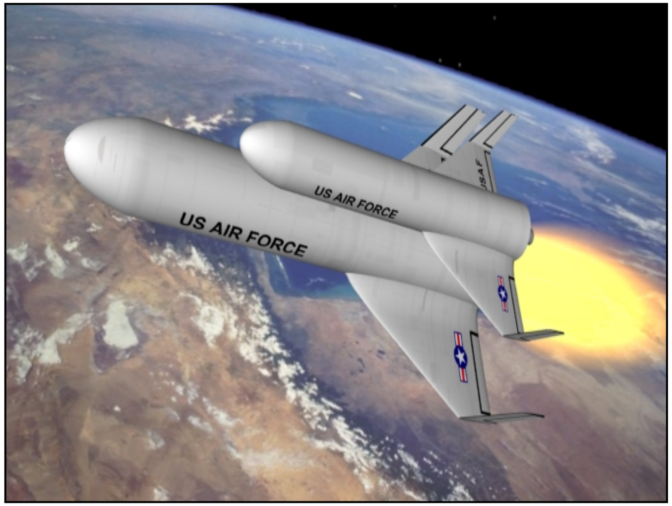
Outline

- Motivation
- AFRL ISHM Roadmap
- Future Direction



Military Need

- Operationally Responsive Spacelift ensures the Air Force has the capability to rapidly put payloads into orbit and maneuver spacecraft to any point in earthcentered space.
- The AF Strategic Master Plan shows a Vision End State including:



- ✓ Launch Operations for Satellite Operations and Counter Space
- ✓ Robust and Responsive Spacelift
- ✓ Regeneration and Augmentation of Satellite Constellations
- ✓ Reposition, Recover, and Service on-Orbit Assets
- ✓ Terrestrial Point-to-Terrestrial-Point Transport Through Space
- ✓ Sortie Military Missions

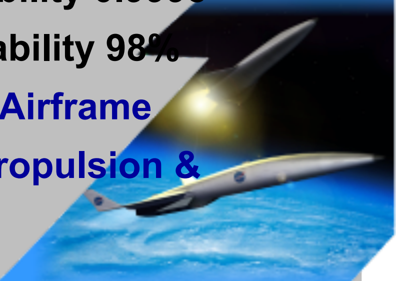
Space Access Technology Goals

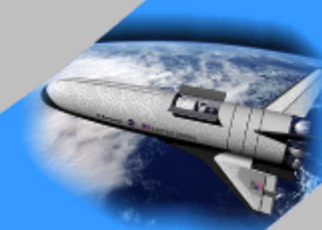
- Incremental Steps to Future Vision -

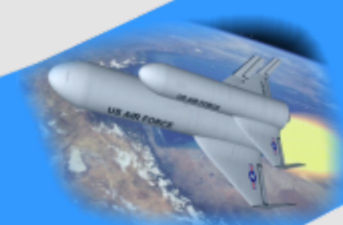
- Rapid turn 48 hrs
- 3X lower ops cost
- Vehicle reliability 0.995
- All Wx availability 90%
- 250 Sortie Airframe
- 100 Sortie Propulsion & Systems

- Rapid turn 24 hrs
- 10X lower ops cost
- Vehicle reliability 0.999
- All Wx availability 95%
- 500 Sortie Airframe
- 250 Sortie Propulsion & Systems

- Rapid turn 4 hrs
- 100X lower ops cost
- Vehicle reliability 0.9998
- All Wx availability 98%
- 1,000 Sortie Airframe
- 500 Sortie Propulsion & Systems







BASELINE
EELV, Shuttle, Aircraft Ops

Near Term

Mid Term

Far Term

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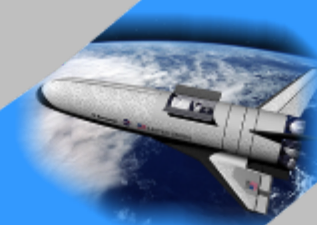


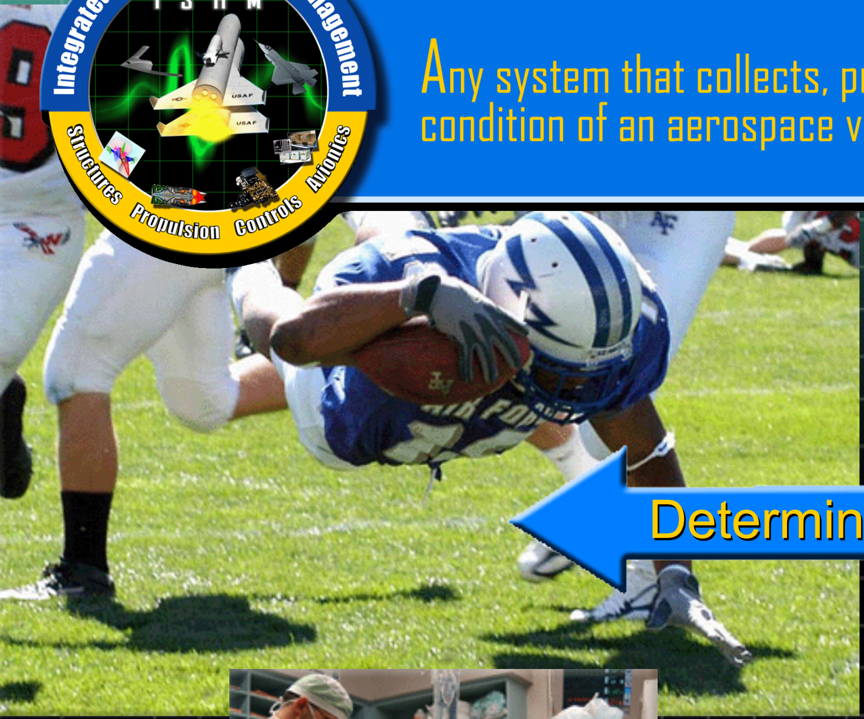
Near Term

Mid Term

Far Term

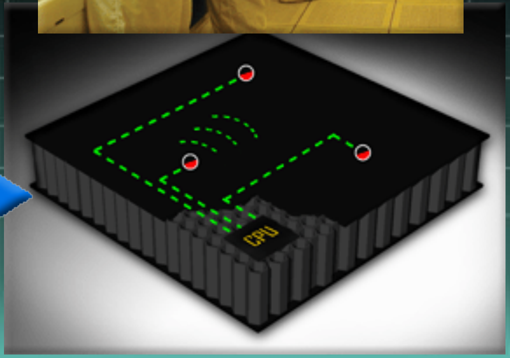
Integrated Systems Health Management

Any system that collects, processes and manages health data to assess the current condition of an aerospace vehicle and determine its ability to perform a given mission.



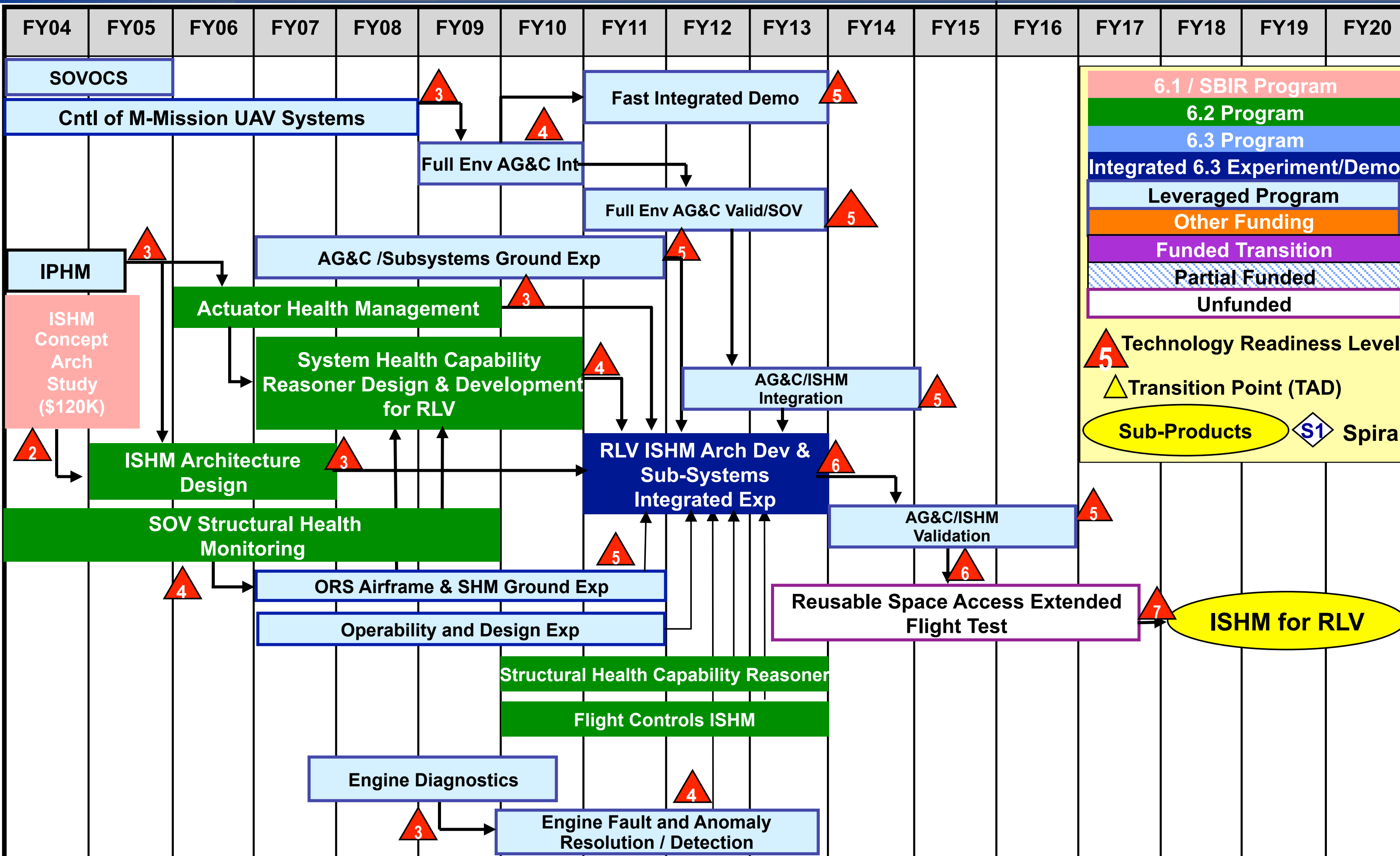
Determine Ability to Perform Mission

Assess Damage

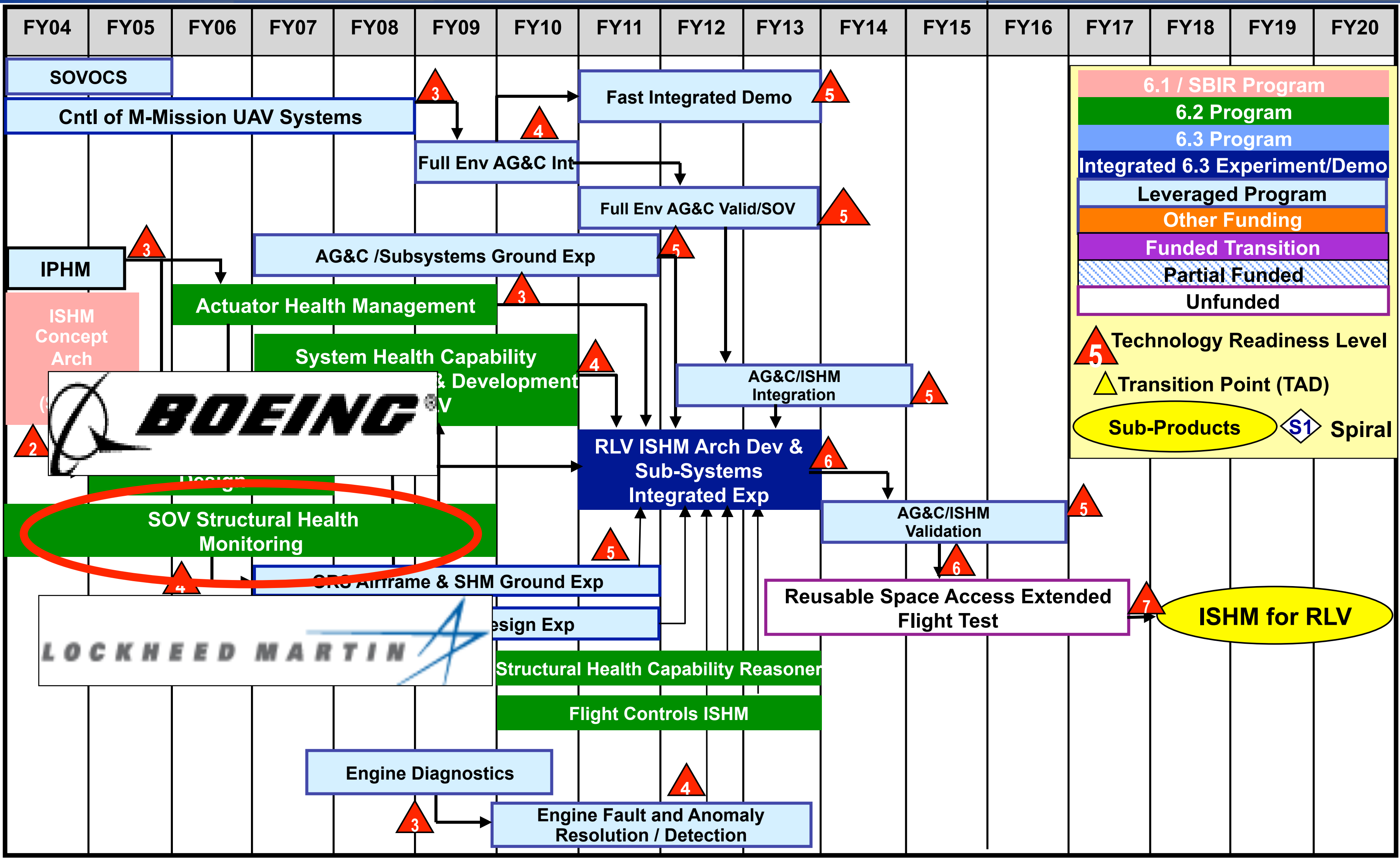


Detect Damage

ISHM for RLVs Roadmap

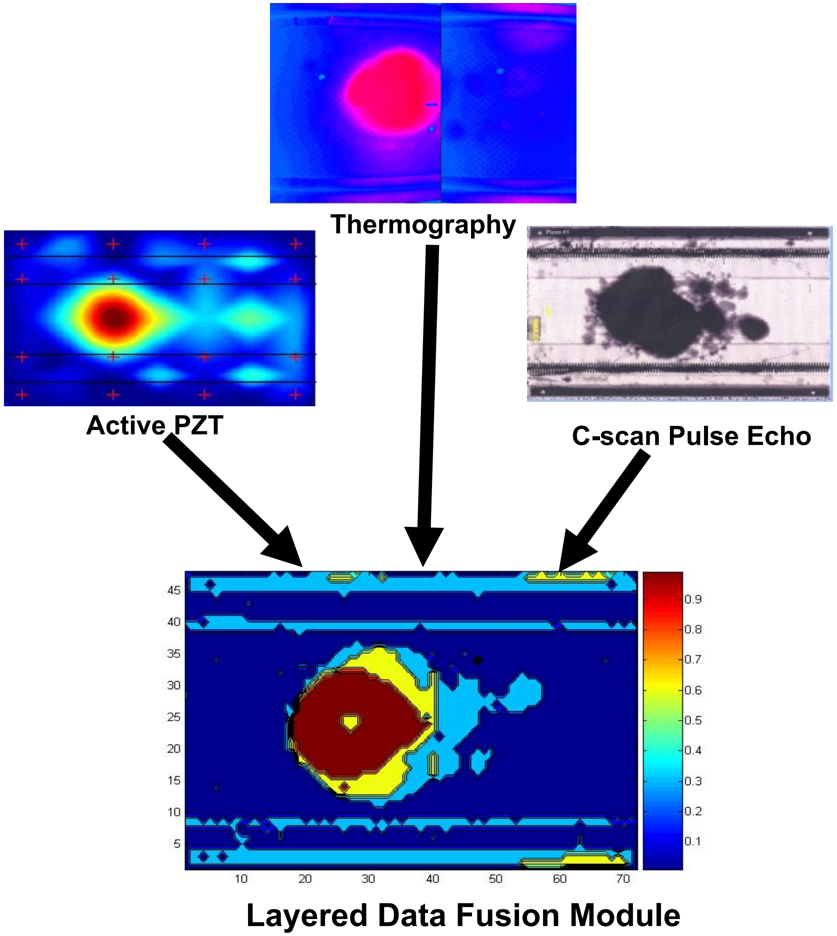


Structural Health Monitoring



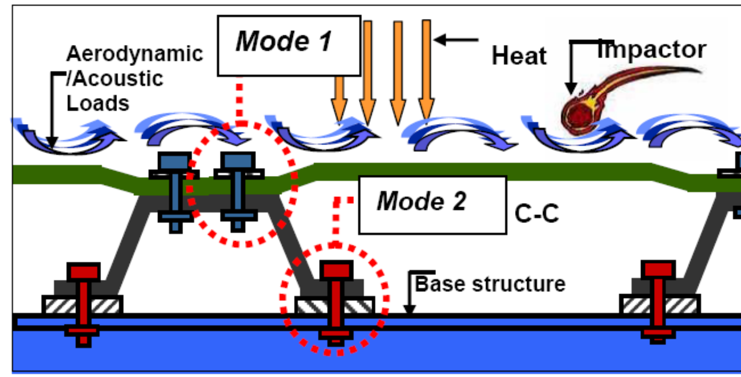
Structural Health Monitoring

- Determined critical focus area for mechanically attached TPS to meet quick turnaround goals
- Downselected technology to reduce turn time for a next generation space vehicle
- Techniques developed:
  - Delamination using AE and PZT system
  - De-bond using active PZT system
  - Bolt loosening detection using AE
  - Impact detection using AE
  - Crack growth using AE and PZT



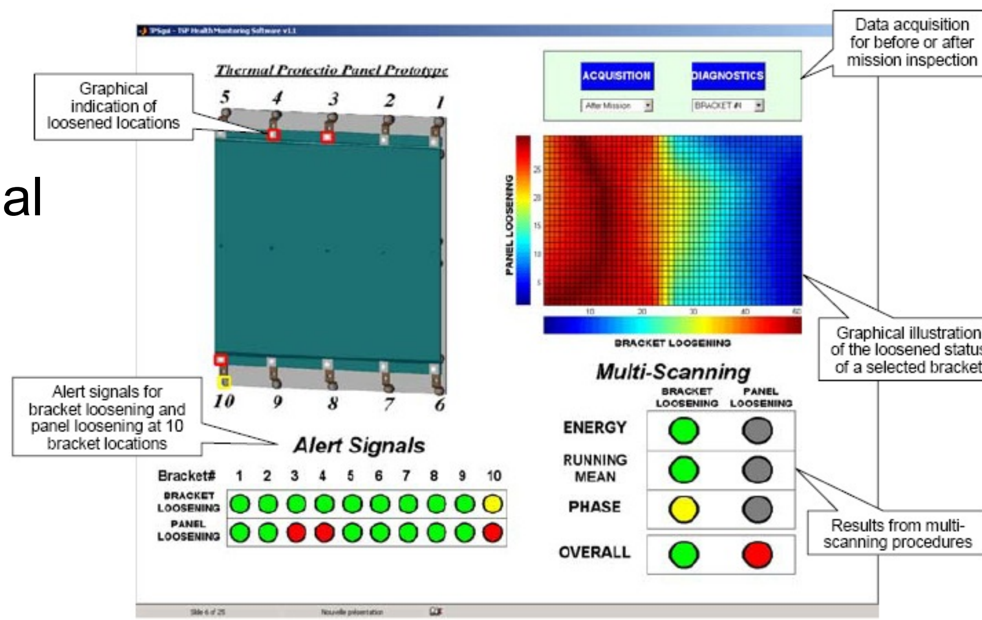
Structural Health Monitoring

- Determined critical area (mechanically attached TPS) to focus on to meet quick turnaround goals for a next generation space vehicle and downselected technology to attack that problem

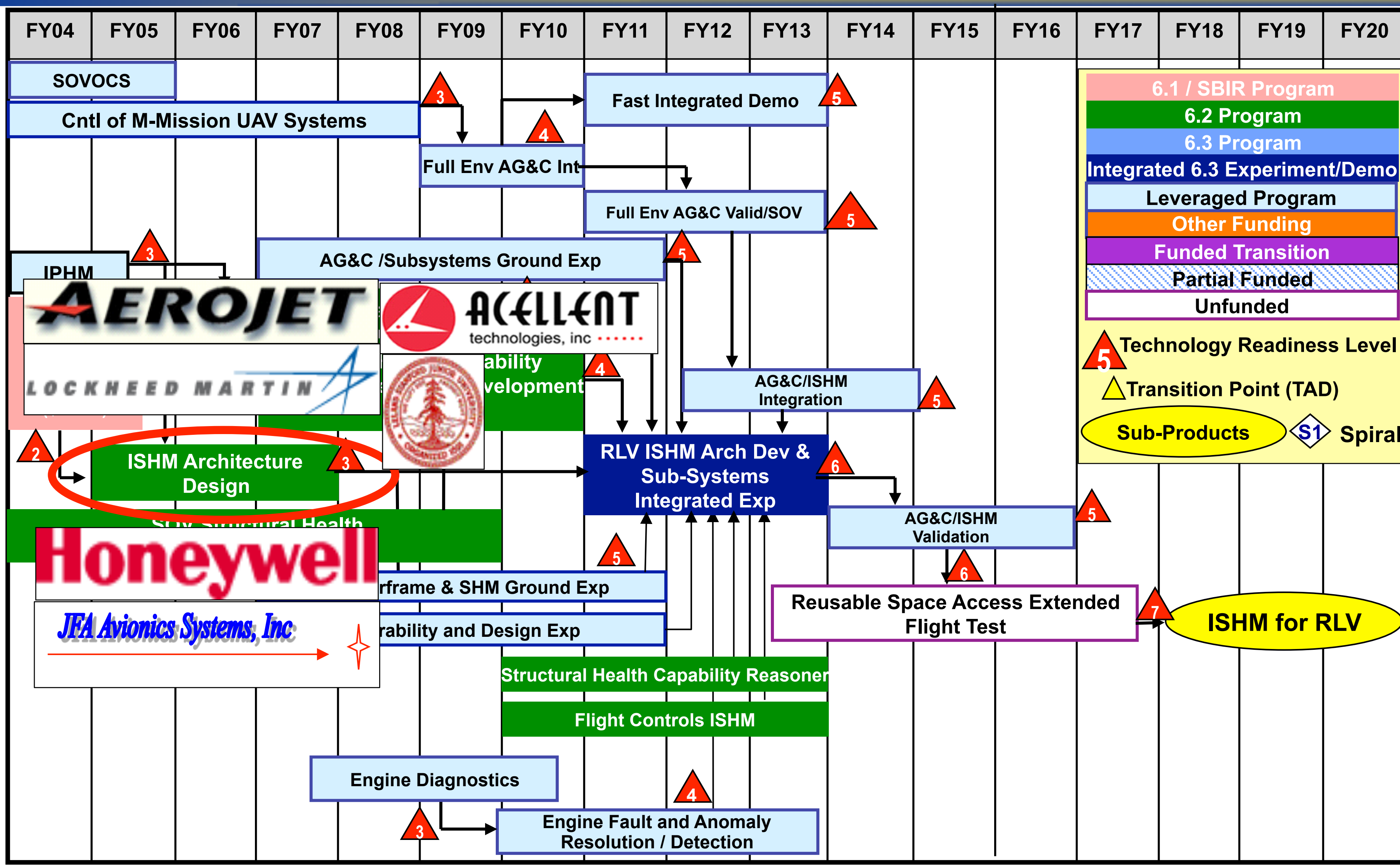


- Effective bolt/panel loosening damage detection method established for use in operational environment

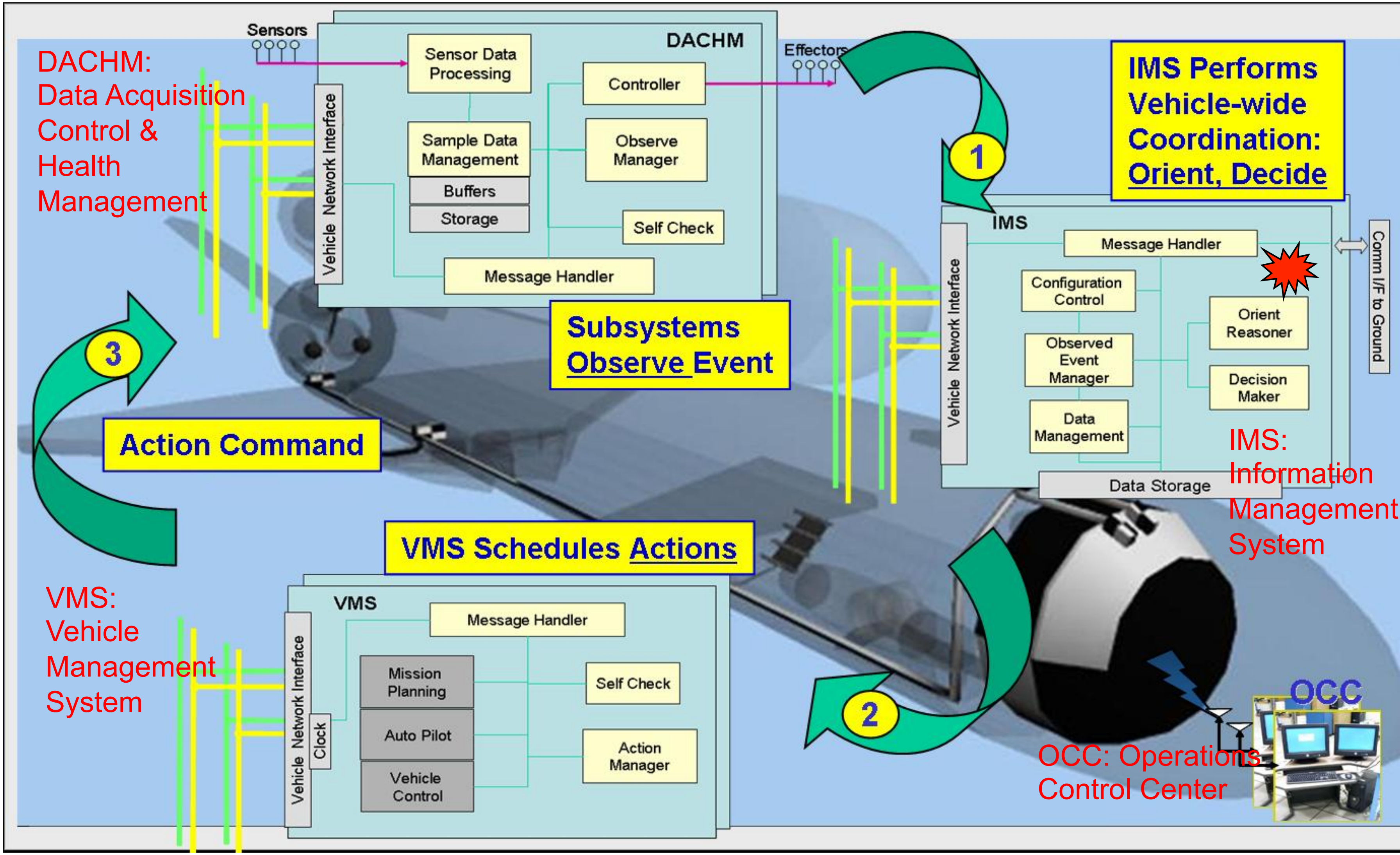
- Fed the ISHM Architecture program



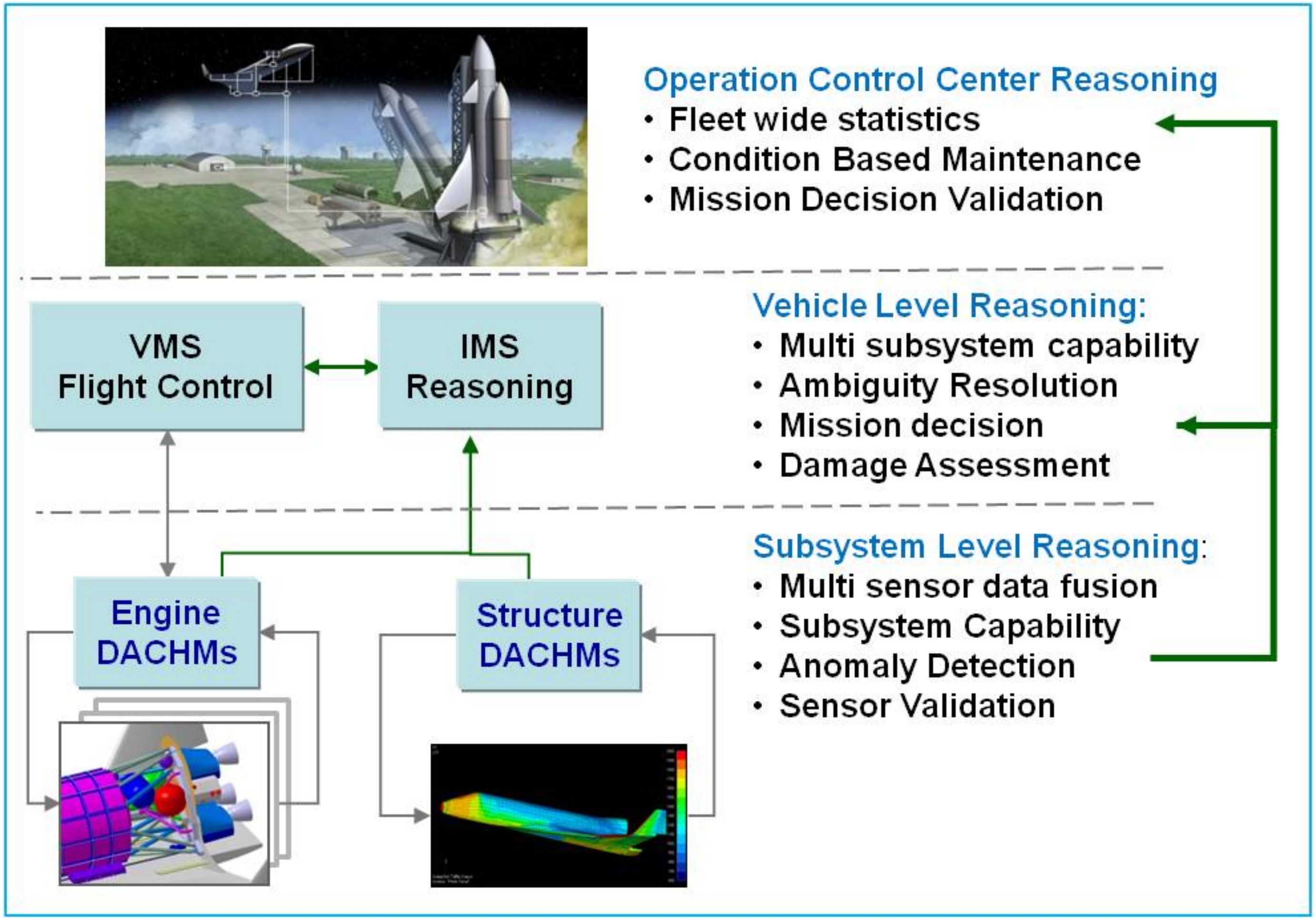
ISHM Architecture Design



Integrated System Health Management Architecture Design

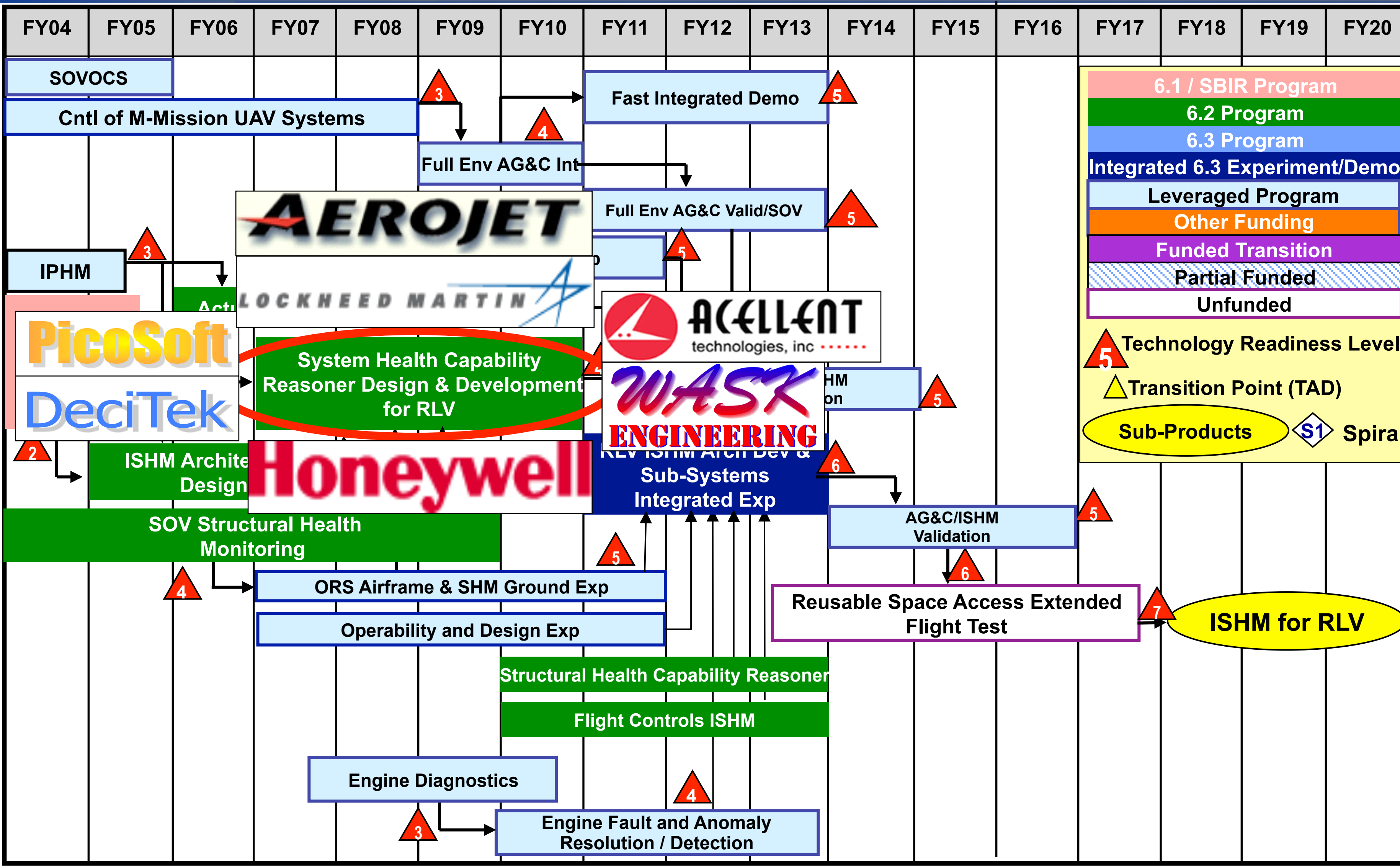


Benefits of ISHM Architecture

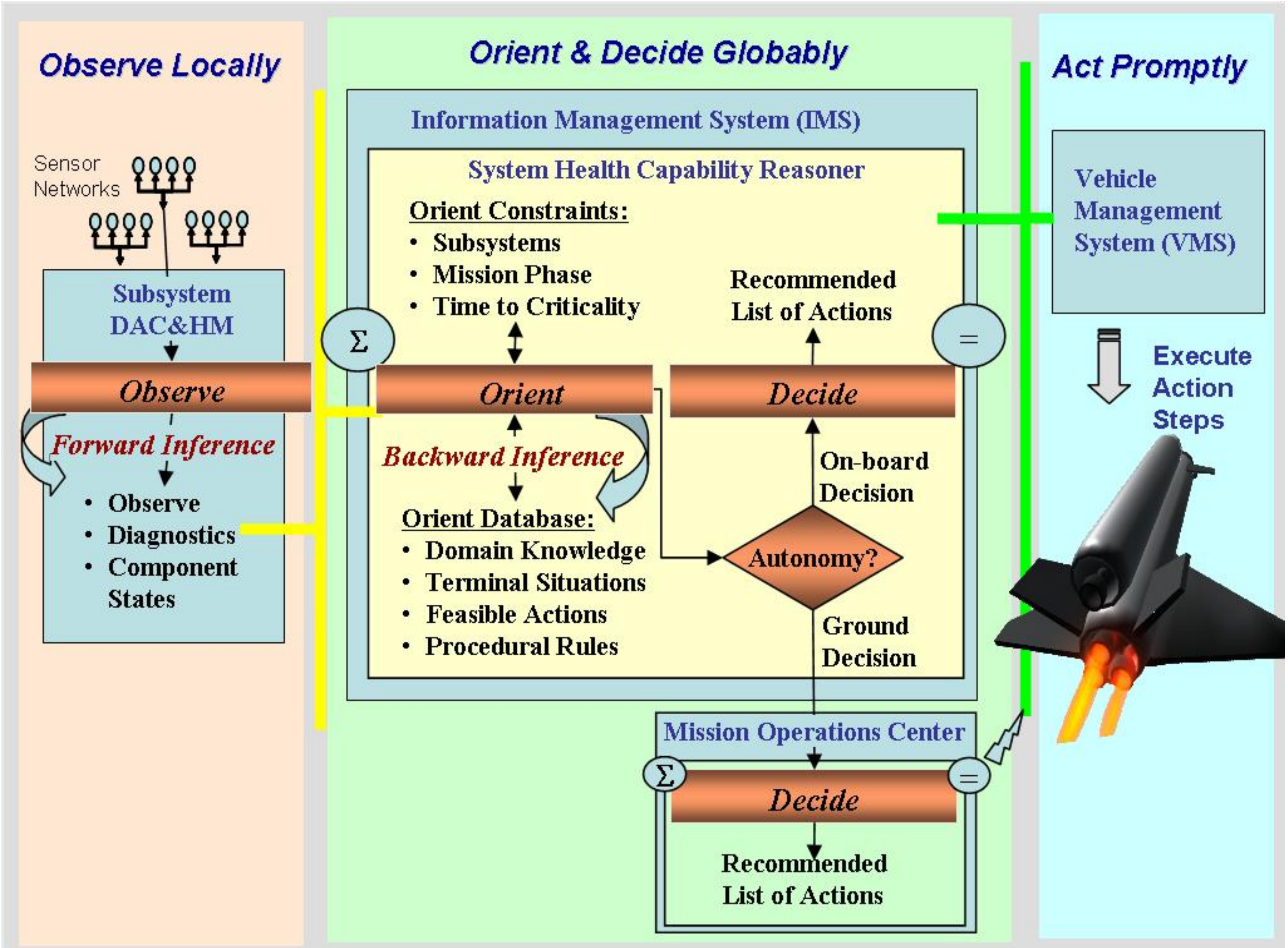


Minimize False Positives, Validation at All Levels, Provides Corroboration

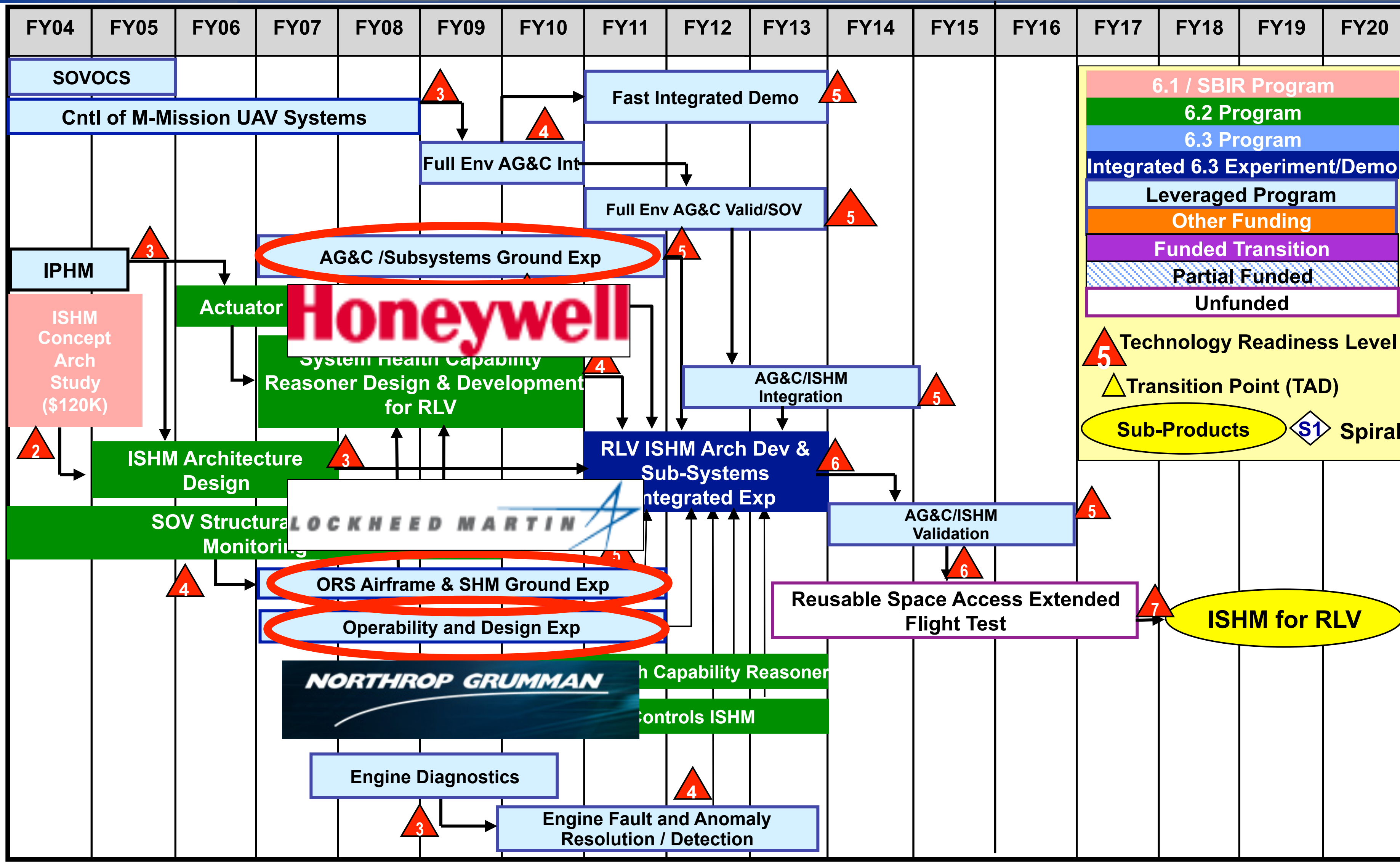
System Health Capability Design & Demonstration



System Health Capability Reasoner Design



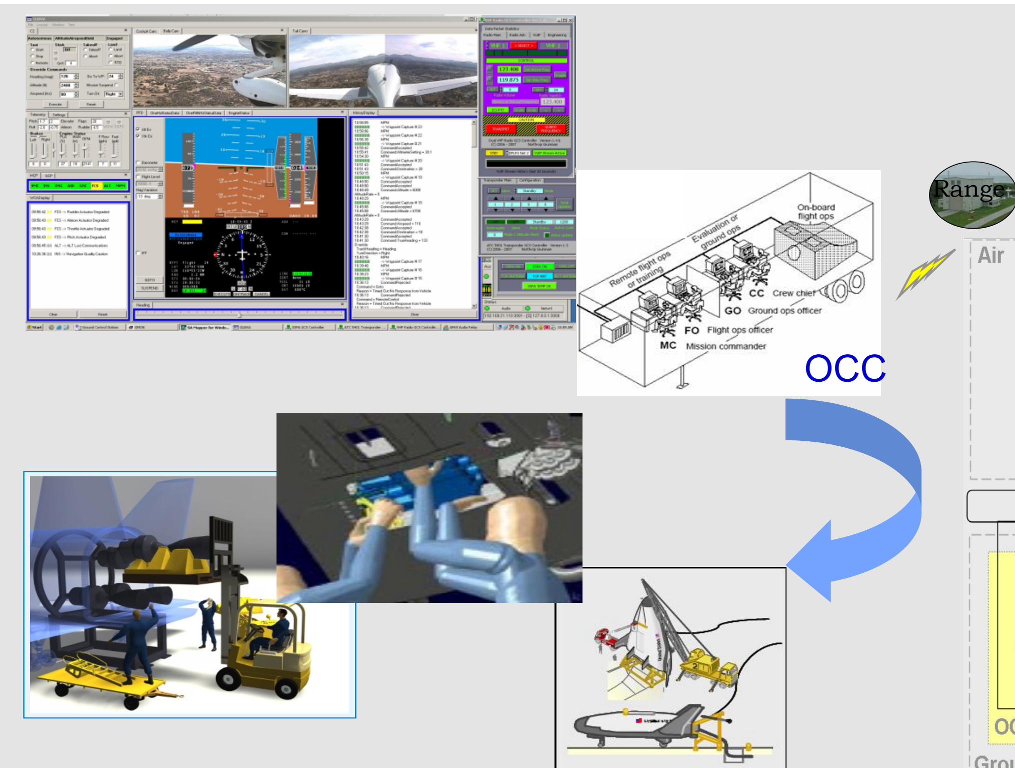
Fully-reusable Access to Space Technology (FAST)

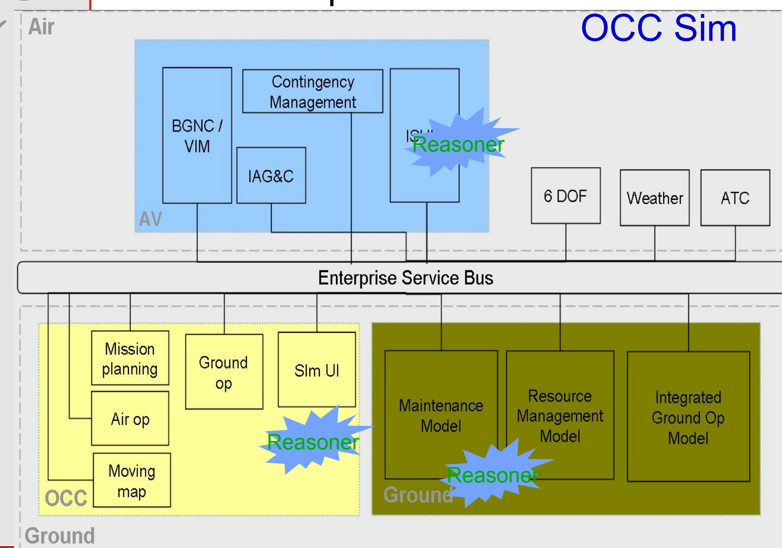


ISHM for FAST Operations and Control Center

ISHM Ground Functions:

- OCC Reasoner Module I/F with Air Vehicle to provide vehicle status
- Landing & Pre-launch Checkout
- Validates repaired LRU

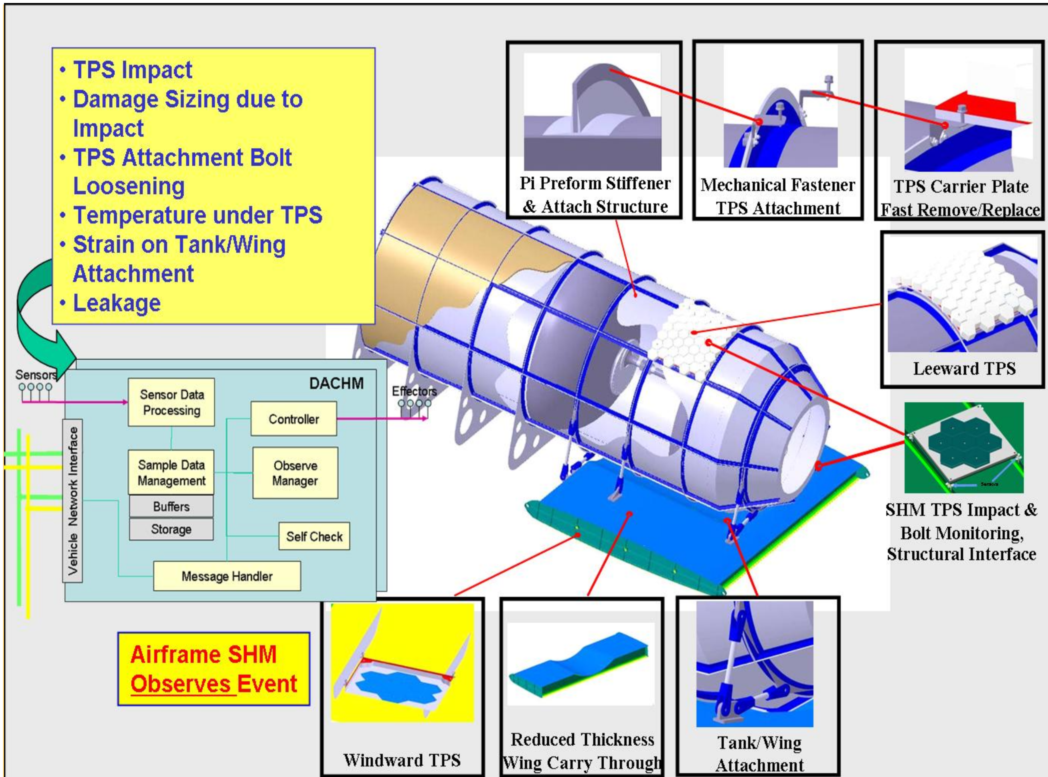




Description: ISHM is an active ground system during both flight & ground ops. As an OCC module, it provides subsystem status for display, gathers data to improve on-board algorithms, and relays maintenance information for vehicle repair. ISHM validates components during horizontal processing & performs pre-launch calibration & vehicle checkout.

CONOPS:
In-flight – on-board IMS sends vehicle health assessment, configuration status, events, and maintenance messages to OCC and receives commands back.
On-Ground – Reasoner provides status of each system being monitored by OCC. Participates in maintenance & checkout.

ISHM for FAST Structures Experiment



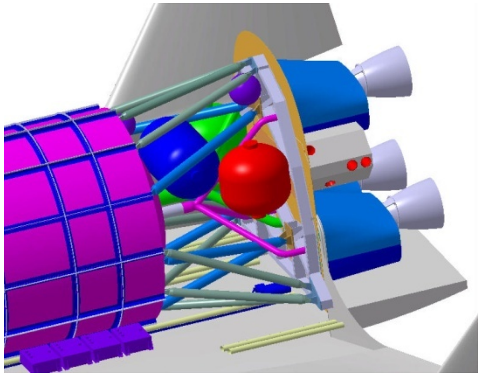
SHM Anomalies:
- TPS Impact & Damage Assessment
- Temperature under TPS
- Strain on Tank/Wing Attachments
- Tank Delamination/Cracking & Leaks

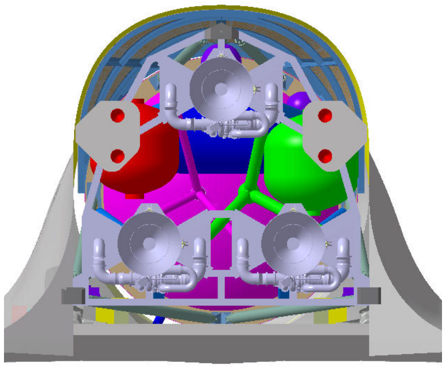
Stats:
- Sensors per DACHM: 16-256
- No. DACHMs: 2 for TPS (1 fore/1 aft), and 1 for tank and attachments
- Events: health status, detections with severity, sensor failure, calibration, TPS bolt loosening scan results
- No. samples per sensor: 100–400
- Processing speed: 50 ms – 500 ms
- Impact Sensor: 800 bytes at 25 KHz
- Bolt Sensor: 2* 8000 bytes at 40 MHz

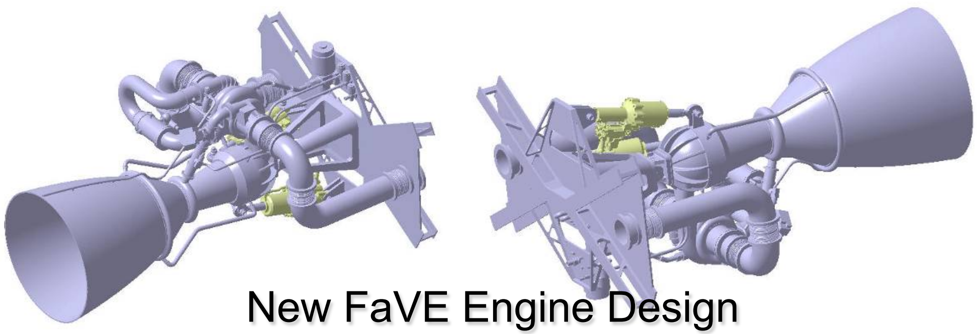
Description: SHM instrumentation to detect micro-cracking, delamination, and leaks in composite propellant tank, impacts and damage to TPS, and strain on structural attachments. Utilizes PZT sensors & SMART Layer strips -sensors/wiring in one, to minimize weight and volume and maximize coverage and detection.

CONOPS:
In-flight – detects faults and assesses damage for tanks, attachments, & TPS, reports to IMS, maintenance messages sent to OCC =>Ground Ops
On-Ground – remove & replace damaged TPS, re-scan to insure complete repair, re-calibrate sensors

ISHM for FAST Propulsion System







New FaVE Engine Design

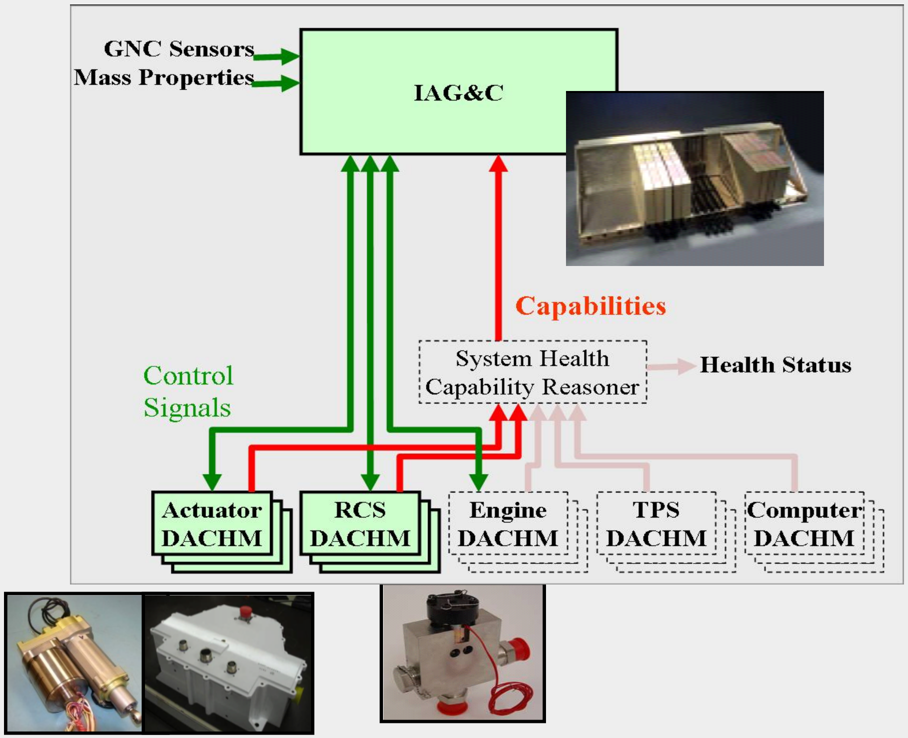
Description: Propulsion DACHMs acquire data from the engine sensors, digitize, condition, and validate all engine health and performance sensor signals. Engine Health Management (EHM) employs algorithms that determine engine status, detects faults, and determines corrective actions, consistent with OODA cycles. Interfaces to VMS & IMS.

Engine Anomalies:
- Fuel icing
- Foreign Object Debris (FOD)
- Stuck Thrust Control Valve
- Damaged bearing
- O-ring leak
- …

Stats:
- Sensors per DACHM: <64
- No. DACHMs: 1 per engine
- Events: health status, self-checks,
- anomaly detections –with severity & time to criticality, sensor failure, sensor calibration results
- Sample rates: 300 -8000 Hz
- Data rate: 42KBytes/sec

CONOPS:
In-flight – assesses health status, detects faults, takes action if autonomy authorized, reports to IMS, maintenance messages sent to OCC =>Ground Ops
On-Ground – remove & replace or perform pinpoint repair, utilize IMS to re-validate engine and perform self-check

ISHM for FAST Flight Control System



Anomalies:

- Aerodynamic surface effectors
  - Upper/lower position limits
  - Stuck/Free
  - Rate limit
  - Power and hinge moment limits
- RCS Stuck on/off
- Avionics - reconfiguration

Stats:

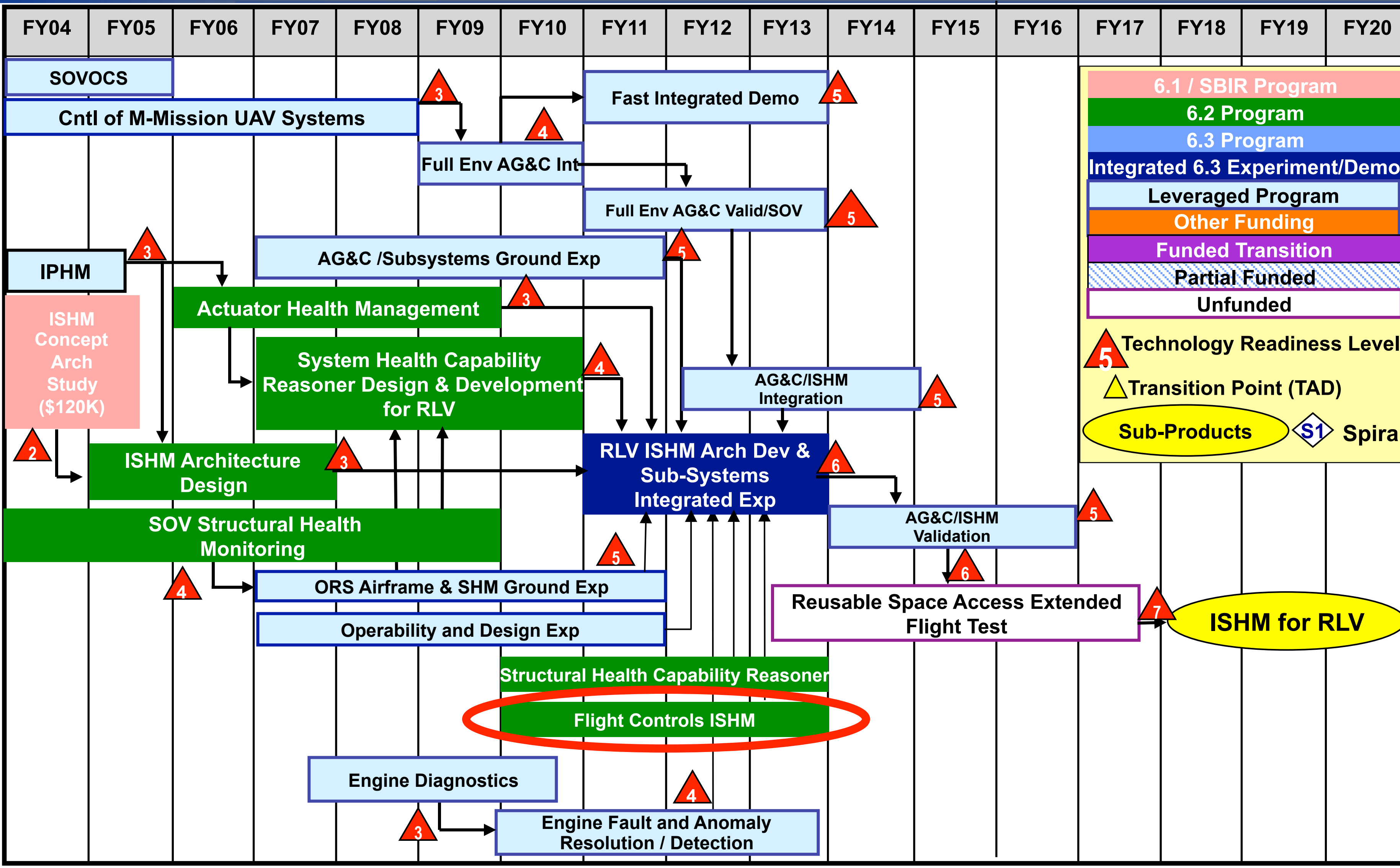
- No. DACHMs: x for Flt Actuators,
  x for RCS
  1 for Vehicle Avionics
- Events: health status, anomaly detections, sensor failure, calibration
- Sensors: TBD
- Processing: TBD

Description:
Integrated Adaptive Guidance & Control (IAG&C) responsible for Reconfiguration, Trajectory reshaping calculation, Footprint calculation, and Autonomous trajectory changes. IMS sends VMS/IAG&C vehicle health status, vehicle capabilities (effectors, RCS jets, propulsion, thermal, structure) & mitigations.

CONOPS:
In-flight – assesses status and detects faults for RCS, Flight Actuators, Avionics which are reported to IMS, maintenance messages sent to OCC =>Ground Ops
On-Ground – repairs directed to specific LRU problems, re-calibrate sensors, checkout to validate unit is operational

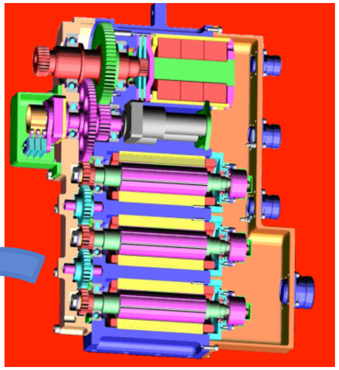
FAST ISHM Integration

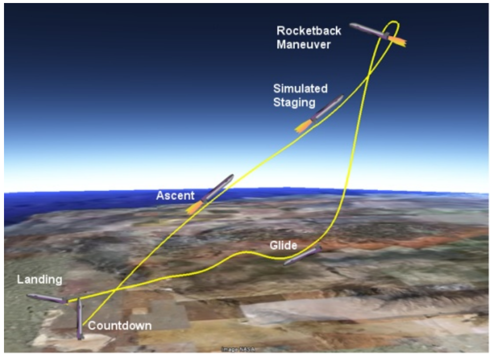
Flight Controls ISHM



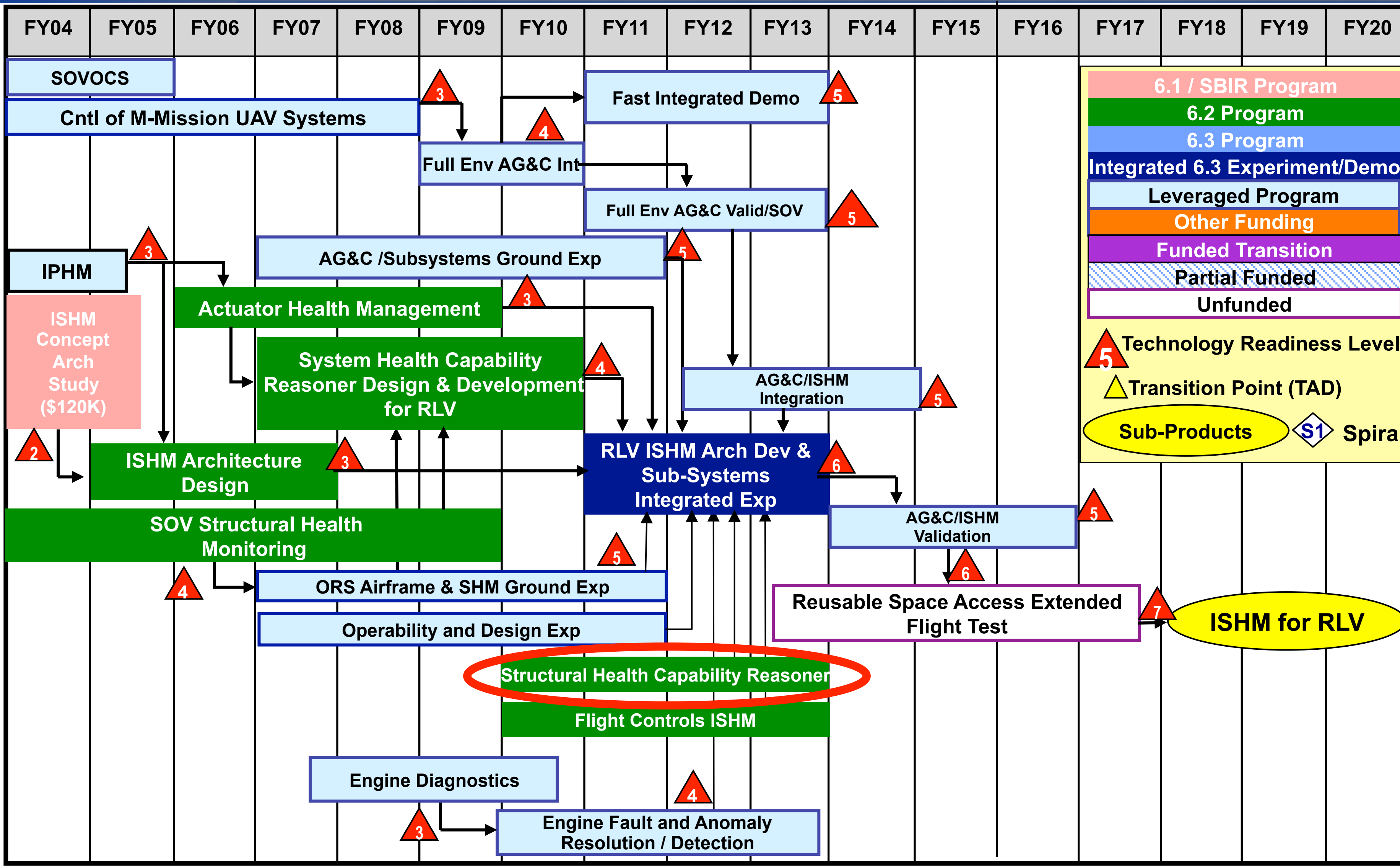
Flight Controls ISHM

- Determine current health capability of the flight control system through onboard, real-time analysis of sensor information
- Utilize diagnostic techniques to compute an estimation of current health capability
- Provide system health capability reasoner current flight control capability to enable determination of system health capability
- Ensure system integrity



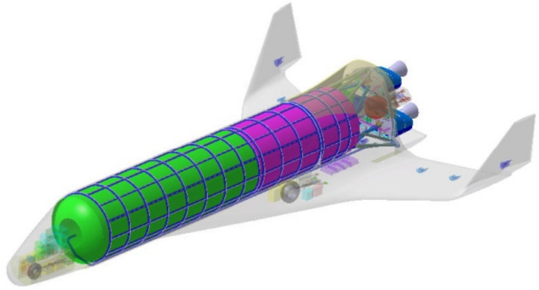


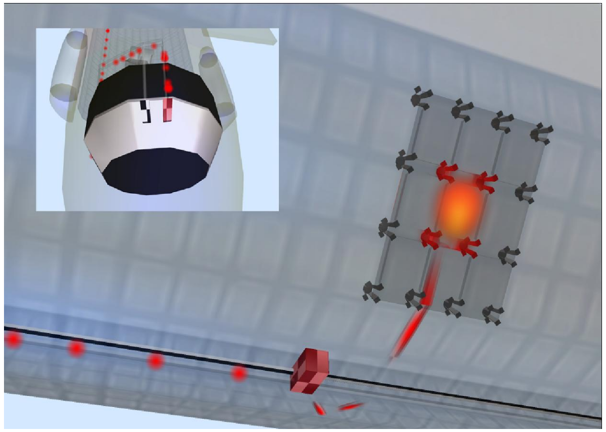
Structural Health Capability Reasoner



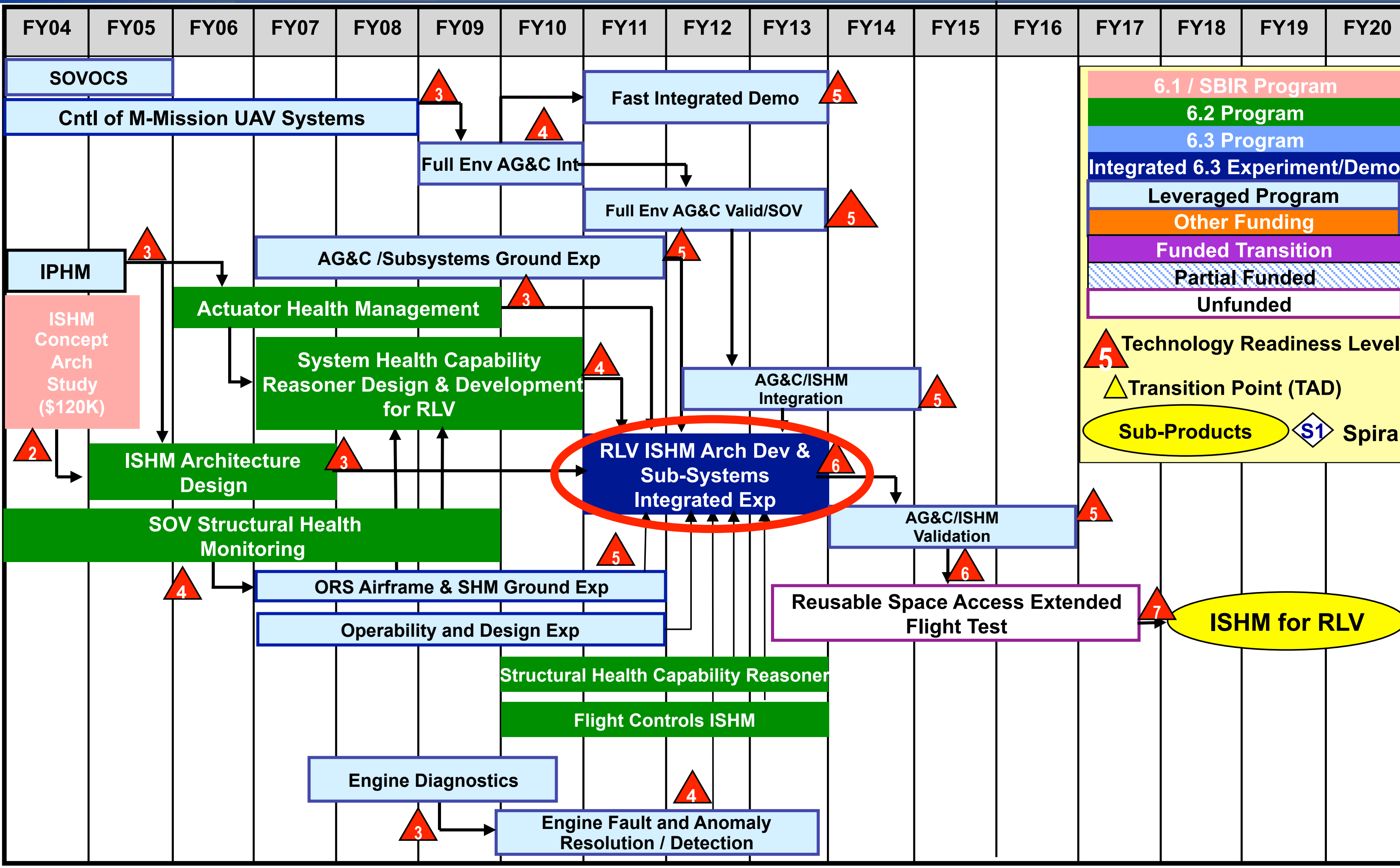
Structural Health Capability Reasoner

- Determine the current capability of an aircraft's structure through the onboard, real-time analysis of sensor information
- Utilize physics-based models and active & passive techniques to compute an estimation of current capability
- Provide system health capability reasoner current structural capability to enable determination of system health capability

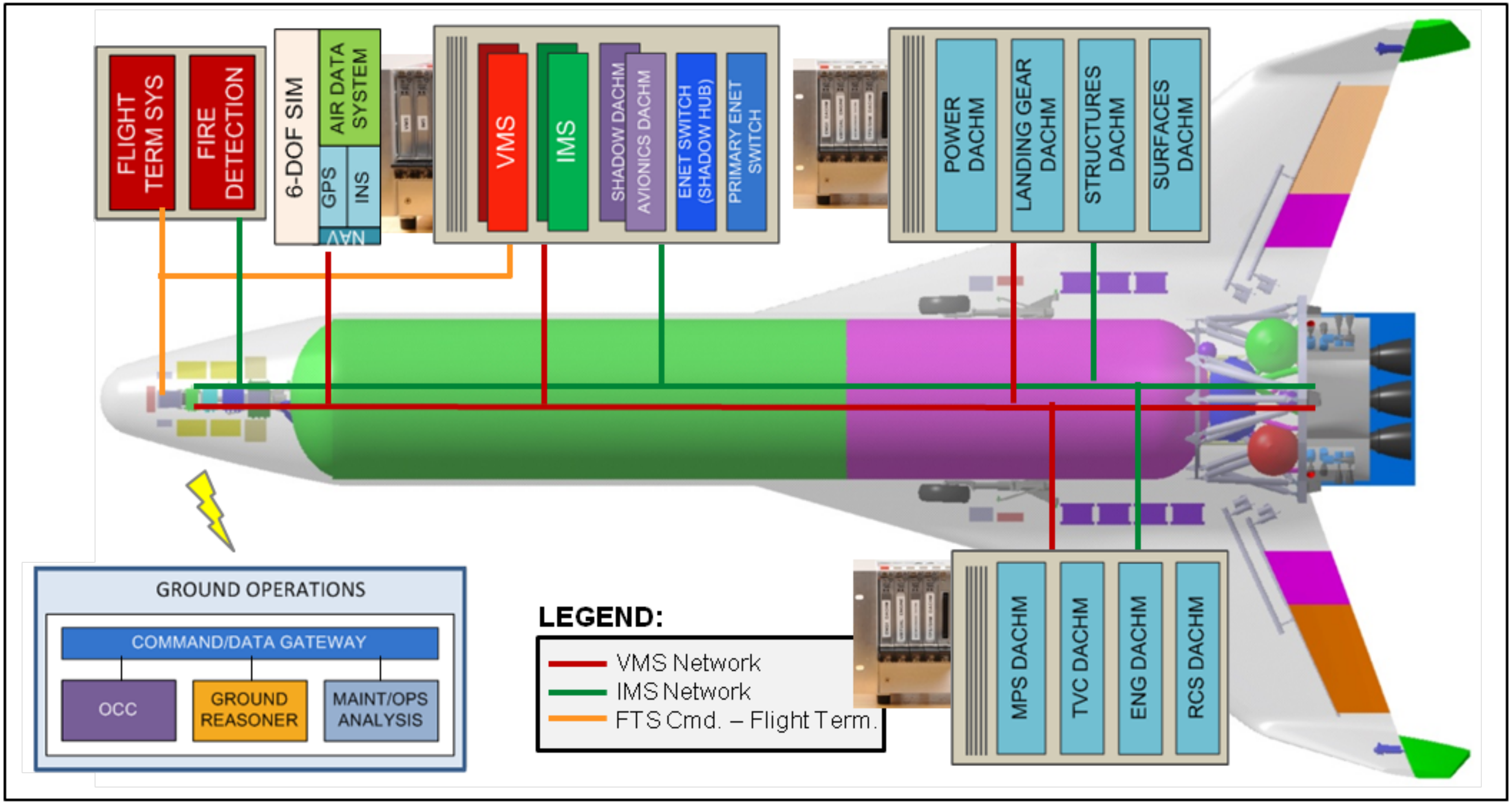




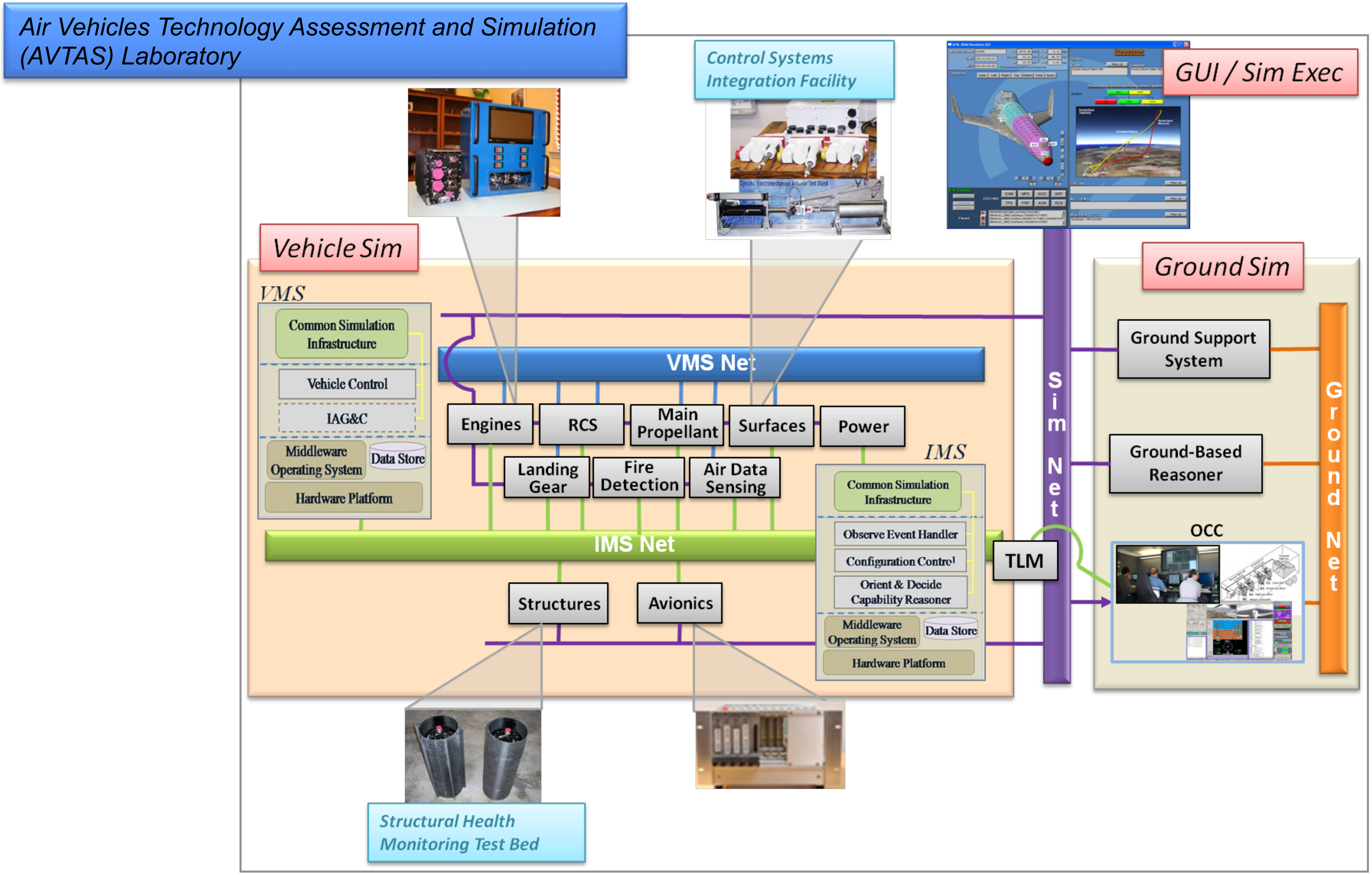
ISHM Integrated Subsystems Demonstration



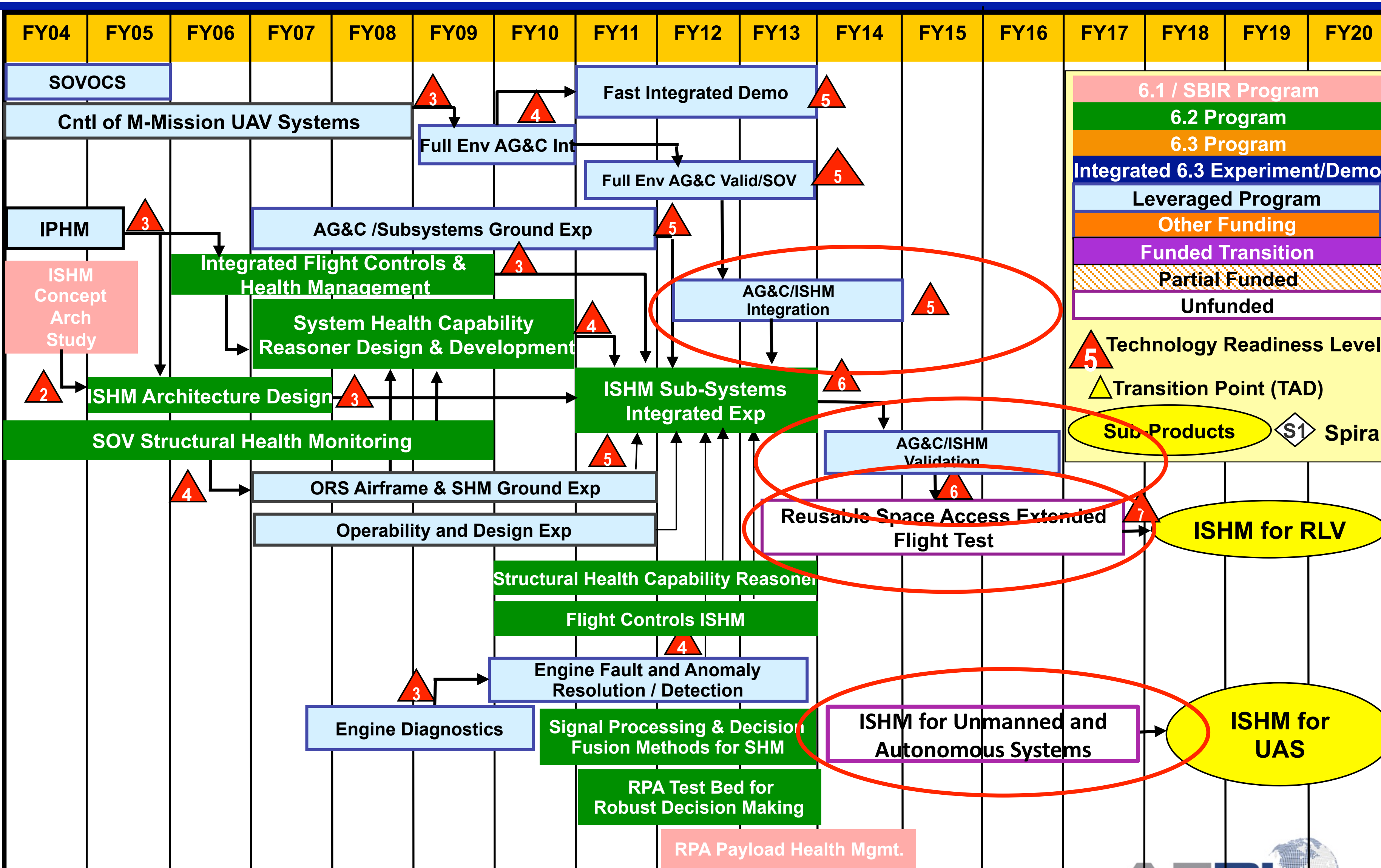
ISHM Simulation for FAST RFS



ISHM Laboratory



Integrated Systems Health Management (ISHM)



State Awareness & Real-time Response

	Now	Next	Future
Goals	**Failure Driven Reconfiguration: Flight control actuator state driving adaptive guidance and control (AG&C) for autonomous space access vehicles** • Finite set of failed control actuator states (e.g. stuck, floating, reduced bandwidth) • Inner-loop controllability and outer-loop trajectory planning adaptation under flight control health constraints • Defined requirements for complete system adaptation	**Degradation Driven Adaptation: Self state awareness of major subsystems driving AG&C and cooperation/teaming** • Real-time determination of system capability for engine, power, flight control, and structural subsystems • System capability assessment driving AG&C • System capability assessment feeding cooperative/collaborative control • Uncertainty of self state awareness assessments quantified	**Performance Driven Optimization: Comprehensive self state awareness driving efficient, effective operations and maintenance** • Fleet management based on individual systems' self state awareness • In situ characterization of and response to emergent behavior/unexpected states • Characterization of each system's unique response to environment • Prognosis feeding real-time response • Self state awareness feeding inner-loop control
Key Questions to be Answered	1. Are there sufficient control effectors to an off-nominal flight condition? 4. Can the algorithms be verified for real-time performance through simulated ground tests, supplemented by limited flight demonstrations? 5. What system state information is required for complete system adaptation by an autonomous space access vehicle?	1. Is there sufficient cost-benefit for 3. Can self state awareness be generated without adversely impacting size, weight, and power? 4. How will system reliability be impacted by added fault mitigation capability and resulting complexity? 5. To what extent can degradation be reliably incorporated into adaptation? 6. What is the cost-risk for V&V'ing the resulting system?	1. How will comprehensive state 4. How far can current and predicted system states be extrapolated to mission impacts and how should uncertainties be accommodated?

Future Research is Focused on Investigating Common Theories For ISHM