Earth Observations and the Role of UAVs:

Volume 3
Background Data

Version 1.1

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http://www.nasa.gov/centers/dryden/research/civuav/index.html

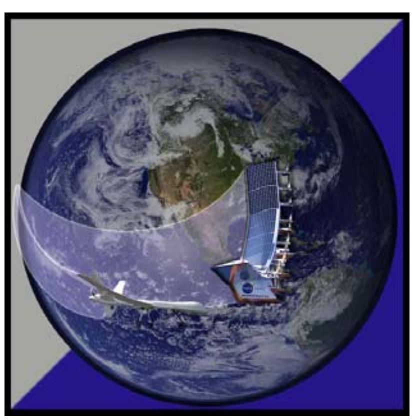

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Table of Contents

List of Appendices

List of Figures

List of Tables

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1. Introduction

This volume of the Assessment contains the completed templates from the Technology Working Groups (TWGs) and the technology peer reviews from the Universities Space Research Association (USRA). Also contained are the Executive Summary and the Final Report by the USRA By design, this volume will change with time as new assessments of the states-of-the-art for each of the technology areas change and as new technologies that have impacts on the UAV missions evolve. It is expected that the updates to this volume will occur periodically.

The Executive Summary of the USRA peer review will be followed by each of the technology area TWG templates as defined in Volumes 1 and 2. After each TWG input, the specific USRA peer review for that technology will follow. The USRA Final Report is contained as an addendum at the end of this volume.

2. Executive Summary (USRA Review)

In March 2006, the NASA Civil UAV Capabilities Assessment Team engaged the Universities Space Research Association (USRA) to initiate the Civil UAV Technology Review Project. This activity, implemented over the period from April – June 2006, enlisted thirty-six Subject Matter Experts (SMEs) proficient in the thirteen identified UAV Enabling Technologies, and the sixteen related notional Mission Capabilities. The participating SMEs provided not only an independent, peer-review and evaluation of the forty-three technology areas identified, but also an independent systems review across the technical disciplines involved in UAV/UAS missions.

The objective of the Review Project was to evaluate and comment on the platform capabilities and technologies required to support current and future Civil UAV missions, and to assist in providing foundations for development of a comprehensive Civil UAV Roadmap. Subject Matter Expert's (SMEs) from a broad spectrum of technical and systems disciplines from academia were engaged as part of this process. A two-step review approach was utilized, consisting of an initial UAV Enabling Technology Report Review and a subsequent integrated UAV Technology Panel.

2.1 SME Review Process

The SMEs were asked to review provided technology reports, and provide feedback in the following thirteen (13) criteria, providing strengths/weaknesses/comments for each:

- Technology Description
- State of the Technology
- Development of Enabling Technology
- Technology Dependencies
- Technology Forecast
- Technology Gaps
- Technology Cost Drivers
- Competing/Disruptive Technologies
- UAV Application Demonstrations
- Sources of Information
- Technology Capabilities
- Current Research (US/International)
- Regulatory/Security Issues

The six members of the Review Panel were convened as a working group, assembled to evaluate the NASA Enabling Technology Reports and the related SME reviews with the objectives of…

- Commenting on the technology reports & reviews, with respect to evaluation criteria;
- Identifying cross-cutting findings and recommendations across enabling technologies (related to Broad Area Technologies);
- Identify and track potential technologies that could revolutionize the capabilities of UAV systems and their applications;
- Recommending Civil UAV Enabling Technology area programmatic priorities;

- Establishing the engagement of the academic community as partner with NASA in the Civil UAV Capabilities Assessment.

2.2 Findings and Recommendations

Major findings and recommendations of the Technology Review Panel were as follows:

1. Establish a balance of 'Requirements Driven' technologies (needed to meet the anticipated reference mission set) with the identification of an 'Technology Opportunities' set, reflecting a complete approach to technology development and maturation, enabling new capabilities and/or missions that will provide a forecast of future mission opportunities.

2. Recommend an overall systems ('UAS') perspective (rather than UAV platform) to assure significant and cost effective enhancement to the overall capability of C-UAVs in order to execute the anticipated reference mission set.

3. Consider program investments in a systems context to fully assess the net impact of incorporating these enabling technologies into C-UAVs, ensuring the overall viability of their application as an integrated system, to assess their net cost/benefit, and to help steer the priorities of these investments.

4. Establish UAV mission requirements baseline(s) and capabilities traceability, and forecast future requirements through broad joint involvement of the academic, industry, and inter-government user communities.

5. Create a greater, general awareness (government, industry, academia) of the state-of-the-art across capabilities and enabling technologies.

6. UAS safety should be a considered a cross-cutting 'capability', and it includes the elements of Contingency Management/Collision Avoidance, UAS Reliability (Reliable Mission Systems), and the proactive influence on policy and regulatory issues.

7. Human Interfaces and factors are critical in the supervisory control of UAS (Intelligent Mission Management), and should be viewed as a cross-cutting element of the enabling technologies.

8. Establishment of standard interfaces (platform-to-payload) is critical to mission integration, operability, and ultimate success.

2.3 Summary of Project Results

The Civil UAV Technology Review Project affirmed the approach and methodology of the NASA Civil UAV Capabilities Assessment Initiative, offered constructive programmatic recommendations, and provided specific insights and references related to the Enabling Technologies presented. Summary Project results are identified as follows:

1. The results/findings of the Civil UAV Technology Review were assessed with respect to the NASA UAV Capabilities Assessment initiative.

2. The Civil UAV Mission Capabilities and Enabling Technology focus areas are sufficiently well-defined and interrelated to support the technology development objectives and requirements – providing guidance to the government, industry, and academic Research and Technology sectors.

3. The academic Subject Matter Experts (SMEs) provided an *initial* assessment of the state of the technology, and articulated the critical R&T challenges.

4. The role of Human Interface and related Factors cannot be overstressed in its importance with respect to Unmanned Aerial Systems.

5. A systems assessment process should be established to ensure the overall viability and return-on-investment for the various R&T in a systems context, and to help establish the overall priorities of these investments.

6. Based on a preliminary 'capabilities' and systems concept, and an assessment of the technology state of maturity, a national Roadmap which integrates the Civil UAV development efforts can be designed and implemented.

Detailed description, findings, and recommendations of this project are available in the Civil UAV Technology Review Project Report contained in the Appendix of this volume.

3. Technology Working Group Templates and USRA Review

The following sections present the data from Technology Working Group (TWG) efforts. As previously discussed in Appendix H of Part 2 this document (Earth Observations and the Role of UAVs – Appendices), there were two types of TWG templates: one for a status overview of a particular enabling technology, and one for supporting sub-component technology areas. Table 3.1 provides a convenient review of the actual Broad Enabling Technologies that were reviewed, with their associated Sub-level Technologies. The right column provides an overall list of the actual TWG templates that were provided by the SME's as part of the TWG process, and which were then provided to USRA for their subsequent review.

Following Table 3.1 are the actual TWG completed templates, listed in the order of broad enabling technologies. Immediately following each TWG Template is the associated USRA Review of that template, shown as a matrix summary of each template topic area.

Broad Enabling Technology	***Sub-level Technologies***	***Sub-sub-level Technologies***
Intelligent Data Handling & Ground Processing	Data Archiving & Dist.	Data Mining
	Computing	Real-time onboard processing
Network Centric Communication Systems	Overview	----------------
Navigation Accurate Systems	Micro-UAV NAV	Highly miniaturized, INS-based NAV
Intelligent Mission Management	Overview (v2)	----------------
	Outer Loop Control	Intelligent Outer Loop Control
Intelligent Vehicle System Monitoring	Overview	----------------
	Planning & Scheduling	IMM & ISHM Planning & Scheduling
	Software V&V	Access to NAS Certification
	Design	Design Tools
	Maintenance	Condition Based Maintenance
Contingency Management	Overview	----------------
Open Architecture	Overview	----------------
Payload Sensors	Active Optical	LIDAR
	Passive Optical	----------------
	Active Microwave	SAR & IFSAR
		Wind measurements in precipitation and cloud regions
	Passive Microwave	Light weight, low loss, antenna technology
	In-situ Sensors	Chem. Detection using laser diode spectroscopy
		Meteorological Data
		C02 detection using non-dispersed IR Analyzer

		C02 detection using a Quantum Cascade Laser Spectometer
		Trace gas detection using difference freq. generation lasers
		Trace gas detection using cavity-enhanced absortion spectroscopy
		Microsystems based Chemical Sensor Arrays
	Drop Sondes	Meteorological Sondes
Power & Propulsion	Regenerative Energy Storage	Lightweight Energy Storage using Regenerative Fuel Cells
		Low Volume, High Power Density Solid Oxide Fuel Cells
	Battery Technology	Long-life Rechargeable Batteries using Li-S Technology
	Consumable Fuel Cell	Electric Propulsion using H2-Air PEM Fuel Cells
	Propellent Storage & Feed System	Storage using Layered Silicate Clay Nonocomposites
		Cryogenic Storage using Densified Liquid Hydrogen
		Hydrogen Feed Systems
		H2 Gas Storage using Composite Overwrapped Pressure Vessels
		Lightweight Cryo Insulation using Polymer Crosslinked Aerogels
	Propulsion System	Internal Combustion
		High Pwr Density Propulsoin using High Temp. Superconductor Motors
Collision Avoidance	Overview	----------------
Over-the-Horizon Communication	Overview (v2)	----------------
	Enabling Technology	IRIDIUM L-Band LOE Satellite Constellation
	Enabling Technology	INMARSAT L-Band Broadband Global Arae Network
Reliable Flight Systems	Overview	----------------
Enhanced Structures	Overview	----------------

Table 3.1 - Matrix of the Technology Work Group's finished templates

3.1 Intelligent Data Handling & Ground Processing

3.1.1 Data Archiving and Distribution: Data Mining

- TWG Output

Enabling Technology:_Databases *Date:8 February 2006*

Specific Technology: Data Mining
Contributing Editor: Irving C. Statler
Phone: 650-960-6003 Fax:650-969-0477 Email: Irving.C.Statler@nasa.gov

Specific Technology Description:.A suite of statistical analysis tools that (1) extracts a “signature” for each digitally recorded parameter, (2) identifies and characterizes clusters of typical and atypical signatures using multivariate statistics and variance on each parameter, and (3) searches for differences among clusters. Potential applications to UAV operations include (1) automated identification of deviations from prescribed operations, (2) monitoring each sub-system for on-condition maintenance, and (3) automated identification of unexpected deviations from the norm.

Current State of the Technology:
The capability underlies the invention called Morning Report of Atypical Flights that continuously monitors an airline’s flight-recorded data for the unexpected. Each morning, Morning Report produces a list of atypical flights in the previous day’s operations compared with the previous comparable 1000 flights. Morning Report has been patented by NASA and licensed to a vendor. It is expected to be offered as an added capability to the vendor’s current product for analyzing flight-recorded data.

Identify funded programs that contribute to the development of this specific technology:
The Morning Report of Atypical Flights was developed and fully funded under NASA’s Aviation Safety Program. It evolved through tests and evaluations performed under no-reimbursable Space Act Agreements with several air carriers and their supporting vendors.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
While this is a mature technology, there are further developments that are likely to make it more useful to UAV applications. MR was developed to support strategic decisions. It could be improved to real-time capability to support tactical decisions. MR was developed to analyze continuous parameters (e.g., speed, altitude, rate of climb, etc). A similar capability for analyzing discrete parameters (e.g., control and switch positions in the cockpit) and correlating with the continuous parameters of air craft operation is need and has been demonstrated at a low TRL. Automated linkage of complementary information extracted from digital data and from textual data is needed and has been demonstrated at a low TRL. For application to UAV, for example, this could enable relating an identified atypical operation of a sub-system to the on-board maintenance logs and maintenance manuals for causal analysis and recommended intervention.

Identify funded programs that contribute to the development of the critical supporting technology:
Current related activities are being funded under several of the thrusts of NASA’s Aviation Safety Program, e.g. Integrated System Health Management, and Integrated Intelligent Flight Deck,

Forecast of specific technology:
The additional capabilities needing further development described above have been demonstrated at low TRL. They could all be ready as prototypes for operation test and evaluation within two years with adequate funding and could be operational within two years after that. This forecast is based on the experience in developing the MR and the state of the art of the enhancements that have been demonstrated.

Specific Technology Cost Drivers:
In development, the cost driver will be developing the algorithms for real-time analysis, implementing them in software, and testing them in operational environments. Operating cost driver will be the domain expert to utilize the presented information for strategic or tactical decisions.

Known competing or disruptive technologies:
There is no other technology that would be considered disruptive to the implementation of these capabilities. There are, of course, many other statistical techniques for analyzing numerical and textual data that might be viewed as competitive**.**

Major Events/Milestones:

	2006	2007	2008	2009	2010

Event:
[NOTE: This is so dependent on the available funding, that I choose not to address it beyond what I have stated previously about time to bring to operational capability.]
Demonstrated for UAV application?:
It depends on which application; strategic-decision support, tactical-decision support, flight operations, maintenance, etc.

Technology Assessment – Resource & Research Summary

Known sources of information:

The Human Factors Research and Technology Division and the Computational Sciences Division at the NASA Ames Research Center and the Pacific Northwest Division of Battelle Memorial Institute have been responsible for developing the Morning Report and for its underlying scientific developments.

Capabilities (must have, etc.): Domain knowledge, statistical analysis, natural language processing, computational sciences, information technology, visualization of information,

Research being done: A little continuing research is likely to be supported out of activities under the current Aviation Safety Program.

Regulatory/security issues? ITAR: None, although there may be concerns about protection of proprietary data.

Non-US efforts: High interest, but little advanced development.

List Any Assumptions:

- USRA Analysis

1. Technology Description

The subject area (Digital Signature extraction, identification, and characterization) is important and vital to the success of the mission;however, the focus seems somewhat limited as data classification and feature extraction, for example, could possibly be targets of the Data Mining Technology.

Potential Applications (1) and (3) appear to be similar in content - distinction confusing.

2. State of the Technology

The NASA-patented "Morning Report" can be of great assistance in the early detection and prevention of faults in a flight system. However, It is not clear what the shortcomings of the 'Morning Reports' are. How fast the data can be analyzed? How reliable is the analysis? What are the aspects that need improvement and should be addressed? Therefore, commenting on the “State” of the Technology as described is uncertain.

3. Enabling Technology Development	The contributing units have been described clearly.
4. Technology Dependencies	The needed improvements are described concisely. In case of real-time processing of data for tactical decisions, a mechanism should also be adopted to send the system to a fail-safe state in case of errors. Real-time processing of MR poses many challenges and is more involved (compared to addressing discrete parameters). Much work is needed to bring the implementation to a satisfactory TRL.
5. Technology Forecast	The time period of two years seems reasonable.
6. Technology Gaps	Not addressed.
7. Technology Cost Drivers	Yes, the cost drivers will be program development for analysis, interpretation, and determination of the new course based on the outcome.
8. Competing Technologies	It is not clear specifically what statistical techniques will be used in the current technology.
9. UAV Application Demonstrations	Not addressed; various applications mentioned, but question not specifically addressed.
10. Sources of Information	Factual, related to NASA 'Morning Report'.
11. Technology Capabilities	Some areas mentioned (e.g., information technology) are extremely broad.
12. Current Research	Discussion limited to limited to NASA Aviation Safety
13. Regulatory Issues	Potential proprietary issues

3.1.2 Computing: Real-time Onboard Processing

- TWG Output

Enabling Technology: Intelligent Data Handling *Date: 2/13/06*

Specific Technology: Real-time on-board processing systems
Contributing Editor: Jeff Myers

Phone: 650-604-3598 Fax: -4987 e-mail: jmyers@mail.arc.nasa.gov

Specific Technology Description:
The need for real-time processing of sensor data on-board a UAV is driven by several factors. Imaging devices in particular can produce many gigabytes of data on a single mission. Because the onboard telemetry systems have limited bandwidth, which must be allocated between the aircraft flight control function and multiple payload elements, it may not be practical to transmit all of the data off the platform. Some degree of higher level data processing is therefore needed to reduce the volume of data for transmission, enabling both real-time analyses on the ground, as well as to ensure some level of data capture in the event that the platform is lost.

Current State of the Technology:
Some level of on board data processing is performed on the satellites of the NASA EOS system, however the actual content of the measurements is typically not altered, hence the overall volume is not significantly reduced. This is based on the theory that the basic Level-0 data products coming down from the platform may need to be re-processed multiple times, with evolving algorithms, to maximize the science value of the data. The UAVs have the advantage that the Level-0 mission data can still be recorded on board, and thus be available for post-flight re-processing, while Level-1 or -2 products can be produced in real-time on-board and down-linked using the best current algorithms. The hardware required for real-time digital data processing is mature, typically involving some mixture of Field Programmable Gate Arrays (FPGAs,) Digital Signal Processors (DSPs,) and fast CPUs. This may be considered at TRL 9 for most Earth science applications. The customized firmware and software however will need to be developed for specific applications, notes on which follow:

- Data Compression: Applies mainly to imagery. There are several new state-of-the-art wavelet compression transforms, including JPG2000, and region-of-interest (ROI) algorithms that offer high fidelity image compression, which is critical to the science application. The ROI techniques automatically determine the areas of greatest interest (based on pre-defined rules) and then selectively compress the data. This technique is in the TRL 3 range, with work ongoing at several universities; JPG2000 is now operationally available. For the real-time application, these algorithms are best implemented in hardware (e.g. on FPGAs.)
- Image geo-rectification and co-registration: The mathematics of geo-correction is well understood, however the operation is usually undertaken post-flight. For the real-time application, this would be best implemented in on-board hardware, as it is computationally very intensive, and requires a digital elevation model (DEM) of the area to be pre-loaded into the system. The algorithm must also be tailored to the individual geometry ("camera model") of each particular sensor. (TRL 5 – 6)
- Precision navigation/location is a mature technology, involving a combination of Inertial Measurement Units (IMUs) or gyro technologies for platform attitude, and GPS systems for location. The highest accuracies are obtained by expensive aircraft-grade IMUs and real-time differential GPS systems. Some airborne sensors capture the navigation data from the aircraft flight control system; however this approach has some inherent sources of error (time latency, airframe flexure, sampling rate incompatibility, etc.) A more accurate approach is to embed the attitude and position hardware within the sensor optics, and sample and ingest the ensuing data coincident with the imagery itself. This approach is in use on several NASA systems, but currently requires post-processing. Although several commercial digital camera systems (e.g. Applannix) are using this technique in a manned-application (TRL-9,) the autonomous real-time implementation is closer to TRL 5 (the NASA AMS line-scanner system (Autonomous Modular Sensor) being one example.)
- Real-time on-board processing: The hardware itself for this is available, however a significant stand-alone implementation for the UAV application (at least in the un-classified domain) is not known by this writer beyond those mentioned above.
- Software architecture: The need exists for generic and universal hardware/software systems that can easily accommodate new payloads, sensor types, processing algorithms, and data handling/data understanding requirements.

Identify funded programs that contribute to the development of this specific technology

Most UAV-related on-board processing development appears to be inside the Defense community. The NASA Science Applications and Suborbital Science Programs have funded some development in this area, with some overlap with the Intelligent Mission Management programs of the Aeronautics Directorate. An initial implementation of these technologies will be tested on the NASA Western States Fire mission with the Altair platform in 3Q 2006.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

The primary need appears to be for integrated hardware and software development, directed towards the requirements of the autonomous UAV environment. Packaging of commercially-available hardware components to survive the high-altitude, un-pressurized environment has been demonstrated, however custom engineering is typically required. The development of generic, programmable processing systems, utilizing standard commercial interface protocols that can support a variety of missions and sensor suites, appears to be indicated.

Identify funded programs that contribute to the development of the critical supporting technology:

See funding note above.

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

The timeline for the maturity of these concepts is directly related to available R&D funding. As this constitutes primarily the integration of existing hardware technologies, and related software development, powerful on-board computing systems could be fielded within about two-years, with an initial suite of mission-specific software (with TRLs progressing from 3-4 to 7 -8.)

Specific Technology Cost Drivers: *Operating and development costs.*

Costs to develop these capabilities are not thought to be high, as the effort involves mainly integration of existing technologies, together with some software development. An ROM estimate to produce a prototype UAV mission computer module, including the ingest of precision navigation data, and deploying image geo-rectification and data compression algorithms, is about $3M.

Known competing or disruptive technologies:

No known.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

TBD, based on available R&D funding

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:
Dr. Joe Boardman, Analytical Imaging and Geophysics (Geo-Rectification, Precision Navigation Systems)
Robert Green, JPL (Geo-Rectification)
Dr. Roberto Manducci, Univ. Calif. Santa Cruz (Data Compression Algorithms)
Don Sullivan, NASA Ames (Data Compression Algorithms, Software Architecture & Algorithms)
Dr. Edward Hildum, NASA Ames UARC (Real-time Processors, Precision Navigation Systems)

Research being done:

NASA Western States UAV Fire Mission (Vincent Ambrosia, P.I., REASON-CAN with USFS)

Regulatory/security issues? ITAR:

- USRA Analysis

1. Technology Description

A much needed technology for UAV design is high-density embedded computing and communications. UAVs rely on two approaches to implementing flights - autonomy and pilot-in-the-loop - which rely predominantly on microprocessor and communication (data link) technology, respectively. And while both are used in differing levels in all of today's fielded UAVs, those together are what compensate for the absence of an onboard pilot and thus enable unmanned flight. Advances in both depend on commercial markets, the PC industry for microprocessors and memory - just as embedded computers such as VME and Compact PCI do - and the wireless communication industry for data protection and compression.

2. State of the Technology

Airborne data link rates and processor speeds both contribute to enable future UAV capabilities. Today, the idea is to relay almost all airborne data to the ground and process it there for interpretation and decision making. But eventually, onboard processing power will dominate data link capabilities and allow UAVs to relay results to the ground for decision making. Thus, the requirement for data link rates in certain applications, particularly imagery collection, should drop significantly. Data compression will remain relevant as long as band-limited communications exist, but it is unlikely compression algorithms alone will solve the near-term bandwidth requirements of advanced sensors. Airborne optical data links (lasercom) will potentially offer data rates two to five orders of magnitude greater than those of the best future RF systems. However, lasercom data rates have held steady for two decades because their key technical challenges were adequate pointing, acquisition, and tracking (PAT) technology to ensure the laser link was both acquired and maintained.

Even though today's processors allow UAVs to fly entire missions with little or no human intervention, if the ultimate goal is to implement superior processing speed, memory capacity, and responses (algorithms) gained from training and experience, then processors with human-like speed, memory, and situational adaptability are necessary. Human capabilities are generally agreed to equate to 100 million Mips in speed and 100 million Mbytes in memory. Today's supercomputers are probably within one or two orders of magnitude of achieving human equivalence in speed and capacity and could achieve the required performance in the next 10 to 15 years.

3. Enabling Technology Development

Suspect that there are projects performed by the private sector with goals similar (if not identical) to those of the Technology as described. A concerted effort to transfer the existing knowledge and technologies will prove effective in improving the technology readiness.

4. Technology Dependencies

Custom engineering is the key as most existing relevant technologies have not been designed to work in the UAV environment.

5. Technology Forecast

To reach the maturity as stated in both data link and processing technologies, a period of 3 to 5 years is anticipated (especially for software development).

6. Technology Gaps

Not specifically addressed, but should review Software Development, Processing and Memory Requirements, RF Systems vs. Optical Data Links for Communication.

7. Technology Cost Drivers	Appears realistic, and the integration of existing technologies and additional software development efforts are highlighted.
8. Competing Technologies	Analogous applications could have been characterized.
9. UAV Application Demonstrations	Not addressed; general demonstration framework would have been helpful.
10. Sources of Information	
11. Technology Capabilities	Not addressed.
12. Current Research	Current Research can be summarized as follows: Push for low-power low-weight on-board embedded and reconfigurable processors; Embedded Supercomputers; Techniques to eliminate human/pilot interventions and migrate control/monitoring tasks from ground to the craft.
13. Regulatory Issues	Not addressed.

3.2 Network Centric Communications Systems

3.2.1 Overview

- TWG Output

Enabling Technology: Network Centric Communication Systems

Contributing Editor: Dr. Ivan Somers, and David Fratello (in lieu of other inputs) ***Date: 3/23/06***

Phone: **Fax:** **Email:**

Enabling Technology Description:
Net-centric communications is an information-enabled concept of operations that exploits advanced technology to move from an application centric to a data-centric paradigm – that is, to provide users with the ability to access applications and services through Web services – an information environment comprised of interoperable computing and communication components.
This approach generates increased situational awareness and mission robustness by networking sensors, decision-makers, and researchers to achieve shared awareness, increased speed of command and control, greater mission success and focus.
A net-centric information environment utilizes emerging standards and technologies to optimize information sharing among all users. It results from implementing component architectures in accordance with the open system architecture.

Current State of the Technology:

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Forecast of enabling technology:

Identify and articulate any technology gaps discovered:

Enabling Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Technology Assessment – Resource & Research Summary

No information provided.

- USRA Analysis

1. Technology Description	Good *general* definition of network centric concept, but fails to address UAV specific issues. No real discussion of network centric efforts by NASA, DoD, and contractors who are very active in this area and working programs that the UAV efforts can leverage. Communications will drive UAV applications. Whether one has a centralized command structure, or decentralized cooperation between multiple UAV's, communications assumes critical importance. To facilitate successful development net-centric communication must be integrated with command and control strategies.
2. State of the Technology	Not addressed; should consult technologies developed within the context of ad hoc and sensor networks, with emphasis on issues such as medium access control, synchronization etc. These do not go far enough to meet UAV requirements, but provide insights. The assessment mentions "emerging standards and technologies", and these should also be outlined here.
3. Enabling Technology Development	Not addressed; misses significant DARPA-funded research. Need to address academic research in this area. Information networking is a very broad area of wide interest to government and industry. A few key projects should be outlined here.
4. Technology Dependencies	Not addressed; there is much more to this than just regulatory development. The technological challenges are very substantial. Comments on how the local and remote station operations interact should be included here.
5. Technology Forecast	Not addressed; address integrating communications with other mission oriented tasks. There are government and industry applications where networking has been employed. Comparisons to a few programs should be included here. Unlike a lot of the UAV development, simulations could effectively be used here and the lack of access to NAS shouldn't be as much of an issue here.
6. Technology Gaps	Not addressed; this application will likely require new networking standards to be developed. Discussion on mission protocol(s) should be included here.
7. Technology Cost Drivers	Not addressed; open architecture systems are probably going to be the most cost effective for development and expansion.
8. Competing Technologies	Not addressed; one potential competing technology are existing communication protocols. These are not naturally designed for integration of controls and communications in cooperative collision Avoidance tasks. Protocols dedicated toward this are needed, but the temptation to implement off-the-shelf protocols may be persuasive. Discussion of existing networks and network security issues should be addressed here.

9. UAV Application Demonstrations	Not addressed; there are probably some existing applications that could be referenced here - suggest consult DARPA and DoD funding agencies. Doubt that existing systems utilize the advance capability outlined in the technology description of the assessment.
10. Sources of Information	Not addressed
11. Technology Capabilities	Not addressed; for single UAV's confronted with unexpected circumstances, adaptive control techniques must be developed. For cooperative UAV's the science and technology of cooperation must be developed. A tight integration of communications, computing, signal processing, and control issues is needed.
12. Current Research	Not addressed; academic research, dedicated both to acquiring a fundamental understanding of the issues noted in Tech Capabiliites, and developing technologies toward them, is ongoing. Numerous networking projects could also be referenced here.
13. Regulatory Issues	Not addressed.

3.3 Navigation Accurate Systems

3.3.1 Micro-UAV NAV: Highly Miniaturized INS-based NAV

- TWG Output

Enabling Technology: Nav. Accurate Systems_ *Date:3/29/06*

Specific Technology: Micro Air Vehicle Navigation Systems
Contributing Editor: David J. Fratello (in lieu of other input)
Phone: (757) 722-5565 Fax: Email: dfratello@zeltech.com

Specific Technology Description:
A Micro Air Vehicle (MAV) is defined by DARPA to be a UAV with less than a 10 cm (6 inch) wingspan. Technological feasibility follows from advances in several micro-technologies, including the rapid evolution of micro-electromechanical systems, also known as MEMS. These systems combine micro electronics components with comparably - sized mechanical elements of varying complexity to achieve useful, and often unique functionality (e.g. integrated systems of sensors, actuators and processors).
A key component of small vehicle's onboard systems is a GPS-based, and typically INS-enabled Navigation System. A MAV vehicle typically has a low-aspect ratio wing and flies with low-Reynolds number unsteady flow, so the onboard system must provide active stabilization. Typically, a highly integrated system that employs a GPS receiver and a miniaturized Inertial Navigation System (INS) is required.

Current State of the Technology:
In many cases, MAV onboard components are produced with established micro fabrication techniques, providing a high degree of optimism for eventual low-cost production potential. Other maturing micro systems such as tiny CCD-array cameras, equally small infra-red sensors and chip-sized hazardous substance detectors, have been catalytic in providing the motivation for like-sized delivery platforms. Yet formidable technical challenges must be met to successfully integrate these payloads into functional MAV systems. Innovative technical solutions must be found for aerodynamics and control, propulsion and power, navigation, and communication.

In regard to the Navigation issue, systems require reliable determination of attitude, velocity and position of the aircraft for good flight performance during fully autonomous flight. An example of a current navigation concept would be the use of an Inertial Measurement Unit (IMU), providing sensor measurements at 100 Hz. An important task of the IMU is the supply of angular velocities so that a high-frequency attitude solution can be computed. A high attitude update frequency is necessary because of the high rotational dynamics of the aircraft (e.g. roll time constant ~ 0:1 s). Due to the small size and weight of a MAV, only miniaturized sensors are applicable. Unfortunately, such small and usually silicon-based inertial sensors (micro-electromechanical systems, MEMS) have significant and strong temperature correlated deterministic errors.

Identify funded programs that contribute to the development of this specific technology
The earliest suggestions of technical viability appeared in the early 1990's from studies such as RAND Corporation's investigation of microsystems, and MIT Lincoln Laboratory's early investigations of micro flyers. The latter's more recent study helped energize a DARPA workshop on Micro Air Vehicle feasibility in the fall of 1995. The outcome of that effort has been a newly created DARPA program to develop this new dimension in flight. The DARPA program was initiated early last fall through the Small Business Innovation Research (SBIR) Program, together with a more detailed study by Lincoln Laboratory.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*
Recent reports of successful MAV flights, and a recent claim of a new world endurance record of over one hour for this class of vehicle indicates a TRL of 4-6.

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Technology Assessment – Resource & Research Summary

No information provided.

- USRA Analysis

1. Technology Description

The report proposes using MEMs-based Inertial Navigation System (INS) together with GPS for MAV applications. The proposed idea is attractive and feasible as advances in MEMs have made is possible to build low cost, low power reliable sensors and actuators. As the size of UAVs shrink, more research needs to be done in MEMS to address the practical challenges. Differential GPS is critical to provide more accurate UAV's 3D coordinates. Small size of the MAVs comes with challenges - miniaturization and integration of the subsystems. Decreasing vehicle size and increased functional complexity, integration of subsystems becomes very challenging. Since miniaturization of the subsystems is key to development of MAV technology, micro-electro mechanical systems (MEMs) devices are very promising for MAV applications. Recent advances in micro-fabrication technology have enabled mass production of low cost MEMs devices. Emerging MEMs technology has led to the development of transducers as small as tens to hundreds of microns. By integrating MEMs devices with CMOS electronic circuitry, a cost-effective, small, light system capable of sensing and actuation can be created.

2. State of the Technology

Indoor applications might lead to GPS dropouts. Alternative position estimation techniques may be necessary in these situations. Importance of a good measurement unit for MAVs because the flow characteristics for MAVs involve low Reynolds numbers, unsteady flow. MEMS INS devices are plagued with thermal induced errors along with the usual gyro drift issues; however, no idea as to how this will affect performance of navigation systems for UAV. No discussion is provided on computational challenges, which will be crucial for MAVs development.

No discussion of MAV applications needing visual navigation aid. Some proposed applications of MAVs require the vehicle to fly at low altitudes. GPS altitude information is not sufficiently accurate for low level flight. Also, there are frequent GPS dropouts dues to trees and other obstacles at low altitudes. And given the reduced payload capacity of MAVs, current radar technology is not mature enough to provide adequate depth perception. At low altitudes, complex terrain like trees, hills, buildings need to detected and avoided. Vision based navigation is promising. However, the computational needs are large due to fast image processing requirements.
Some interesting complementary tools for improved navigation include: Simultaneous (or Concurrent) Localization and Mapping (SLAM), Mobile navigational aids (e.g., some air vehicles may loiter in a non-GPS-denied area and provide navigational aid through wireless communication or an acoustic signal), and Machine vision: conventional, stereo, compound, ultrasonic.Potential optical flow and biomimetic methods.

3. Enabling Technology Development

DARPA initiatives along SBIR/STTR are mentioned, but no details. In addition, AFOSR and ONR also have similar MAV programs but are NOT mentioned. At least one Multidisciplinary University Research Initiative (MURI) concerning vision-based control for MAVs has been established.

4. Technology Dependencies

Not addressed; integration of IMU/GPS to exploit the complementary properties of both can be useful for MAV development in general, and for navigation systems in particular. Additional issues of power, system component robustness, propulsion, etc. should have been mentioned.

Some of the technology dependencies are
1. Advances in MEMs technology that enable mass production of high fidelity sensors and actuators.
2. Reducing rate gyroscope drift in MEMs inertial navigation systems.
3. Reliable integration of MEMs INS with GPS. (Kalman filtering is the standard approach.)
4. Advanced vision based navigation, image processing and algorithms.
5. Fast computation.

5. Technology Forecast

The author mentions recent successful MAV flights without any specific details. Several research groups in academia and industry, like UFL, Univ. of Notre Dame, Caltech, UCB, Gates, Honeywell, Draper, MIT Lincoln, are actively pursuing MAV development and are famous already in this. No information is provided about the commercial MEMs inertial navigation systems currently being used. Based on all the problems still existing in the MAV area, it is uncertain how a TRL of 4-6 can be assigned.

6. Technology Gaps	Not addressed;Two key issues that need to be addressed are 1. Design of sensors newtowrks and control algorithms that allow a MAV to perform with a high degree of reliability (see comments above) 2. Fitting the entire suite of sensors and controls within the size, weight, and mass distribution constraints of a MAV. Integration of a high fidelity, low cost MEMs INS with a GPS receiver is a challenge and needs further research and investigation. Kalman filtering based on the kinematic equations is the standard approach, but may not be appropriate in all situations.
7. Technology Cost Drivers	Not addressed; Some of the cost drivers are 1. Advances in microfabrication and materials technology might lead to reduced manufacturing cost for MEMs devices. 2. Processor and storage miniaturization (from industry). 3. Safe, reliable, high energy density power supplies.
8. Competing Technologies	Not addressed; some of the technologies that could aid better navigation are 1. Vision-based navigation. 2. Using fixed or mobile navigation aids, perhaps through intelligent coordination among multiple MAVs with different navigational capabilities.
9. UAV Application Demonstrations	Not addressed; Examples of MAV platforms tested in the past are: 1. Black Widow MAV 2. Wasp Micro UAV 3. TACMAV Micro UAV
10. Sources of Information	Not addressed; Some useful references are: • NRC 2000. Uninhabited Air Vehicles. Enabling Science for Military Systems. National Research Council Report. • NRC 1997c. Microelectromechanical Systems. Advanced Materials and Fabrication Methods. National Research Council Report. For a recent study on GPS/MEMS INS performance see “ Performance test results of an integrated GPS/MEMS Inertial navigation package” A. Brown and Y. Lu, Proceedings of ION GSSS 2004, Long Beach, 2004. MAV for Optical Surveillance was explored by MIT Lincoln group.
11. Technology Capabilities	Not addressed; high fidelity sensors, gyro drift, low accuracy MEMS IMU+GPS giving low cost navigation systems, vision enabled navigation, etc. For MAV applications that need frequent obstacle avoidance, the computational needs are high because of advanced image processing requirements. Extremely small and fast image processing devices will be needed for such applications. Advances in nanotechnology and nano-computing might lead to the development of such fast, small computers. Understanding the way animals such as insects use vision to navigate will help us develop better visual navigation systems – biomimetics.

12. Current Research

Not addressed; A few of the many universities/labs pursuing MAV research in the US are...

- CalTech
- Univ. of California, Berkeley
- Georgia Tech
- University of Florida
- Draper Labs

Other non-US universities involved actively are

- University of Braunschweig (Institute of Aerospace Systems), Germany
- University of Bath

One of the biggest conferences for MAVs is the European Conference for Micro Air Vehicles (EMAV).

13. Regulatory Issues

Not addressed; ITAR WILL BE an issue.

3.4 Intelligent Mission Management

3.4.1 Overview

- TWG Output

Enabling Technology: Intelligent Mission Management

Contributing Editors: Joe Totah, Chad Frost, Michael Freed ***Date: 19 March 2006***

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Enabling Technology Description: *Briefly describe the general nature of the technology. How does it support the capability required? This should describe the uniqueness of the technology and project a clear idea of its contribution to UAV capabilities. Are there limitations of the applicability of this technology?*

Intelligent Mission Management (IMM) refers to onboard and ground-system technologies that provide a desired mixture of autonomous and human-directed UAV operation. It shifts the human role in conducting UAV missions from operators of vehicle and payload systems towards being users of and requesters for observation data products. IMM increases Level of Autonomy (LOA) for sustained or complex UAV operations. This technology offers several benefits sought by the civil UAV user community including:

1. An ability to operate in environments where unreliable communications make conventional remote operation infeasible
2. An ability to conduct tedious, long duration missions where conventional remote operations would be expensive and excessively strenuous for human operators
3. An ability to optimize use of limited airborne sensing assets and to maintain optimality in changing conditions by modifying mission plans
4. Reduced need for highly trained pilots and payload operators in order to reduce operational costs and increase access to airborne sensing assets
5. Enhanced integration with command and control systems, particularly as mobile elements of automated sensor networks

IMM encompasses a range of specific technology areas. For onboard systems, these include Automated Planning & Scheduling (APS) and Intelligent Outer Loop Control (IOLC) as autonomy-enabling technologies. Augmenting these, technologies for Verification & Validation of Autonomy software (V&V) and advanced systems for Contingency Management and Intelligent Vehicle System Management are needed to assure safe autonomous and semi-autonomous operations. Ground system technologies include Advanced Decision Support (ADS) that facilitate, e.g., cooperative mission planning for autonomous systems among geographically dispersed mission stakeholders and operational processes that vary level of UAV autonomy dynamically during a mission.

Current State of the Technology:
Simple mission management capabilities such as the ability to script inputs to a UAV autopilot have been deployed in fielded systems for a long time (TRL 9). Various capabilities that might be incorporated into a general and highly capable mission management system such as the ability to select routes based on predicted weather and to plan at-target observation behaviors in situ to meet user data product requirements have been demonstrated in flight (TRL 4-6) or are in development. In FY06, the NASA/Army Autonomous Rotorcraft Project demonstrated a UAV system emphasizing advanced mission autonomy (TRL 6), but with less emphasis on ground system capabilities than would be required for a mature IMM system. An IMM system including both ground and flight components and encompassing a wide range of capabilities was successfully demonstrated in simulation in FY05 at TRL 3 under the NASA Aeronautics/Vehicle Systems Program. It is anticipated that with continued funding, achieving TRL 6 would take approximately 2 years.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?
Currently there is no funding for Intelligent Mission Management of UAVs focused on civilian applications. Defense-oriented IMM capabilities are being developed under several DoD programs including those listed below.

- The Army's **Unmanned Autonomous Collaborative Operations** program intends to develop capabilities for high-level tasking of multiple UAVs by a single operator. It focuses specifically on a set of autonomous mission behaviors including avenge kill/team protection, network adaptation for assured communications, surveillance of multiple moving targets in urban terrain and team adjustment to component failures.
- ONR's **Intelligent Autonomy** program funds technology development for fully autonomous mission planning and dynamic retasking of heterogeneous unmanned naval systems (ground, sea surface, underwater and air) to perform littoral reconnaissance, search, persistent surveillance, tracking and strike. It also includes work on human operator support including display of mission information, plan understanding, tasking interfaces and alert management.
- DARPA's **Heterogeneous Urban RSTA Team (HURT)** program is developing technology for delivery of real-time urban battlefield information (RSTA = reconnaissance, surveillance and target acquisition) to soldiers from multiple heterogeneous UAVs. Technical emphases include fast-paced control of multiple UAVs and decoupling of users from direct control and tasking.

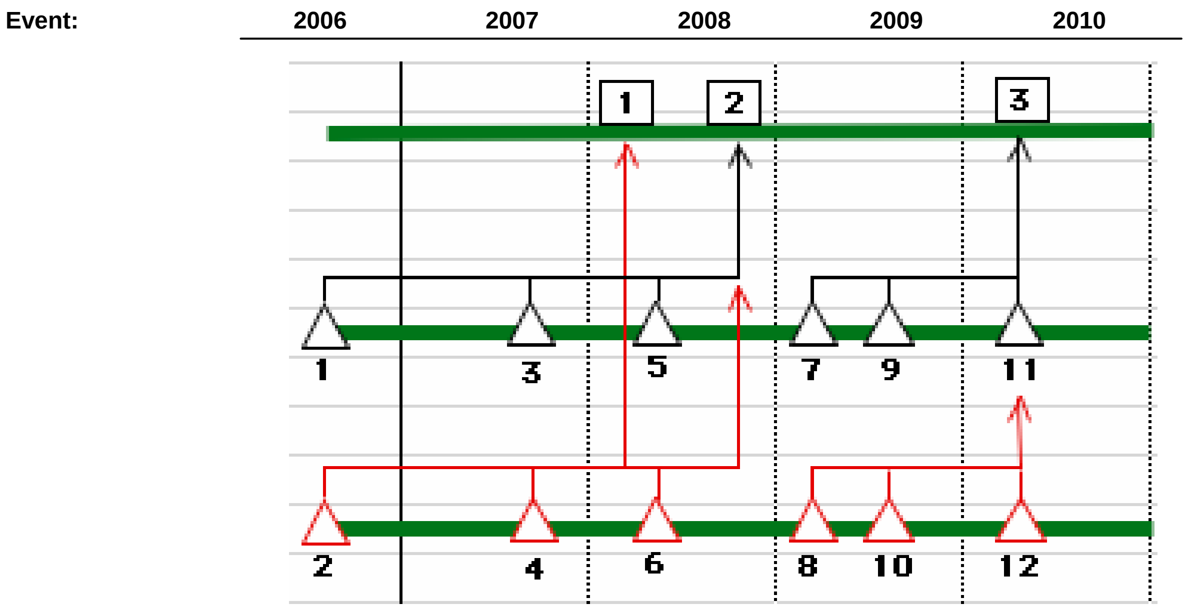
There are important commonalities between these efforts' technology objectives and IMM technology needed by the civilian UAV user community. However, several factors indicate limitations on both the suitability and availability of DoD-developed technologies for civilian applications. First, DoD applications emphasize different kinds of autonomous behavior, pose different criteria for good mission performance, involve UAV platforms and sensors with different capabilities and tend to make very different assumptions about operational context (e.g. the availability of GPS, reliable communications). These factors will likely shape DoD developed IMM technologies, posing a significant problem of adaptation for civilian use.

Second, civilian and DoD systems will tend to require support for very different operational models. For instance, DoD operations take place within a hierarchical chain of command and operate in airspace with one set of rules. In contrast, civilian applications may assume impose complex requirements for cooperation/coordination among peer users (e.g. Lansing 2003) for systems that need to fly in the NAS.

Finally, there may be practical limitations on the availability of DoD technology which may be classified and is typically proprietary, presenting costs that may be too high for many civilian applications.

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
IMM technology capable of meeting the full range of civilian applications requirements requires further development in the following areas: automated planning and scheduling, intelligent outer loop control, verification and validation of autonomy software and advanced decision support. Each of these is discussed in a separate subarea technology document.

Forecast of enabling technology:
An IMM system including both ground and flight components and encompassing a wide range of capabilities was successfully demonstrated in simulation in FY05 at TRL 3 under the NASA Aeronautics/Vehicle Systems Program. It is anticipated that with continued funding (currently unavailable), achieving TRL 5 for a complete and broadly capable IMM technology would take approximately 2 years, and achieving TRL 6 would take another two years. The milestone chart below defines time and technology dependencies, illustrating a path to a fully mature IMM system.



Key Deliverables (Squares)

Key Deliverables: Identify key deleverable coming out of this task.

ID No.	Description	TRL	Date
1	Develop, integrate, and demonstrate a collaborative decision environment with the following specific objectives: mission-level decision support, automated data products, and sensor planning services.	4	Oct-06
2	Develop, integrate, and demonstrate an intelligent/autonomous architecture using fault tolerant software with the following specific objectives: tactical maneuvering, intelligent flight management, and dynamic re-planning.	5	Jul-07
3	Develop, integrate, and demonstrate remote operations of a UAV that is tasked by another UV (satellite, aircraft and/or rover) in a simulated planetary analogue mission with the following specific objectives: multi-role and interoperability.	3	Apr-09

Supporting Milestones (Triangles)

Task Milestones: Identify key task milestones.

ID No.	Descriptions	Date
1	IMM simulation-based System Requirements Document (SRD)	Sep-05
2	Collaborative Decision Environment (CDE) prototype (payload/sensor language standards/interfaces to CIP)	Sep-05
3	Intelligent outer-loop integration with real-time reactive planner (payload/sensor-directed flight)	Jun-06
4	CDE beta testing completed (mission/science visualization)	Jun-06
5	Demonstration of long endurance unaided AutoNav (contingency handling)	Apr-07
6	CDE Phase I deployment (sensor planning service)	Apr-07
7	Planetary mission simulation demonstrated (remote tasking mission scenarios, distributed GN&C architecture/framework)	Dec-07
8	CDE Phase II deployment (opportunity for IVSM integration)	Dec-07
9	Hybrid mode control (conventional/image-guided/payload-directed)	Jun-08
10	CDE upgrade to incorporate test plan and logistics support for Mars analogue demonstration	Jun-08
11	Coordinated flight demonstration in Mars analogue scenario (remote tasking, BLOS operations, automated target acquisition)	Apr-09
12	CDE Phase III demonstration in Mars analogue scenario	Apr-09

Identify and articulate any technology gaps discovered:
Technology gaps for a mature IMM technology capable of meeting the full range of civilian applications are discussed in subarea technology writeups on: automated planning and scheduling, intelligent outer loop control, verification and validation of autonomy software and advanced decision support.

Enabling Technology Cost Drivers: *Operating and development costs.*
Enabling technology cost drivers have been examined in the form of a mission metric, and described in detail at the following link:
http://geo.arc.nasa.gov/imm/index.php?section=products&page=metrics

$$\overbrace{M}^{MissionScore} = \overbrace{\left(\sum_{j=1}^{n} v_j c_j r_j s_j o(t)_j\right)}^{Benefits} - \overbrace{\left(\sum_{k=1}^{m}(H_k \cdot W_k) + P \cdot (R \cdot C_v + M \cdot C_m)\right)}^{Costs}$$

The function makes an analysis of the benefits accrued by having autonomy on the mission, and compares them to the costs of having that same autonomy in place. Initial development work on the function was undertaken in FY05, and further work to test and refine the metrics is proposed.

Benefits:

- **Aggregate value of all observations made over mission (ideal v_j=1)**
- **Function of target coverage (c_j), resolution (r_j), clarity (s_j), and obsolescence of measurements and data products upon delivery ($o(t)$).**
- **Challenge is in measuring the aggregate value of returned information.**

Costs:

- **Sum of operational personnel costs (100% autonomy implies $H_k \bullet W_k$ = $0)**
- **Probability of failure (P) X Cost of failure of the vehicle (C_v) or mission (C_m)**

The primary goal in most IMM applications is to acquire as much high quality data as possible within a timeframe defined by vehicle endurance or a specified maximum duration. Each observation target is associated with a value (v) and a set of data quality preferences for image resolution (r), clarity (s), coverage (c) and timing (o). For example, it may be desirable for a particular target to get 10m per pixel image data (requiring a certain maximum altitude), prevent image gaps (requiring wings-level attitude while observing), acquire data on the perimeter but not necessarily the interior of the target area, and to synchronize observation of the target with a MODIS satellite overpass. If these preferences are not fully met, the value of having observed the target is discounted from v. The autonomy software is responsible for maximizing information benefits by generating and executing an optimal flight plan. Implicit in the metric are tradeoffs that the autonomy may need to reason about – e.g. which subset of the targets to visit, whether to sacrifice resolution to gain clarity by ascending out of a turbulent altitude and whether to visit one less target in order to recover from wings-level violations at the current target by reflying certain segments. In addition, plan validity may be constrained by several factors including target visit ordering constraints, airspace restrictions and a requirement to remain within some maximum distance of an emergency landing locale.

A second goal of IMM is to minimize mission costs. Personnel costs depend on the number of people with an operational role in the mission and the time and pay rate of each. This accounts for a basic economic contribution of increasing autonomy: reducing the need for human operators, particularly those who cost the most or have the rarest and most in-demand skills. Failure costs result from unanticipated losses such as damage to a sensitive optical sensor accidentally pointed at the sun, or aircraft loss resulting from a critical system failure. Autonomy software can minimize failure costs both by avoiding bad decisions that cause failure and by responding quickly and correctly to failures in other systems.

Known competing or disruptive technologies:
None.

Major Events/Milestones:
None.

Demonstrated for UAV application?:
Yes, as noted above.

Technology Assessment – Resource & Research Summary

Known sources of information:

1. http://geo.arc.nasa.gov/imm/
2. http://geo.arc.nasa.gov/sge/WRAP/
3. Schoenung, S., Wegener, S., et. al., Intelligent UAV Airborne Science Missions, AIAA-2005-6937.
4. Burley, J., Autonomous Robust Avionics Project Plan – Version 1A, September, 2004
5. Freed, M., et. al., An Architecture for Intelligent Mission Management of Aerial Observation Missions, AIAA-2005-6938.
6. Kaneshige, J., Krishnakumar, K., Tactical Immunized Maneuvering System for Exploration Air Vehicles, AIAA-2005-6936.
7. D'Ortenzio, M., Enomoto, F., and Johan, S., A Collaborative Decision Environment for UAV Operations, AIAA-2005-6939.
8. Whalley, M. S., Freed, M., Harris, R., Schulein, G., Takahashi, M., and Howlett, J., "Design, Integration, and Flight Test Results for an Autonomous Surveillance Helicopter," *Proceedings of the AHS International Specialists' Meeting on Unmanned Rotorcraft*, Jan 2005.
9. Lansing, J., "Sensor Planning Service," OpenGIS Draft IPR OGC 03-011r1, Open GIS Consortium, Inc., 2003.
10. Huang, H., "Autonomy Level Specification for Intelligent Autonomous Vehicles: Interim Progress Report," *Proceedings of the 2003 Performance Metrics for Intelligent Systems (PerMIS) Workshop*, August 2003.

Capabilities (must have, etc.):

Research being done:

Regulatory/security issues? ITAR:
The publications cited in the "known sources of information", items #2, 4, 5, and 6 have been published and can be obtained through the American Institute of Aeronautics and Astronautics. An examination of regulatory/security issues (including ITAR) will need to be performed if IMM technology development is funded to proceed.

Non-US efforts:
Unknown

List Any Assumptions:
None

- USRA Analysis

1. Technology Description

Very well written and comprehensive overview discussion of the range of issues. (Even the deleted material is valuable, and some of it should find its way back into the text; e.g., Global Earth Observing System.)

Within the next decade or so cooperation will extend beyond mission planning within geographically distributed stakeholders to on the spot cooperation between multiple UAV's conducting a mission. Integration of the mission management issues with communications restrictions will be a fundamental requirement. Issues such as the level of information that must be exchanged between units such as satellites need to be investigated. Feedback control methods for relative UAV positioning for enhanced communication throughput when constructing, for example, a communication network in an emergent situation, or to meet GPS requirements, need to be reviewed.

For dynamic mission planning, command, and control, numerical algorithms are needed for real-time computation.
Most of the challenges identified can be modeled as optimization problems (optimal control, dynamic games, etc.), thus necessitating the need for computationally efficient algorithms.
The approach of augmenting these technologies for Verification & Validation of Autonomy software (V&V) and advanced systems for Contingency Management and Intelligent Vehicle System Management needs to be fully explored to assure safe autonomous and semi-autonomous operations. Adaptive control is a viable technology for achieving this, and the authors might want to look-up into some of the recent developments on this developed at Virginia Tech.
Cooperative mission planning for autonomous systems can be enhanced if the authors look into graph-theoretic concepts and tools, intensively used by NPS.
Supervisory control might also be useful for enhancing the IMM. Impressive results have been reported by Carnegie-Mellon, PSU/ARL, et al.
It would be useful to have a list of assumptions made when defining the IMM; e.g., the IMM assumes the existence of highly reliable UAV capable of tracking a defined mission profile, etc. A definition of general terms like, "Conventional Remote Operation and "Intelligent Outer Loop Control", "Automated Sensor Network" would be helpful to understand the write up. The IMM would also need to have technologies that provide a real-time situational awareness of the vehicle health and performance and the environmental conditions.

The primary goal of an IMM should be to concentrate the human component of the system onto payload, rather than vehicle, operation. The description of the technology lacks coverage of the entire mission. Many of the difficulties in terms of low-level vehicle operations arise during seemingly trivial ground operations (system preparation) as well as vehicle take-off and landing. To allow true autonomy requires IMM to encompass these phases of vehicle operation as well.
The assessments should be based on specific tasks or mission for civil UAVs. Recommend more work to identify civil UAV roles followed by a study of the operational models and requirements for those roles and missions.

2. State of the Technology	Good mention of both vehicle and ground system issues relevant to TRL and current technology state assessments; however, assessment would be stronger if it were made relative to the different operational models. Visual sensors are already finding their way to UAVs in military applications. Learning from those and incorporating those into UAVs for civilian applications is one of the directions that can enhance the current state of the technology. It can, however, delay the TRL development. Need more general discussion that would allow comparisons to other (non-UAV) applications and their TRL capability would be helpful. Much of future systems will use cooperative methods with less reliance on a remote operator. Need to mention of the current or planned FAA National Airspace System technology. Should address other activities in various communities & institutions. The report focuses currently on integrated technologies for vehicle autonomy. However, the report does not focus on individual technological elements, such as: Path-planning primitives, vision primitives, man-machine interaction elements, sensor primitives, and so on. An assessment of the individual components that are required to build the IMM would help the reader answer the question as to whether the effort should be put at the level of system integration, or component development, or both.
3. Enabling Technology Development	Good awareness of current DoD programs. Excellent discussion of the potential problems with applying military technology to the civil problem. The DoD applications have different type of requirements for autonomous behavior, pose different criteria for good mission performance, involve UAV platforms and sensors with different capabilities, and tend to make very different assumptions about operational context (e.g. the availability of GPS, reliable communications). If interpreted on a theoretical level and treated within accurate mathematical models, useful generalizations can be made. Civilian applications requiring complex cooperation/coordination among peer users may be addressed using graph theoretic tools. Successful demonstrations of similar missions, subject to temporal and spatial constraints, have been reported in some recent NPS publications. There are civilian programs sponsored, e.g., by NSF, which definitely require the use of an IMM architecture similar to that described by the authors. These programs, however, do not focus on developing the architecture per se. Instead, these programs are technology users. Another source of technology requirements and system definition might be found in examining the NASA Small Airplane Technology System program long term goals.

4. Technology Dependencies

Fairly comprehensive asessment, but sub-areas need further discussion. Would recommend formulating the dependencies based on requirements.

Should include a discussion of inter-dependencies between technologies and development challenges. In the context of cooperation, communications must be integrated with control issues as these tend to drive each other. Current communications protocols may not be reactive enough for this. Much needs to be done to understand this interplay.

IMM technologies are dependent on various factors - flight regulations, sensing technologies, comm, computation, etc.

One supporting technology that is missing is advanced man-machine interfaces: The modalities of interaction between a human and an advanced outer-loop management system are a necessary part of the overall system. Unfortunately, very few programs currently focus on these. Examples of advanced interfaces include natural language interfaces between humans and UAVs, which have remained very sketchy so far.

5. Technology Forecast

This is one of the rare and real forecasts seen in the assessments reviewed.

How will development plan be executed/implemented, especially across organizations ? Seems to be limited to the author's personal technology development plan, and would be good to have an overview of competing projects as well.

No specific mention of the IMM's need for situational awareness or how this would be accomplished.

Tech and scientific challenges associated with cooperation should be addressed. Contingency analysis (deliverable delays if funding is not available or slips) would be helpful here, but this is clearly a second-order issue.

6. Technology Gaps

Refers to several documents/information that seem to address this issue - access to documentation ?

Identify technology gaps and how they impact the IMM. Operational model(s) and the underlying IMM requirements drive the requirements for the sub-area technologies. Integration with network centric communication and the various other areas listed is essential.

7. Technology Cost Drivers

Excellent assessment. A real "mission score" metric with actual cost descriptions. The presented Cost-Benefit methodology may be a useful tool for detail system design decisions.

The presented Cost-Benefit methodology may be a useful tool for detail system design decisions. Major Cost drivers would seem to be the overall system design failure rate levels. What requirement this would place on the reliability of the IMM Element is not clear. What is needed is the development of IMM design and operation strategies that permit graceful degradation of IMM operation.

One of the primary cost drivers for developing intelligent mission management technology is the cost of flight testing. Extensive work has been completed in the simulation world, sufficient to have confidence that algorithms will work.

However, flight test still is very expensive increasing exponentially with size of the UAVs involved. For smaller, less expensive UAVs reliability is still the issue.

8. Competing Technologies

Although there are not competing technologies per se for IMM (V&V for Autonomy Software might be viewed from different perspectives), there are serious competing technologies for the underlying civilian missions envisioned for UAVs e.g. use of driftsondes and dropsondes for atmospheric science applications.

Several disrupting and/or competing technologies: for example, GPS signals for navigation and guidance.
Existing communication protocols are not naturally designed for integration of controls and communications in cooperative IMM. Protocols dedicated toward this are needed, but the temptation to take off the shelf protocols may win out.

Recommend focusing the program on those applications where economies of scale or physical limitations exclude humans as a viable alternative to advanced autonomy functions.

9. UAV Application Demonstrations

Good overview interspersed through the document; included in forecasts and current state evaluations.

Assesment of this area is hampered by lack of access to industry information. Significant work has been done by various UAV manufacturers on moving the IMM and supporting technology forward, but most of this is proprietary, particularly flight test experience.
Are integration demonstrations, as well as component tests, also scheduled ?
Additional DARPA and DoD demonstrations probably available. One approach to flight demonstrations is to use optionally-piloted vehicles as potential flight test tool.

10. Sources of Information

Goodstart on list of sources...
Suggest consulting additional controls journals and conference proceedings.
The sources used by the authors are very scarce and must be expanded further. In particular, there are numerous articles in the AIAA *Journal of Guidance, Control, and Dynamics* that aim at advancing the level of autonomy of UAVs and their outer-loop control. While these individual technologies do not necessarily constitute an integrated product yet, they certainly describe interesting elements of autonomy. Another interesting and new publication that may be worth looking at is the *Journal of Field Robotics*.

11. Technology Capabilities

Integration with human decision makers, and using UAV to provide real-time updating of others' planning and scheduling data/algorithms, is not clearly called out as a separately required capability.
Efficient numerical algorithms that can solve optimization problems derived for various applications in time with good accuracy.
For single UAV's confronted with unexpected circumstances, adaptive control techniques must be developed. For cooperative UAV's the science and technology of cooperation must be developed. A tight integration of communications/computing/signal processing and control issues is needed.
Need to map required capabilities based on operational models. This will allow a more systematic assessment.

12. Current Research

Good overall summary and awareness of current DoD programs. Excellent discussion of the potential problems with applying military technology to the civil problem.
More complete literature and research activities survey is needed. University research, dedicated to acquiring a fundamental understanding of the issues, is noted in Tech Capabilities, and developing technologies toward them, is ongoing. Includes work in US, Italy, and Australia.
Non-US efforts could include the VITAS project in Sweden, several autonomous helicopter projects in Japan (N. Noguchi at U. Hokkaido, see also Kyoto University). In France, ONERA-CERT in Toulouse is having a project in this area too (Patrick Fabiani). Australia also offers extensive research (See projects led by Hugh Durrant-Whyte, for example).

13. Regulatory Issues

There are several issues identified in the known sources, and the suggestion that identification is contingent on funding makes sense here. FAA regulations/restrictions on UAV unaddressed.

3.4.2 Outer Loop Control: Intelligent Outer Loop Control

- TWG Output

Enabling Technology: **Intelligent Mission Management** *Date:19 March 2006*

Specific Technology: Intelligent Outer Loop Control
Contributing Editor: Michael Freed
Phone: 650-604-5975 Email: michael.a.freed@nasa.gov

Specific Technology Description:
Intelligent Outer-Loop Control (IOLC) provides an on-board capability for autonomous and semi-autonomous operation. A traditional outer-loop control system such as an autopilot or flight management systems (FMS) achieves human-defined navigation and guidance goals, mainly by controlling vehicle flight surfaces. IOLC extends the traditional approach to achieve high level mission goals. For example, whereas an FMS might be tasked with making the aircraft follow a specified route, an IOLC might be tasked with a much broader goal such as repeatedly monitoring a set of ground targets for events of interest and alerting users whenever such events occur. To meet these goals, the system needs to be able to control not only vehicle flight surfaces, but also sensor payload, communications and other subsystems. IOLC entails specific capabilities including:

- Mission planning: The ability to generate a mission plan that meets user defined goals and preferences. This function is carried out by an automated planning and scheduling (APS) component – see separate technology subarea writeup on automated planning and scheduling.
- Mixed-initiative planning: Depending on operational requirements and user preferences, users may interact with the APS component to help formulate the plan or to select among alternative APS-generated plans.
- Monitored execution: Input from system sensors, payload sensors, IVSM and human controlled ground systems may be used to track progress, determine when it is time to advance to the next plan step and determine if anything has occurred that threatens, invalidates or reduces the effectiveness of the plan.
- Payload-directed execution. Sensor payload inputs may be used to fill in details about the plan that could not be determined as part of mission planning. For example, a mission requirement to follow a moving object or shifting contour can only be met by sensing and acting in a tight loop. Path decisions cannot be incorporated into the mission plan in advance, so the IOLC makes these decisions as the plan is being carried out.

- Adaptive execution. When the IOLC detects events that conflict with a mission plan, it can allow contingency management software to safely abort the mission or it can attempt to adapt to the new circumstances. Examples of events that the IOLC should attempt to adapt to depend on specific mission and operational requirements, but may include non-critical system failures, temporary loss of communication, weather changes, unexpectedly high time or resource requirements (e.g. fuel, power, onboard memory) to carry out a plan step, ATC directives, user-initiated changes to mission goals and user commands that require deviating from the plan. When such events occur, the IOLC either modifies the plan to deal with new circumstances or generates a new plan. This function extends Contingency Management technology (see separate writeup) and integrates it into the IOLC system.

Current State of the Technology:
Particular requirements IOLC technology depend on the complexity of missions and mission success criteria that need to be planned for, the unpredictability of the task environment (physical environment, system, users) in which the plans are to be executed and the need to develop the technology for a braod range of missions, vehicles and sensors. Simple IOLC capabilities such as the ability to script inputs to a UAV autopilot have been deployed in fielded systems for a long time (TRL 9). Specific behaviors of a more advanced nature such as the ability to select routes based on predicted weather and to plan at-target observation behaviors in situ to meet user data product requirements have been demonstrated in flight (TRL 4-6) or are in development. In FY06, the NASA/Army Autonomous Rotorcraft Project demonstrated a UAV system emphasizing advanced mission autonomy (TRL 6) for one class of missions (optimal monitoring of multiple fixed sites). An Intelligent Mission Management (IMM) system including both ground and flight components and encompassing a wide range of IOLC capabilities was successfully demonstrated in simulation in FY05 at TRL 3 under the NASA Aeronautics/Vehicle Systems Program. It is anticipated that with continued funding, achieving TRL 6 for the full IMM capability would take approximately 2 years.

Identify funded programs that contribute to the development of this specific technology
Development of IOLC capabilities for spacecraft is funded by NASA's Exploration Systems Mission Directorate to develop "Spacecraft Autonomy for Vehicles and Habitats" with a specific focus on Crew Exploration Vehicle system automation. In addition, work in this area is funded under several DoD programs. See the Intelligent Mission Management writeups for further discussion.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
See separate writeups on
- Automated Planning and Scheduling
- Verification and Validation of Autonomy Software
- Contingency Management
- Intelligent System Health Management

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology:
DoD funded development of IOLC technologies for specific UAV missions and vehicle/sensor configurations is ongoing, with demonstrations at TRL 6 scheduled starting in FY07. However, it is unlikely that these will have significant carry over to civilian applications in the near term. Very little funding is available for development of IOLC directed at civilian UAV applications. An IOLC capability able to meet the demanding requirements of the civilian UAV user community is therefore unlikely to become available for the indefinite future.

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Remotely piloted aircraft can be used on most tasks that might otherwise be performed autonomously, though often at prohibitive expense or risk.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Technology Assessment – Resource & Research Summary

Known sources of information:

An architecture for intelligent management of aerial observation missions
Freed, M., P. Bonasso, K.M. Dalal, W. Fitzgerald and R. Harris. 2005. Proceedings of *American Institute of Aeronautics and Astronautics "Infotech@Aerospace" Technical Conference*, September 26-28, Arlington, Virginia.

A Playbook for Real-Time Closed-Loop Control. 2006. Funk, H, Goldman, R., Miller, C., Meisner, J. and Wu, P. Proceedings of the 2006 Conference on Human-Robot Interaction, Salt Lake City, UT.

Research being done:

Regulatory/security issues? ITAR:

Non-US efforts:
http://www.uav.ewi.tudelft.nl/index.htm

List Any Assumptions:

- USRA Analysis

1. Technology Description

Good generic description of the field. Generic, non-mission-specific descriptions are helpful to help identify cross-cutting and tangential areas of relevance and potential impact.

It is unclear how the IOLC interacts with the other system elements. A high level block diagram would be useful when discussing a enabling technology or specific technology element.
Incomplete discussion of how UAV could help update mission plans for other assets, or improve other planning systems. Would like to see more discussion of time scales of outer loop control; i.e., time scale/time required for planning effort compared to time scale of execution.

While IOLC appears to break down into “Planning” and “Execution” tasks, the former tasks really fall under the APS subarea, leaving only three “Execution” capabilities within the IOLC subarea: Monitored Execution, Payload-Directed Execution, and Adaptive Execution. These capabilities are not formally defined in the Technology Description, although they are briefly illustrated with examples.

Successful IOLC operation will require processing of much more information than typical flight management systems. Much need to develop efficient numerical algorithms.

Suggest the use of the term 'control effectors' rather than control surfaces. Control effectors are more inclusive and include engine throttle and thrust vectoring.
A key design decision would be the inputs to the IOLC, what is actively determined by the IOLC, and what is outputted from the IOLC. For example, what is the allocation of intelligence between the IOLC and the payload sensors? For example which system would perform the processing of raw sensor data to determine mission status? Similarly, what would be the source of weather data and who would process this data so it could be used for mission status and modification?

2. State of the Technology

Apparent contradiction later in report as far as tech applications from DoD.
The TRL 6 seems a bit too high of an expectation to be achieved over the next two years. The tasks identified above will take longer to accomplish.
More comparisons to other (e.g., ground-based mobile systems, air traffic control) outer-loop planning systems could be useful.
The report mentions the NASA DFRC work (and the lack of continuing funding for it), but there is little or no mention of complementary and/or competing efforts.

3. Enabling Technology Development

The description mentions 'development of IOLC capabilities for spacecraft', but does not discuss direct application to UAVs.

Despite the report's misgivings about parallel DoD programs, there is a lot to be gained from investigating the specific projects those programs are sponsoring, whether or not they are focused specifically on UAVs. Many of the same problems come up regardless of the platform type or operating environment. Robustness and fault tolerance, for example, are key issues for autonomous underwater vehicles, as is the general mission management problem in complex, collaborative tasks like minefield mapping.
There are several government programs outside of NASA which are funding work that directly supports civilian applications of UAVs. Examples include ONR's Ocean Modeling and Prediction Program, NSF's CISE, etc.

4. Technology Dependencies

No apparent effort made to facilitate an independent evaluation of the IOLC technology. Only cursory references to other reports.

Issues such as Medium Access Control must be integrated with control strategies.

5. Technology Forecast

No discussion on the application of the NASA Exploration work to the Civil UAV platforms and systems. There is no mention of competing efforts. No real forecast or schedule for tech development.

Review suggests limited civilian system carryover from DoD (and other) projects. Review suggests that Katrina response scenarios provide ample civilian system carryover opportunities, instead considering rescue, rather than destruction, as target prosecution goals. The point that transfer of DoD research to the civil sector is problematic undermines the technology readiness discussion.

6. Technology Gaps

Not addressed: Integration with network centric communication, and indeed the various other areas listed is essential.

There is no mention of any technology gaps in the report. Possible gaps include the usual suspects: hardware (fast, low-power, light-weight processors and data storage; low-power, light-weight, high-bandwidth, spread-spectrum communications) and algorithms (decentralized control algorithms for multi-vehicle collaboration; real-time optimization methods; robust, adaptive controllers).

7. Technology Cost Drivers

Not addressed.

8. Competing Technologies

Suggestion that remotely piloted aircraft is a 'disruption' undermines the principle of providing user updating of outer loop control and planning. Rather should be seen as complementary.

Another important technology that competes with UAVs is remote (spacecraft-based) sensing. Many of the sampling tasks that can be accomplished by UAVs could also be accomplished from space, assuming that the sensor technology could be improved to provide comparable resolution.

Additionally, existing communication protocols are not naturally designed for integration of controls and communications in cooperative IMM. Protocols dedicated toward this are needed, but the temptation to take off the shelf protocols may win out. Cost benefits of the autonomous operation are uncertain. There is however a major opportunity to improve the quality of the data obtained.

9. UAV Application Demonstrations

Not addressed; One approach to flight demonstrations is to use an optionally-piloted UAV.

10. Sources of Information

Limited, not definitive.

11. Technology Capabilities

Updating of situation assessment and interfaces to support current state and decision-maker's goal functions/intents are not discussed as critical required technology capabilities.

For single UAV's confronted with unexpected circumstances, adaptive control techniques must be developed. For cooperative UAV's, the science and technology of cooperation must be developed. A tight integration of communications/computing/signal processing and control issues is needed.

12. Current Research

Adaptive execution in the presence of unexpected changes will require robust adaptive outer-loop control system for maintaining the system performance. Some references...
Proceedings of American Control Conference 2006, AIAA Guidance, Navigation and Control Conference 2006, and IEEE Conference on Decision and Control 2006 (Cao & Hovakimyan)

In Europe, EURO UVS and Asia, Japanese UAV initiatives.

It would be useful to look also in issues like collaborative behavior, 3D path following and/or trajectory tracking, interference with human operators, etc.

13. Regulatory Issues

Not addressed; UAV represents a critical challenge to all known models of civil airspace Free-Flight management. How will such vehicles provide transponder and intent information to TCAS systems ?

3.5 Intelligent Vehicle System Monitoring

3.5.1 Overview

- TWG Output

Enabling Technology: Intelligent System Health Management

Contributing Editor: Jeremy Frank ***Date:*** *15 March 2006*

Phone: 650-604-2524 **Fax:** **Email:**

Enabling Technology Description: *Briefly describe the general nature of the technology. How does it support the capability required? This should describe the uniqueness of the technology and project a clear idea of its contribution to UAV capabilities. Are there limitations of the applicability of this technology?*

Intelligent System Health Management (ISHM) is technology designed to assess the "health" of a system and recommend or perform actions to ensure the vehicle remains healthy in the future. ISHM is a broad term encompassing a variety of capabilities. These include:

1. Built-in Self Test (BIST) to reduce checkout time and ensure in-flight reliability of redundant systems.
2. Component fault detection identification and recovery (FDIR) Traditional low level rules built into software to identify component failures and to recover automatically.
3. Caution & Warning: System off-nominal detection and first order root cause analysis displayed to operator.
4. System/Vehcile Level FDIR: System off-nominal detection and first order root cause analysis displayed to operator or used to reconfigure vehicle.
5. Data Stored/Transmitted on Demand for On-Ground Decision Support: Selective downlink of data on flight data recorder. Parameterization, clustering or compression of data.
6. Data Stored/Transmitted to Support Logistics & Maintenance (L&M): Operational data stored onboard and transmitted to the operator or maintenance crew.
7. Component Health Determined for L&M: Health status information inferred from sensor readings and transmitted to ground maintenance or used in long duration flights for other purposes.

ISHM technology contributes to safe UAV operation in several ways. ISHM technologies used in-flight can recover automatically from some faults, and recommend actions to operators in the presence of other faults. Note that some ISHM techniques can be used on the vehicle itself, while others can be used on the ground. ISHM technologies used post-flight can reduce the likelihood of faults during operations by recommending maintenance or replacement of faulty parts.

Most ISHM techniques require sensors to provide awareness of vehicle state. These can be structural sensors (e.g. strain gauges), mechanical sensors (e.g. interrogation of gears or fans) or component sensors (e.g. heartbeat from the communication system or status from the payload). Sensors add cost, weight, power usage and avionics bus traffic to vehicles. Storage of sensor data or component level FDIR requires either onboard storage or a communication link, imposing some computational requirements and associated power and avionics bus loads. ISHM systems like C&W and System FDIR require computational resources, either onboard the vehicle or on ground with a communication link in-between. Small vehicles may not have the computational resources for ISHM.

ISHM does not traditionally include related vehicle safety considerations related to "external" threats to health and safety, for example, see-and-avoid, collision detection, or the like.

Current State of the Technology:

<u>High TRL approaches:</u>

Intelligent Flight Control (IFC) exploits the fact that a vehicle is over-actuated, and uses non-traditional (and hence not ideal) control methods to accomplish goals. IFC in particular does not do traditional fault ID and recovery, instead it decides "what works" and makes it happen. In a sense, this technique recognizes that there are larger "safe" control envelopes that can be exploited under certain circumstances. IFC has been tested on thrust variable F-15, F-18, and C-17 flight hardware.

Boeing and Honeywell developed a 777 central computer "cabinet" which includes a "Central Maintenance Computing function". There are about 250,000 electrical components on a 777. The fault system requirements are no false alarms, one message for one fault, no misdirection e.g. wrong message for a fault. About 11,000 faults detectable by system. The driver is reduced delay at gate. Technician has 5-10 mins to diagnose and repair aircraft. Need accurate diagnosis of fault. The system differentiates between critical faults and economic faults. You can fly with economic faults, it just costs more. Faults are detected onboard, telemetered to ground, and fault diagnosis is done on the ground. Annecdotally, all faults for aircraft all over the U.S. are actually diagnosed at a single facility (in San Francisco.)

Honeywell has developed an engine fault mode prognostics system used for the LF-507, a 2-spool turbofan engine used in regional jets. The system uses a combination of sensors of engine operating conditions (altitude, speed, ambient pressure, engine speed, exhaust temperature) and a prediction system to predict faults such as temperature sensor offset, bleed-band leakage, and spool deterioration. The system has been deployed and is in use.

<u>Medium TRL approaches:</u>
Livingstone is a system level FDIR technology. It takes in sensor data from across the vehicle, and compares this data with a model (built by a human) of how the system is expected to operate. If expected behavior deviates, Livingstone performs a search for the most likely (set of) faults using the same model. It has been tested on flight hardware, (X-37 as part of the PITEX project) and on satellites (EO-1), which do not demonstrate quite the same classes of failures as aircraft do, but it does demonstrate that the software can be deployed on flight hardware in harsh environments.

APEX could be used for fault condition handling, with hand-built control rules. Tested on the RMAX.

HUMS stuff Ed huff was doing for helicopter rotor maint. Prediction? (Ask Anne Patterson Hine)

ARC Inductive Monitoring System (IMS) is a learning system that learns normal behavior of a system to predict abnormal behavior. It seems to be usable onboard, but since it's slated for SOFIA the aircraft in question might need to be rather large.

JPL Beacon Based Exception Analysis for Multimissions (BEAM) is primarily a data fusion technology meant to reduce the amount of required telemetry for spacecraft.

Both of these technologies were tested on an Iron Bird simulator at DFRC but (AFAIK) not onboard anything.

<u>Low TRL approaches:</u>
Mode identificcation has been done with Kalman Filters and Particle Filters on rover testbeds, but never on flight hardware.

Nonlinear optimization approaches to structural faults (Honeywell)

RMPL and Titan (Brian Williams) can do what APEX can do; I can't find any info on testing of this on real hardware, but wasn't it flown on SPHERES? Maybe not.

Other techniques in this category inform logistics and maintenance functions, but are not used for in-flight control; should they be interesting I will follow up. Examples include work for F-22 and F-18 maintenance.

<u>Missing:</u>
Component FDIR
BIST
Sensors

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Forecast of enabling technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast. What is the time estimate for this enabling technology to be ready to support the capability for the mission?*

Identify and articulate any technology gaps discovered:

Enabling Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Technology Assessment – Resource & Research Summary

Known sources of information:

Capabilities (must have, etc.):

Research being done:

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Fu-Kuo: Structural Health Monitoring

http://www.stanford.edu/~gorin/DGResearchPubs2005.html

Brian Williams

Gautam Biswas

Regulatory/security issues? ITAR:

Non-US efforts:

List Any Assumptions:

- USRA Analysis

1. Technology Description

Good general overview of some critical ISHM topics. The document is a good compilation of expected functionalities from an ISHM system for a single UAV. In that regard, it follows closely similar research done on manned vehicles.

The technology description appears to miss the point that ISHM may also apply to a fleet of UAVs, rather than a signle UAV. Many UAV applications will require not one, but several UAVS, and they can keep running even if one of the vehicles is impaired or even destroyed. In a multi-UAV environment, it makes more sense to look at the health of the system as a group, rather than as a set of individual vehicles.

No mention of condition-based maintenance (CBM), an industrial area of research and development clearly linked to ISHM. Strongly debate the claim "small vehicles may not have computational resources for ISHM", given what we see with even consumer devices conducting serious signal processing work.

2. State of the Technology

Good overviews of some systems (F-15, F-18, C-17, 777). Again, the state of the technology focuses on ISHM for single vehicles. The author correctly identifies Livingstone as a space-borne technology that's also applicable to UAV systems.

The author missed the early NASA Dryden experiments with an MD-11 where flight using engines only (failed control surfaces) was achieved, in the wake of the Sioux City United airlines 1989 accident. The report misses several programs such as AFRL's RESTORE program, which demonstrated extensive reconfiguration capability using adaptive control technologies. Tony Calise (GTech), Kevin Wise (BAC-St Louis) and Siva Banda (AFRL-WPAFB) would be excellent POCs.

Lots of incomplete thoughts. No mention of CBM and ISHM work done on aircraft engines at Glenn Research Center.

3. Enabling Technology Development

Some fielded systems do exist, but no additional discussion of programs in this section. Recommend MIT work on UAV IVHM (funded by Boeing - PI/Jon How). Also look at the ongoing work of Brian Williams. At GaTech, Eric Johnson and JVR Prasad in Aero Engr.

4. Technology Dependencies

No discussion of on-board processing or transmission/compression needs - clearly an important issue for transmitting ISHM information.

5. Technology Forecast	Not Addressed; report fails to be more forward-looking in terms of new needs for IHSM technology. The presented IHSM program is really a decade too late ! Should identify the UAV-specific needs as opposed to a boilerplate derived from manned aircraft research.
6. Technology Gaps	Not addressed.
7. Technology Cost Drivers	Not addressed.
8. Competing Technologies	Not addressed.
9. UAV Application Demonstrations	Not addressed.
10. Sources of Information	Not very much information given for additional insight/reference. Additional references should at least include RESTORE reports. Numerous articles on the subject from AIAA *Journal on Guidance, Control, & Dynamics.*
11. Technology Capabilities	Not addressed.
12. Current Research	At least one ongoing research effort listed, but very little provided, nothing in CBM.
13. Regulatory Issues	Not addressed; potential system impacts of disruption of the IHSM data stream.

3.5.2 Planning & Scheduling: IMM & ISHM Planning & Scheduling

- TWG Output

Enabling Technology:__IMM & ISHM__ *Date: 03/21/06*

Specific Technology: Planning & Scheduling
Contributing Editor: Dave Smith
Phone: 650-604-4383 **Fax:** **Email:** de2smith@email.arc.nasa.gov

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Specific Technology Description: *Briefly describe the general nature of the technology. How does it support the capabilities required? This should describe the uniqueness of the technology and project a clear idea of its contribution to UAV capabilities.*

Planning and scheduling is a general cross-cutting technology that takes higher level goals, objectives and constraints and turns these into more detailed plans and schedules that can be executed by humans or machines. The difference between planning and scheduling is that planning involves more choice about which objectives will be achieved, and the actions needed to achieve them, whereas in scheduling, the activities are given, and the principle decisions involve ordering the activities and perhaps assigning resources to the activities. Both planning and scheduling are cross cutting technologies that have wide application to many areas of intelligent systems including both IMM, and ISHM.

For IMM, planning and scheduling technology is useful for automated or interactive mission planning and replanning throughout the course of the mission. It can be applied to long term planning (days, weeks, months) of mission campaigns for fleets of UAVs, to the detailed planning or scheduling of routes and objectives for individual UAVs, or to the detailed actions required for operating sets of instruments on board individual UAVs. Note that automated mission planning and scheduling technology has application both on the ground (to assist humans in the mission planning process) and onboard a UAV to adapt mission plans to rapidly changing events or capabilities. Onboard planning or replanning may be essential if quick responses are needed to changing events (e.g. observation of fires or volcanic eruptions) and there is limited bandwidth or communication with the vehicle.

The automation of planning and scheduling in IMM tasks has a number of potential advantages:

- Quicker response to unexpected events, changing objectives, or degraded capabilities
- Better optimization of mission plans and schedules, yielding cost reductions (fewer flights), better coordination between vehicles, and/or greater productivity from individual vehicles
- Reduction in errors and drudgery over manual human planning and scheduling

In large measure, for UAV mission management this technology impacts efficiency and quality of operations, although rapid replanning capabilities and elimination of errors could improve (or be essential to) mission safety.

For ISHM, planning and scheduling is useful in at least two distinct ways: 1) planning and scheduling of maintenance activities for individual UAVs and fleets of UAVs, and 2) onboard replanning to permit continued operation in the face of degraded capabilities. For maintenance activities, the automation of planing and scheduling has the same advantages listed above for IMM, and largely impacts efficiency and cost of maintenance operations. Condition-based maintenance makes maintenacne planning and scheduling more dynamic and more complex, increasing the need for such capabilities. Onboard replanning for degraded capabilities has the potential to improve both mission safety and mission efficiency – for example, changing smoke or ash plumes from a fire or volcanic eruption might dictate rapid changes in the mission both for the safety of the vehicle, and to continue to obtain useful observations.

Current State of the Technology: Scheduling systems have been widely deployed both in industry and within NASA. For example, automated systems are used to schedule observations for the Hubble Space Telescope and for many Earth-observing satellites such as Landsat7. An automated system is also used for scheduling shuttle maintenance activities. Ground-based scheduling technology should therefore be consider fairly mature and at a relatively high TRL level. This, however, does not mean that it is simple to build such systems – most deployed systems have been highly tuned for their particular application, and significant effort and cost may be required. Recent advances in scheduling technology continue to 1) improve the efficiency and optimization capabilities of scheduling systems, 2) expand the range of applications suitable for automated scheduling systems, and 3) make it somewhat easier to develop such systems.

It is a somewhat different story for planning systems. In general, there are relatively few deployed automated planning systems. Within NASA, two notable exceptions include the CASPER onboard planning system for EO-1 and the MAPGEN planning system being used to plan daily activities for the MER rovers Spirit and Opportunity. Both of these systems should be seen as exemplars of what is currently practical in the arenas of ground-based planning for IMM and rapid on-board replanning for quick response to unexpected events. While both of these systems are clearly at a high TRL level, they have limitations and are highly tailored to their specific applications. As a result, the general readiness level for the technologies should be considered somewhat lower, perhaps TRL 6 for ground based planning and scheduling systems, and TRL 5 for onboard replanning systems. For ground based planning systems additional research and development work is still needed in the areas of :

- mixed-initiative (interactive) planning systems
- plan optimization, particularly in the presence of soft constraints and preferences
- construction of plans involving complex resources
- improving planning speed
- explanation of plans

For onboard replanning improvements are still needed in the areas of:

- improving replanning speed
- plan optimization, particularly in the presence of soft constraints and preferences
- minimizing plan change
- trading off planning and execution time.

Identify funded programs that contribute to the development of this specific technology
Exploration systems ESRT program is currently funding work in this area relating to mission planning for CEV. Science directorate is funding work related to mixed-initiative planning for future MSL rover mission.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
The requirements and characteristics of on-board replanning systems depend heavily on the responsiveness required and on the architecture chosen for the intelligent system. Advances in intelligent system architecture may play a significant role in the requirements for such systems.

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology:
The general TRL levels for these technologies are likely to continue to slowly increase, perhaps at the rate of 1 TRL level every two years or so, as a result of continued academic and NASA work in this area. However, the specific deficiencies mentioned above receive less attention from the academic community, and are essential for NASA mission applications as well as UAV applications. As a result, continued or increased NASA investment in this area is necessary to advance the TRL level.

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Technology Assessment – Resource & Research Summary

Known sources of information:

Research being done:
Planning and scheduling research and development is being carried out both within the academic community, and within industry and government labs worldwide. Little if any of this work is focused on the development of systems specifically tailored for UAV applications.

Regulatory/security issues? ITAR:

Non-US efforts:
Planning and scheduling research and development is being carried out both within the academic community, and within industry and government labs worldwide. Little if any of this work is focused on the development of systems specifically tailored for UAV applications.

List Any Assumptions:

- USRA Analysis

1. Technology Description	Good general description, and nice integration of IMM and ISHM issues in ways that are helpful, but not required in original layout.
2. State of the Technology	Good mention of CBM, and other non-UAV applications (e.g, Hubble Space Telescope, STS maintenance). Several industries, driven by tough economic constraints, have developed extremely efficient software for task scheduling. Among these, air transportation stands closest to the subject discussed here. It is extremely important to include this literature and its reliance on operations research to claim a complete assessment of the technology. Need more discussion of comparisons of time scales: on-board replanning and execution are much shorter timeline processes than original mission planning.
3. Enabling Technology Development	Awareness of Exploration Systems efforts for CEV, mixed-initiative planning for current and future Mars Rover missions. Several programs outside NASA focus on mission planning and execution and should be investigated. These include the past Software-Enabled Control project (DARPA), and DARPA's current HURT program also deals with these questions. AFRL Wright Patterson (Siva Banda) also looked at mission planning problems a great deal.
4. Technology Dependencies	Good recognition of architecture dependencies and mission profile limits to on-board replanning (many things easy for UAVs with 1 second lags to update decision makers are virtually impossible for Mars Rovers with 20 minute lags) Non-UAV examples of successful workarounds?
5. Technology Forecast	The forecast is accurate – the planning technologies keep improving, part due to increased speed of computer processors, part algorithms, but no real data or discussion of source of forecast. Not definitive.
6. Technology Gaps	Some mention in other sections of various technology approaches and gaps.
7. Technology Cost Drivers	Not addressed.

8. Competing Technologies	Not addressed; another assessment suggested remotely piloted UAVs are a competition. Don't agree, but if they are, there is a significant burden on the autonomous community to demonstrate value added.
9. UAV Application Demonstrations	Not addressed; are capabilities demonstrated (mentioned) in space environments relevant to terrestrial UAV settings ? If so, should address.
10. Sources of Information	Implicit in several sections of this report, but not called out here.
11. Technology Capabilities	Communications with decision makers, updating information and presenting usable, utility-driven interfaces of system state are clearly required here, but no mention provided.
12. Current Research	The authors indicate that there is a lot of active work going on in a number of locations, but the overall assessment of research is inaccurate: There has been and still is much research going on mission planning for UAVs. The industry leader is BAE (formerly Alphatech). Ref #3 above. There are indeed few non-US efforts. Lots of work, but it's clear that a UAV-focused effort (research center?) will be required in 2-4 locations.
13. Regulatory Issues	Not addressed: conceptual as well as operational concerns regarding security and hacking/reprogramming of IMM/IHSM data streams could make these systems very unstable and/or untrustworthy.

3.5.3 Software V&V: Access to NAS Certification

- TWG Output

Enabling Technology: V&V for Autonomy Software *Date: March 17, 2006*

Specific Technology: Certification of Autonomy and IVHM Software

Contributing Editor: Dr. Michael R. Lowry
Phone: (650) 604-3369 Fax: (650) 604-3594 Email: Michael.R.Lowry@nasa.gov

Specific Technology Description:
The specific technology proposed is an advanced, automated approach to the comprehensive verification and validation of autonomous UAVs to allow these complex vehicles to be certified for operational use in the National Airspace (NAS) with a minimum time investment.

Certification is approval of a product for use within an operational envelope by a governing body, such as a flight readiness review board. If the product is an aircraft to be flown in the United States, that certification authority is the Federal Aviation Authority (FAA). Before granting a certificate, the FAA will need to ensure there is a sound engineering basis for certification.

The proposed technology will provide the sound engineering basis for certifying UAV autonomy software, and will meet the anticipated expansion of the operational envelope of autonomy software over the next two decades. This technology will ensure that there is an engineering basis for verifying and validating autonomy software to ensure coverage of the operational envelopes needed by complex UAV mission objectives. The certification technology developed by this project will meet the coverage requirements for verification and validation of both the current state of the art in autonomy software and the increasing capabilities of tomorrow's autonomy software.

The goal of this work is to develop certification technology that goes beyond the current state of the practice and state of the art in two conceptual steps: first by developing an advanced and highly automated form of testing that can greatly expand the number and variation of certified scenarios, and then by progressively augmenting testing by advanced formal verification techniques (e.g., static analysis and symbolic model checking) that provide higher levels of coverage, thereby meeting the demands of certifying of larger operational envelopes.

The certification technology will address the three principle components of the standard autonomy architecture for autonomous UAV missions: planners, executives, and model-based fault diagnosis and recovery. Despite the fact that the functions of these three components are necessary elements of any flight mission, they are currently done through a mixture of labor-intensive ground operations and limited on-board software, such as command and data handling. These three components of autonomy systems share the same following structure:

- a model, which contains application-specific information in the form of constraints, and,
- an engine, which searches constraints of the application to find an appropriate solution.

The certification requirements for autonomy software depend on the operational envelope that the software needs to meet. The relevant metrics for the operational envelope of an autonomy system, in addition to the specific functional requirements, include the following:

1) The time interval between human supervision
2) The scope and variation of nominal scenarios for which the system needs to correctly function.
3) The degree of robustness and fault-tolerance in meeting off-nominal scenarios.
4) Degree of deployment, from off-line advisory ground software to inner-loop on-board software.

Our approach to autonomous UAV certification is based on the following comprehensive tree of fault classes. The certification technology that we develop will provide assurance with respect to these fault classes up to an expanding operational envelope. Assume, for example, that a mission needs to support "science on-the-fly". This may require the UAV to be able to execute plans with more contingencies than have been used in missions flow thus far. Moreover, if humans were to produce such plans they would have to create extremely complicated plans that account for all the possible environmental conditions that may be encountered during the flight. Such capabilities therefore require both on-board planning, and sophisticated plan execution, which in turn increase operational envelopes far beyond the current state of the art. To be able to test for these envelopes to a satisfactory degree for certification is an extremely complicated, if not impossible task to be performed by humans within a limited timeframe with state-of-the-art verification technology.

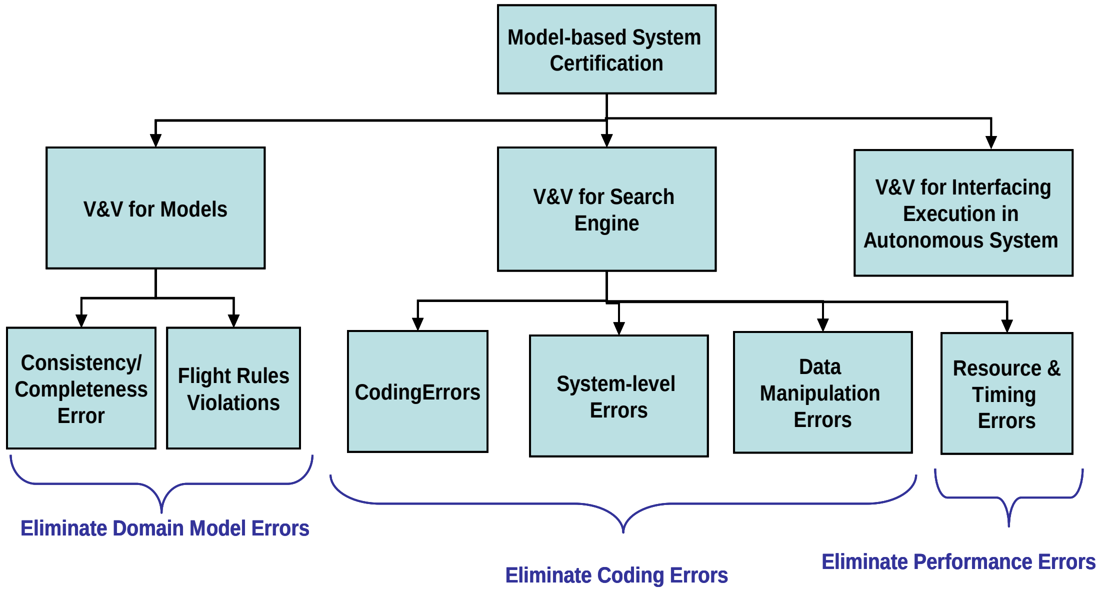


Figure 3.1 - Property decomposition for model-based software.

Current State of the Technology:
For aerospace technologies, the certification process typically begins with a developer proposing a process for ensuring the safety, reliability, and effectiveness of the technology for a specified operational envelope to the FAA. This process is usually a series of verification and validation activities; such as unit testing, system integration testing, and scenario-based testing. The FAA then asks for amendments to the proposed process that it believes is necessary for ensuring safety, reliability, and effectiveness. Once the process is approved, the developer then needs to demonstrate that the process was followed to the FAA. TheFAA can ask for further evidence of safety and effectiveness, including examining the product itself.

The current state of the practice in autonomy software is to use planners on the ground (Mars Exploration Rover) and rely on standard command and data handling systems and local subsystem health management on board. Current mission verification and validation practices ensure safety by testing the system for a set of nominal scenarios and some off-nominal scenarios. This process is costly and does not certify variations to nominal scenarios. Moreover, it offers little coverage of the off-nominal scenarios.

Functional properties to verify include flight rules (to enforce safety, and includes conformance to ATC requirements such as IFR procedures for lost communication), consistency (to guarantee the absence of contradictory solutions), and completeness issues (to guarantee the coverage of all behaviors). While verifying the enforcement of flight rules is a key to the verification process, checking for consistency and completeness is critical for validation. Early simplistic versions of planners and diagnosis systems used discrete-state models. However, realistic UAV applications will require more complex models involving discrete and continuous variables, time constraints, and possibly, stochastic reasoning. Reasoning about consistency and completeness is extremely hard with such complex models; as of now, the V&V community does not know how to scale the verification of such models.

Although the current TRL varies somewhat with the specific technology, the average is about TRL 3. This technology would advance the readiness level to TRL 6 within 2-3 years.

Identify funded programs that contribute to the development of this specific technology
At present, there are two NASA programs that are expected to contribute to the development of UAV verification, validation, and certification technology. These programs are:
- Reliable Software Engineering Project, NASA Exploration Systems Architecture Study
- Software for Advanced Health Software, NASA Exploration Systems Architecture Study

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Certification of model-based autonomy involves at least two steps, which we expand below for IVHM. Similar analysis for certification of model-based execution and planning are available on request:

1. Verification and validation of the (application specific) model used in model based diagnosis (for consistency, diagnosability and other properties). An important issue (often ignored in practice) is the validity of the models with respect to the physical system. This is especially true for models that are very coarse abstractions (e.g. as used in Livingstone 2 system developed at Ames), both in variable domains and in time. A large part of this problem lies in the implementation of the abstraction layer that interfaces the diagnoser with the (physical) system.
2. Verification and validation of the (generic) model based engine used in the IVHM software. This involves simulation and/or testing of IVHM software to ensure that it functions properly – i.e. ensure that diagnosis results are sound with respect to the model and that the system as a whole performs appropriate diagnosis for the desired application.

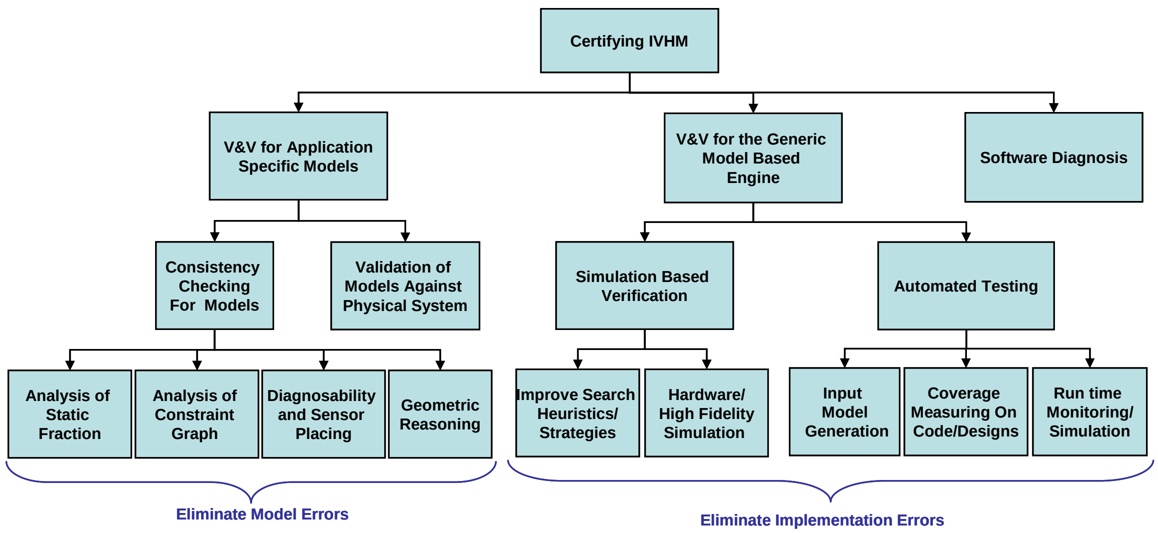


Figure 3.2 - Certifying IVHM

Rationale

We are proposing the following approaches:

- **Analysis of diagnosis models using model checking techniques.** This was done (partly) for Livingstone 2 (automated translation to the input language of the SMV model checker). Extend this work for Livingstone 2 and start working on models for Livingstone 3 (the new generation of diagnosis systems developed at Ames) – involves hybrid model checking. Possible research directions:
  - **Analysis of the static fraction of the model** — This provides, in essence, an envelope of the "legal" states of the model, on which it is possible to check various classes of properties such as consistency of transition pre-conditions and post-conditions, some application specific expected model properties (e.g. connectivity, functional dependency between variables), liveliness of enabled conditions (there exists a post-state). Experiment on real-life applications such as EO-1.
  - **Analysis of constraint graphs** — The goal of this would be to chain through the graph of constraints to detect (derived) variables that are not connected to root (state) variables. This potentially points to under-specified models that will lead to ambiguous values. A related problem is finding circularities in the propagation of values through the graph. A simple form of this is to merely trace the graph; a finer analysis is to consider particular state assignments, which entails some amount of case-splitting and constraint reasoning. This is another form of static constraint analysis like the previous item; the same remarks about relevant models apply.
  - **Diagnosability and Sensor Placement** — Previous work on diagnosability has been limited to proving a given diagnosability condition on a given model. The next logical step is to consider alternative sensor configurations and evaluate diagnosis capabilities with respect to the number and choice of sensors. Then one may investigate optimal sensor placement, i.e. finding the minimal-cost set of sensors that achieves given diagnosis capabilities. This can all be done naively by enumerating and verifying each alternative, but the cost is exponential. Some form of differential verification may be used, based on the same principles as the incremental constraint solvers used for diagnosis. Then the optimal sensor problem appears as an instance of an optimization problem.

The IVHM Testbed is a very nice application for these ideas, because it proposes essentially the complete set of possible sensors.

- **Geometric reasoning** — The FIDO model, in particular the part dealing with wheels and with the instrument arm, may provide an interesting venue for innovative work. The model provides a discrete abstraction for fairly complex geometrical reasoning. It could be validated against a geometrical model, possibly with the help of the tools from U. Irvine.
- Integration with IVHM Testbed.
- **Simulation-Based Verification of IVHM software** - Previous work on Livingstone PathFinder (LPF) addresses simulation based verification in the context of Livingstone 2. This work can be extended in several ways:
- **Search Heuristics/Strategies** — LPF can do guided search, but is limited to two heuristics so far: breadth-first search and candidate count. Further work would be needed both to assess and measure the benefits of these two and to explore others, possibly tuned to a specific application. Depth-first and guided search are currently supported. A (model) coverage-based search algorithm appears as an interesting candidate for further work.
- **State Matching** — This would allow pruning the search when reaching a state equivalent to an already visited one. The potential benefits from this approach remain to be assessed: as Livingstone retains data not only about the current step but previous ones as well, cases where equivalent states are reached through different executions may be very infrequent. As an alternative, experiments with weaker or approximate equivalences may be performed to reduce the search space, at the risk of inadvertently missing relevant traces. A bit too technical for this proposal – omit state matching.
- **Hardware/high-fidelity simulators** — Another significant and so far untried extension is to connect an exogenous simulation of the system in the LPF testbed (so far a second Livingstone engine has been used for that). There is both a significant engineering effort involved for instrumenting and wrapping the simulator into an implementation of the appropriate Java interface, and potentially deeper methodological issues in mapping between the simulator's finer-grain model and Livingstone's abstract view. In a sense, what is needed is a simulation of both the system and the abstraction layer on top of it.
- **Automated testing for IVHM software** — Involves automated generation of input models (based on our previous work on automated generation of plans), monitoring the execution for conformance, measuring coverage (see discussion below on coverage metrics proposed). Black box approach – could be applied to Livingstone 2 or 3.
- **Diagnosis of Software** — This issue touches both diagnosis and general software reliability concerns. IVHM experts currently have very little insight in how to include software in general, and the diagnosis/ISHM software in particular, as part of their ISHM/diagnosis analysis. We will investigate these issues.

Coverage metrics provide a useful and much needed measure of the thoroughness of verification activities. They allow the comparison of alternative verification methods and assessment of improvements across generations. We distinguish between functional (black-box) coverage and structural (white-box) coverage criteria.

- **Functional coverage** for model-based diagnosis will typically be expressed in terms of hazard analysis data. In a first approach, fault coverage will require that diagnosis of every single fault has been tested. Multiple faults may be considered too; the number of test cases increases exponentially but so does the likeliness of occurrence, assuming independent faults. Obviously, highly correlated faults are strong candidates for testing. Finer grain of analysis may combine other measures: decompose and test failure cases into individual fault conditions (e.g. MCDC coverage), test each fault in each mode of the corresponding component, etc. This corresponds to current practice, though the elaboration of test cases is currently done manually. One of LPF's benefits is to automate this process.
- **Structural coverage** should be measured with respect to the application specific "code", i.e. the model, rather than the code of the engine, for which coverage would likely be quickly achieved but provide little overall confidence w.r.t. the application under consideration. Measuring structural coverage on models requires to be able to track how modeling statements (rules, constraints) are exercised during analysis. I would expect that a lot of that information is tracked internally in engines such as Livingstone, if only to allow efficient incremental operation. One only needs to provide the programmatic interface to access that in a usable way. Once this is available, different coverage criteria (cover all clauses, all literals, combined clauses-literals a la MCDC) can be defined and experimented with, to measure both their filtering capabilities (e.g. using mutation testing) and their scalability (i.e. the number of tests needed to achieve coverage). I am not aware of any existing results of that nature.

Identify funded programs that contribute to the development of the critical supporting technology:

At present, there are two NASA programs that are expected to contribute to the development of UAV verification, validation, and certification technology. These programs are:

- Reliable Software Engineering Project, NASA Exploration Systems Architecture Study
- Software for Advanced Health Software, NASA Exploration Systems Architecture Study

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

2007 – TRL 3
2009 – TRL 4
2010 – TRL 5-6

From the start of the project, we need to study what makes some technologies (e.g., static analysis) scale and how we can adapt these scalability enablers to reasoning about timed, hybrid, or stochastic models. This early investment will greatly impact the quality of our delivery two or three years from now. Moreover, as the push towards on-board autonomy increases so is the need to complement the V&V of each sub-system (i.e., planner, executive, application layer, IVHM) with an integrated V&V of the whole system. We have to identify from the start what properties flow from one sub-system to another. Again, even though the integration capability will be available only in later years, the foundation work has to be started now.

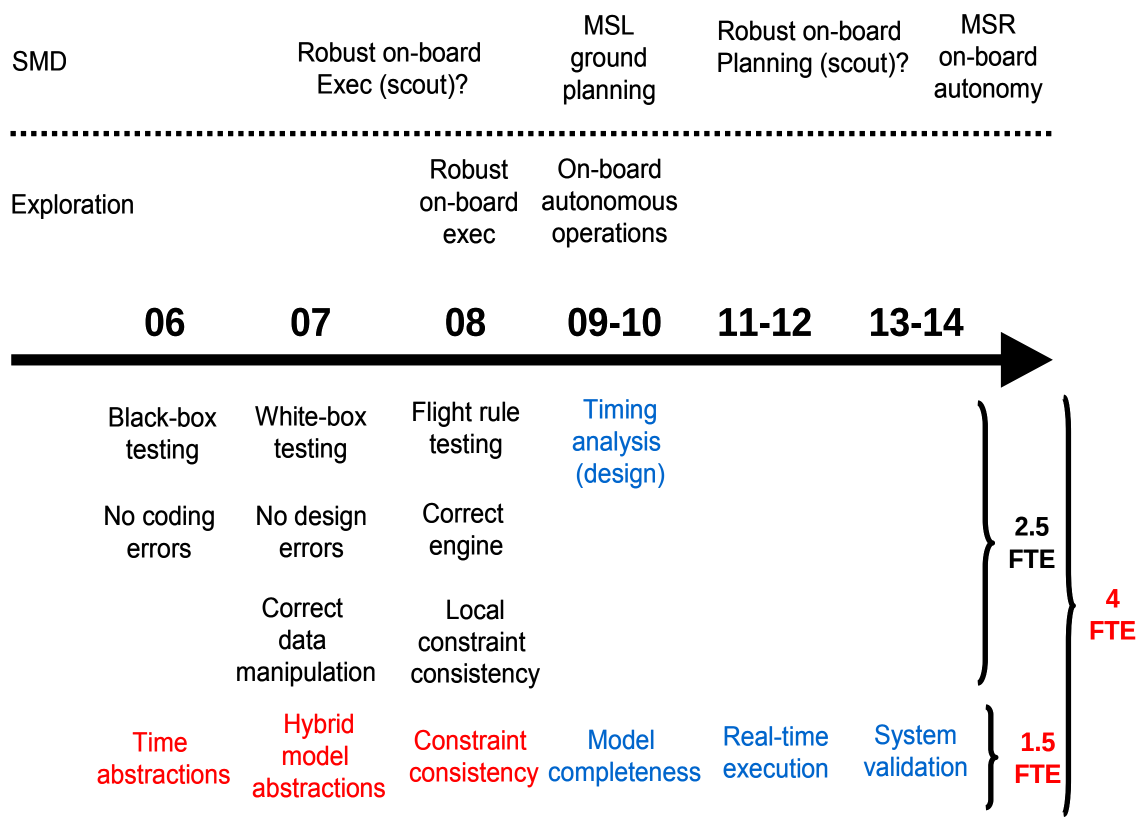
Specific Technology Cost Drivers: *Operating and development costs.*
Software development costs; assess to UAV platforms to demonstrate technology approaches.

Known competing or disruptive technologies:

Competing technology is largely model based analysis and extensive testing conducted via computer simulation and followed by limited flight testing. Although the nominal operating conditions can be tested using this approach, only a small subset of possible off-nominal conditions can be tested.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					



Schedule for V&V of autonomy and IVHM.

Demonstrated for UAV application?:

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:
Surveys:

- P. Meseguer, "Verificaiton of multi-level rule-based expert systems", in Proceedings of the Ninth National Conference on Artificial Intelligence, 1991.
- A. Preece. "principles and practices in verifying rule-based systems", The knowledge engineering review (7) 1992.
- R. O'Keefe and D. O'Leary, "Expert system verification and validation: a survey and tutorial", Artificial Intelligence Review (7), 1993.
- N. Zatlereva and A. Preece, "State of the art in automated validation of knowledge-based systems", Expert systems with applications 7 (1994).
- B. Smith, M. Feather, N. Muscettola, "Challenges and methods in validating the remote agent planner", in Proceedings of AIPS 2000.
- Charles Pecheur. "Verification and Validation of Autonomy Software at NASA". *NASA/TM 2000-209602, August 2000*
- S. Nelson and C. Pecheur, "NASA processes/methods applicable to IVHM V&V", NASA Report *NASA/CR-2002-211402*, 2002
- T. Menzies and C. Pecheur, "Verification and Validation and Artificial Intellgience", in Advances in Computers, vol. 65, Elsevier, 2005

Workshop:

- AAAI-93 Workshop on Validation and Verification of Knowledge-Based Systems
- ICPAS 05 Verification and Validation of Planning and Scheduling Systems
- Annual Workshop on Model Checking and Artificial Intelligence
- RIACS Workshop on the Verification and Validation of Autonomous and Adaptive Systems

Research being done:
Papers:

- G. Brat *et al.* "Verification of Autonomous Systems for Space Applications", IEEE Aerospace Conference, 2006.
- G. Brat *et al*., "A Robust Compositional Architecture for Autonomous Systems", IEEE Aerospace Conference, 2006.
- J. Schumann et al. , "Autonomy Software: V&V Challenges and Characteristics", IEEE Aerospace Conference, 2006.
- L. Markosian, "Maturing Technologies for V&V of ISHM Software for Space Exploration", IEEE Aerospace Conference, 2006.
- Charles Pecheur, Reid Simmons, Peter Engrand. **Formal Verification of Autonomy Models: From Livingstone to SMV**. *In: Rouff, C.; Hinchey, M.; Rash, J.; Truszkowski, W.; Gordon-Spears, D. (Eds.), Agent Technology from a Formal Perspective, NASA Monographs in Systems and Software Engineering, Springer Verlag, 2006.*
- Franco Raimondi, Charles Pecheur, Alessio Lomuscio. **Applications of model checking for multi-agent systems: verification of diagnosability and recoverability**. *In: Proceedings of Concurrencey Specification and Programming (CSP 2005), Ruciane-Nida, Poland, Sep 2005*.
- Tony Lindsey and Charles Pecheur. **Simulation-Based Verification of Autonomous Controllers with Livingstone PathFinder**. *In: Proceedings of the Tenth International Conference on Tools And Algorithms For The Construction And Analysis Of Systems (TACAS'04), Barcelona, Spain, Mar-Apr 2004. Lecture Notes in Computer Science, vol. 2988, Springer Verlag.*
- A.E. Lindsey and Charles Pecheur. **Simulation-Based Verification of Livingstone Applications**. *Short paper, Workshop on Model-Checking for Dependable Software-Intensive Systems, San Francisco, June 2003*.
- Alessandro Cimatti, Charles Pecheur, Roberto Cavada. **Formal Verification of Diagnosability via Symbolic Model Checking**. *Proceedings of IJCAI'03, Acapulco, Mexico, August 2003.*
- Stacy Nelson, Charles Pecheur. **Formal Verification of a Next-Generation Space Shuttle**. *In: Second Goddard Workshop on Formal Aspects of Agent-Based Systems (FAABS II), Greenbelt, MD, October 2002. Lecture Notes in Computer Science, vol. 2699, Springer Verlag.*
- Charles Pecheur, Alessandro Cimatti. **Formal Verification of Diagnosability via Symbolic Model Checking**. *Workshop on Model Checking and Artificial Intelligence (MoChArt-2002), Lyon, France, July 22/23, 2002.*
- Steven Brown, Charles Pecheur. **Model-Based Verification of Diagnostic Systems**. *Proceedings of JANNAF Joint Meeting, Destin, FL, April 8-12, 2002.*
- Reid Simmons, Charles Pecheur, Grama Srinivasan. **Towards Automatic Verification of Autonomous Systems**. *In: Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, 2000.*
- Klaus Havelund, Mike Lowry, SeungJoon Park, Charles Pecheur, John Penix, Willem Visser, Jon L. White. **Formal Analysis of the Remote Agent Before and After Flight.** *In: Proceedings of 5th NASA Langley Formal Methods Workshop, Williamsburg, Virginia, 13-15 June 2000.*
- Charles Pecheur, Reid Simmons. **From Livingstone to SMV: Formal Verification for Autonomous Spacecrafts.** *In:Proceedings of First Goddard Workshop on Formal Approaches to Agent-Based Systems, NASA Goddard, April 5-7, 2000. Lecture Notes in Computer Science, vol. 1871, Springer Verlag.*
- Reid Simmons, Charles Pecheur. **Automating Model Checking for Autonomous Systems.** *Proceedings of AAAI Spring Symposium on Real-Time Autonomous Systems, Stanford, March 20-22, 2000.*
- John Penix, Charles Pecheur and Klaus Havelund. **Using Model Checking to Validate AI Planner Domain Models.** *In: Proceedings of the 23rd Annual Software Engineering Workshop, NASA Goddard, December, 1998.*

Regulatory/security issues? ITAR:

ITAR Categroy II may apply.

Non-US efforts:

- Charles Pecheur, Universite de Louvain, Belgium
- Felix Ingram, LAAS/CNRS, Toulouse, France
- Alessandro Cimatti, Instituto per la Ricerca Scientifica e Tecnologica, Trento, Italy

List Any Assumptions:

- USRA Analysis

1. Technology Description	Excellent description of a well thought-out plan.
2. State of the Technology	The author correctly points out the state of the technology and points out the gap between what FAA does today and the functionalities to be certified in the future; however, a bit optimistic in saying that the objectives can be reached within 2-3 years.
3. Enabling Technology Development	The programs identified by the author are worth mentioning. Among non-NASA programs, NSF/Helen Gill, as well as a new certification program at AFRL-WPAFB/Vincent Crum.
4. Technology Dependencies	The list is very long and very complete. The community is already struggling with basic control laws, and the kind of functionalities described are way beyond that. Also, it appears this document came in part from a previous document involving ground robots… or I did not know wheels were a central component of UAVs !
5. Technology Forecast	The forecast includes the right elements. Bringing in static analysis as a central element is wise. However, it is a bit aggressive.
6. Technology Gaps	Not addressed.
7. Technology Cost Drivers	Cost drivers are indeed associated with software development. Before developing any certification software, a significant amount of basic research must be done. What is the certification problem? Lack of investment in basic embedded software V&V research during the past many years, in order to prove embedded software is an integral part of the design cycle and of its certification. Need to formally prove the absence of well-known software defects prior to delivery. If unmanned systems are to operate within civilian operation boundaries, issue becomes critical challenge. Current efforts are vastly undersized compared with the economic significance of the problem. Software V&V requires very sophisticated mathematical analysis techniques to get anywhere, and in particular to achieve scalability that no manual approach will ever be able to reach.

8. Competing Technologies	Analysis, simulation testing, and flight testing can be integrated as complementary technology. Wherever automated software verification has become reality, it has considerably reduced the cost of these other steps.
9. UAV Application Demonstrations	Not addressed.
10. Sources of Information	This is the most longest list of sources I have seen in all reports; however, list limits itself to a handful of authors and does not seem to look much beyond NASA's boundaries. While these publications are probably the most relevant, the author might find it useful to point out the enormous literature that exists in real-time software V&V, including testing, static analysis methods (model checking, abstract interpretation) and others.
11. Technology Capabilities	Not addressed.
12. Current Research	Good listing
13. Regulatory Issues	Addressed in limited fashion.

3.5.4 Design: Design Tools

- TWG Output

Enabling Technology: Design Tools for ISHM

Contributing Editor: Joe Totah (ref. Dr. Irem Tumer) ***Date: 23 January 2006***

Phone: (650) 604-1864 **Fax: (650) 604-4036** **Email:Joseph.J.Totah@nasa.gov**

Enabling Technology Description:
Integrated Systems Health Management (ISHM) is responsible for maintaining nominal system behavior and function, and assuring mission safety and effectiveness under off-nominal conditions. For manned missions and vehicles, it is considered a critical aspect of crew safety. For unmanned missions and vehicles, it is a key aspect of autonomous operation and reliability. A key challenge is to ensure these systems are not designed and implemented as an afterthought when design decisions that preclude effective ISHM might have been made. Instead, ISHM functions should be considered in system-level design as early as possible in the requirements and architecture definition phases.

The Complex Systems Design Group in the Intelligent Systems Division at NASA Ames Research Center (http://ic.arc.nasa.gov/tech/groups/index.php?gid=46&ta=4) conducts research to enable the system-level *co-design* of ISHM Systems along with the vehicles and systems for which they are intended, including *functional failure analysis*, and *risk assessment under uncertainty*. The CSD group's focuses on Complex Systems Design research involves developing design principles and formal methods for designing, modeling, and evaluating complex engineering systems with specific emphasis on mitigation and reduction of risks and uncertainty due to failures. This topic covers design theory and methodology, failure analysis, failure detection, health management, functional modeling, system and design optimization, collaborative and concurrent design and teaming.

Current State of the Technology:
Designing and building systems and vehicles for today's aerospace missions requires working with high-risk, high-cost, low-volume missions, under rigid design constraints and conflicting goals, and dealing with high levels of uncertainty and increasingly complex interactions. Success depends heavily upon the ability to meet the stringent requirements of safety, reliability, and performance while having to push the limits of structural integrity, material durability, and autonomous operation. Designers are expected to anticipate every possible contingency and account for interactions among components that cannot be thoroughly planned, understood, anticipated, or guarded against. As a result, it is not only critical to "design out" failures when possible, but also to "design in" the capability to detect, diagnose, and recover from failures throughout the mission lifecycle when they do occur. In response to these critical needs, the aerospace industry as a whole has imposed a requirement to include an Integrated Systems Health Management (ISHM) capability for the next generation aerospace vehicles and systems. The current state of ISHM capabilities is one of designing the ISHM capability separately from the systems and vehicles they are designed for, as an after-thought, and retrofitting existing systems with the ISHM capability. The reason for this is largely historical and cultural. We do not currently have true ISHM capability that is robust and reliable on existing systems. The "M" in ISHM stands for "management", that is mitigation of a failure when it occurs. This becomes a crucial aspect to assure safety, cost, and performance. As a result, the aerospace companies, the military, and the government are currently investing in research that will enable the robust design of such systems. The ISHM co-design research discussed in this document is a significant step towards achieving this goal. ISHM co-design is considered low-to-mid TRL.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?
The set of methodologies and tools are in support of the exploration mission directorate's concept evaluation and engineering analysis goals, as well as the science directorate's various mission design goals.

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Codesign and Optimization of Health Management and Vehicle Systems
Function-Based Failure Analysis during Design

Risk and Uncertainty Based Concurrent Design and Trade Space Analysis

Forecast of enabling technology:
The goal is to have these capabilities matured to a level consistent with ISHM requirements and timeframe for NASA's Exploration Systems Mission Directorate. Integrated Systems Health Management (ISHM) will be a critical element for Exploration mission vehicles and systems. To provide reliable and robust results, we assert that ISHM systems must be integrated with functional design of the systems they will be used for. A significant challenge is the lack of formal design methods and tools to enable this integration. We propose to leverage existing formal design practices and methodologies for functional/conceptual design so that ISHM design can be seamlessly incorporated into system and design work practices.

Identify and articulate any technology gaps discovered:

http://ic.arc.nasa.gov/partner/files/Design_Practices_for_ISHM.pdf
Despite significant improvements in health management solutions, simply retrofitting ISHM systems into existing systems is not effective. Last-minute retrofits result in unreliable systems, ineffective solutions, and excessive costs (e.g., Space Shuttle TPS monitoring which was considered only after 110 flights and the Columbia disaster). High false alarm or false negative rates due to substandard implementations hurt the credibility of the ISHM discipline. There are several challenges to widespread ISHM implementation and use today. These include:
• Lack of tools and processes for integrating ISHM into the vehicle system/subsystem design;
• Standards and interfaces with limited following (e.g., Open System Architecture for Condition Based Maintenance (OSACBM));
• Limited appreciation for ISHM in engineering design practice.

Enabling Technology Cost Drivers: *Operating and development costs.*

Monitoring and management of the health state of diverse components, subsystems, and systems is a difficult task, and will only become more challenging when required and implemented for long-term and evolving missions. The design for ISHM environment envisioned here will enable a robust **system-of-systems level** capability. The result will be designs for robust ISHM systems with an overall impact of reducing operations cost, increasing safety and reliability, sustaining engineering activities.

Known competing or disruptive technologies:

NASA currently employs a number of risk analysis tools and methods, including FMEA, FTA and PRA, and design engineers have used them successfully for designing reliable and safe systems. But these methods have drawbacks that limit their applicability to design for ISHM. We will begin by surveying current Risk Analysis methods and tools at NASA to determine which are most applicable to design for ISHM. Next, we will extend those methods to suit design for ISHM goals. We have already begun work in developing failure analysis methods that determine failures modes during the early stage of functional design.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

None planned for civil UAV applications.

Demonstrated for UAV application?:

None planned for civil UAV applications.

Technology Assessment – Resource & Research Summary

Known sources of information:
http://ic.arc.nasa.gov/tech/groups/index.php?gid=46&ta=4
http://ic.arc.nasa.gov/partner/files/Design_Practices_for_ISHM.pdf

Capabilities (must have, etc.):

Codesign and Optimization of Health Management and Vehicle Systems
Function-Based Failure Analysis during Design
Risk and Uncertainty Based Concurrent Design and Trade Space Analysis

Research being done (see publications):

Codesign and Optimization of Health Management and Vehicle Systems

Project Lead: Dr. Irem Tumer

We investigate standard formal practices and methodologies used in engineering design and propose a design environment where ISHM systems can be developed in conjunction with the system and subsystem design. We are developing a methodology to represent the critical functions, flows, and the interactions (using function-based modeling, before a form or solution is selected) to accomplish the objectives of the vehicle system' performance alongside the objectives of the health detection and monitoring systems, to map these functions to failure modes (see Function based failure analysis method below), and design safeguards and/or additional functionality to enable robust ISHM avoiding these failures. We also are developing an automated system analysis and optimization environment to enable vehicle systems designers to perform tradeoff analyses and determine the impact of ISHM Figures of Merit on the vehicle systems performance and risks, and, to enable ISHM designers to systematically model and provide metrics of candidate system design alternatives for the purpose of aiding the decision making process by selecting or rejecting options based upon clearly identified criteria, including quantified safety and reliability performance and cost benefit analysis. This project involves work on: Automated system analysis and optimization, Multi-objective optimization, Function-based ISHM and Function-based Reasoning.

Function-Based Failure Analysis during Design

Project Lead: Dr. Irem Tumer

Early stage design, especially conceptual design, presents the best opportunity to cost effectively catch and prevent potential failures and anomalies. We use a function based modeling approach which enables designers to think through the system layout by following the input and output flows through the main required functions. In collaboration with the University of Missouri-Rolla, we have developed a function modeling based failure analysis methodology to map historical and potential failure modes to functions, and search the space of functions and components of similar functionality to generate concepts that eliminate potential failure modes associated with certain functions based on historical data, FMEAs, and expert elicitation. Alongside the methodology, we are building generic and reusable functional models (templates), and a list of standardized failure modes for various domains (Rotorcraft, Spacecraft systems, etc.) using historical data, and building a knowledge base to enable searching through various domains. In addition, we are mapping risk to functions to start building the knowledge base for failure rates based on historical data. Finally, we are designing a user interface to enable use for design trade space analysis and for concept evaluation in the early stages of design. This project involves work on: Knowledge base development populated with data from generic functional templates and results from mining of historical anomaly and failure; Methodology development including function to risk mapping, failure modeling, and definition of software functionality and failures; User interface design including usability analysis and concept prototyping.

Risk and Uncertainty Based Concurrent Design and Trade Space Analysis

Project Lead: Dr. Irem Tumer

Uncertainty in the decisions made during the early stages of design introduces a non-negligible amount of risk to concepts being designed and/or evaluated, often facing the possibility of ending up with incorrect solutions in the design trade space. Because of the difficulty in assessing and communicating this uncertainty, most designs allow for contingencies to address the variability introduced due to this risk. In this project, we aim to capture and quantify uncertainty and risks due to lack of knowledge and due to potential failures. In collaboration with Robust Decisions Inc., we are developing an information exchange tool (X-Change) to enable various subsystem designers to capture, quantify, and communicate the risks due to uncertainty from their lack of knowledge and risks due to failures that might not be readily available or quantifiable. We are developing the design environment and scenarios where the tool will be tested and validated, building towards enabling a collaborative and concurrent design environment. Finally, we are developing a Risk and Uncertainty Based Integrated and Concurrent Design (RUBIC-Design) method to provide a mathematical framework to capture risks and uncertainty due to functional failures in the early stages of design, and enable tradeoffs and resource re-allocation to enable on risk reduction and mitigation. This project involves work on: Design team trade study scenario development; Risk modeling and quantification due to failures and uncertainty; X-change tool development and decision making under uncertainty.

Regulatory/security issues? ITAR:
Unknown

Non-US efforts:
Unknown

List Any Assumptions:
None

- USRA Analysis

1. Technology Description	The description does highlight the efforts of the NASA Ames group conducting work in this area. There are many other groups conducting engineering design efforts, and the general concepts of concurrent design and system analysis are certainly not unique to UAV. Other inputs and perspectives should be discussed. Disconnect between what is written and what is expected as a general discussion of enabling technologies. Should be aware/integrate other efforts in NASA roadmapping and technology assessment exercises.
2. State of the Technology	Challenges and limits of current TRL (identified as low-to-mid) capabilities are described in relevant ways. The technology development model presented (as a straw person argument) of designers anticipating all possible contingencies is flawed. Current TRL for ISHM design in non-aircraft systems (building health, other CBM designs) are not mentioned.
3. Enabling Technology Development	Listed response is a non-answer.
4. Technology Dependencies	Some relevant dependencies listed; however, would like to see more descriptions of areas of overlap and challenges.
5. Technology Forecast	The response is not a true forecast, but an identification of challenges.
6. Technology Gaps	Very important technology gaps seen here. The report suggests that the entire area is at low TRL, with few or no inherent capabilities for short-term improvement. Problems with false alarm and false negative rates are not just problems for the credibility of the domain. They reduce operational trust in fielded systems, and limit the ability to understand true failure mode probabilities and response capabilities.
7. Technology Cost Drivers	Clearly, improvements here can significantly reduce life-cycle systems engineering costs, and reduce system failures that limit operational capability during critical mission phases.
8. Competing Technologies	The report is aware of the risks and limits to existing NASA risk analysis tools. Non-NASA design approaches are not discussed or identified.
9. UAV Application Demonstrations	None planned
10. Sources of Information	Significant information regarding NASA Ames research group efforts and project directions. Lack of identification of other work.

11. Technology Capabilities	Based on this report, the field is lacking in required approaches, tools, and demonstrable success stories.
12. Current Research	While tech element is critically important to overall system success, no identification in report.
13. Regulatory Issues	Unknown

3.5.5 Maintenance: Condition-based Maintenance

- TWG Output

Enabling Technology: ISHM Date: 21 March 2006

Specific Technology: Condition-based Maintenance

Contributing Editor: Michael Shafto
Phone: 650-604-6170 **Fax:** **Email:** mshafto@mail.arc.nasa.gov

Specific Technology Description:
Condition based maintenance is an automatic process that determines when a fault has occurred or is going to occur in a system and subsequently diagnoses the cause of the fault in order to enhance the reliability, safety, and maintainability of variable-duty-cycle machines. CBM can reduce the cost of life-cycle maintenance.

Current State of the Technology:
TRL 9 deployed in operational environments in the aerospace, nuclear power and maritime industries. It has been used, e.g., in X38, NGLT, Boeing 777, military rotorcraft. Current maturity level is indicated by attention turning to standards

Identify funded programs that contribute to the development of this specific technology
NIST, ONR, NASA, USAF, Boeing,

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Decision-making criteria applicable to intelligent machines whose dynamics may be approximated by a parametric nonlinear model and are subject to nonstationary effects; software frameworks for the implementation of CBM in high bandwidth real time environments

Open System Architecture OSA for Condition Based Maintenance (CBM)
Definition of a distributed software architecture for CBM with emphasis on the prognostics module
Open Systems Approach to Integrated Diagnostics developed by the Boeing and Honeywell Corporations for the 777 aircraft (Aircraft Information Management System AIMS)

sensors ,algorithms, models, and automated reasoning to monitor the operations of machinery and determine appropriate maintenance tasks prior to an impending failure
example: reliable corrosion sensors can significantly reduce the cost of aircraft operations
example: mechanical faults often show their presence through abnormal acoustic signals

aging precursor metrics correlated with degradation rate and projected machine failure degradation-specific correlations are currently being developed at PNNL that will allow accurate physics based diagnostic and prognostic determinations to be derived root cause analysis focused on quantifying the primary stressors

inferential sensing using mathematical models to infer a parameter value from correlated sensor values regularization can be used to solve ill conditioned problems and produce consistent results example: monitoring nuclear power plant feedwater flow rate

Related benefits from the same technology: optimization of operations through adaptive power management etc.; detection of operational errors via off-line analysis of flight data: alert human analysts to aircraft flights that are statistically atypical in ways that signify that safety may be adversely affected

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology:

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

<u>Technology Assessment – Resource & Research Summary</u>

No information provided

- USRA Analysis

1. Technology Description	Pretty brief
2. State of the Technology	Sketchy
3. Enabling Technology Development	Too brief.

4. Technology Dependencies	Some relevant dependencies listed; however, would like to see more descriptions of areas of overlap and challenges.
5. Technology Forecast	Not addressed.
6. Technology Gaps	Not addressed.
7. Technology Cost Drivers	Not addressed.
8. Competing Technologies	Not addressed
9. UAV Application Demonstrations	Not addressed.
10. Sources of Information	Not addressed.
11. Technology Capabilities	Not addressed.
12. Current Research	Not addressed.
13. Regulatory Issues	Not addressed.

3.6 Contingency Management

3.6.1 Overview

- TWG Output

Enabling Technology: Contingency Management

Contributing Editor: David Smith ***Date: 2/16/06***

Phone: 650-604-4383 **Fax:** **Email:** de2smith@email.arc.nasa.gov

Enabling Technology Description:
Contingency Management refers to an on-board capability to react to unforeseen events, particularly as needed to minimize the likelihood of human casualties and property damage, and to maximize the likelihood of aircraft and payload survival. More generally, it refers to a broad range of techniques designed to increase the robustness of intelligent systems to uncertainty. This uncertainty can take many forms, including degradation or failure of hardware components (sensors or actuators), lack of precise information about environmental conditions (wind, cloud cover, visibility), unforeseen events (fires, volcanic eruptions, algal blooms), or changing objectives. In the face of such uncertainty, contingency management techniques may be useful or necessary for improving both mission safety, and mission productivity. As an example, if hardware degradation or failure occurs, certain mission operations or activities may be too risky, and it may be necessary to quickly alter or restrict a mission plan. In this case, contingency management directly impacts mission safety. In contrast, if a UAV is tasked with certain science observations, and cloud cover or visibility in certain locations proves worse than expected, contingency management techniques could be used to revise the mission plan to concentrate on alternative higher quality observations. In this case, contingency management improves mission value or productivity rather than mission safety.

Contingency management cuts across other high level functional capabilities relevant to UAVs including Intelligent System Health Management (ISHM) and Intelligent Mission Management (IMM). Contingency management techniques would likely be an integral part of an ISHM system for a UAV that must continue to function in a degraded state. Similarly, contingency management techniques would likely be an integral part of an IMM system that is trying to optimize mission productivity or react quickly to environmental events such as forest fires, volcanic eruptions or tectonic events. We have chosen to treat contingency management as a separate top-level enabling technology because it cuts across many different areas and capabilities relevant to UAVs. In many respects, the extent to which a system can react to and handle contingencies is an indicator of its ability to function autonomously. If a system has little or no ability to deal with contingencies, then human intervention and perhaps continuous supervision could be required if the system is to function in an environment with significant uncertainty. For a UAV, the mission plays a large role in determining the type and amount of uncertainty that will be encountered, and hence the need for this capability. For example, a single UAV performing a systematic ground survey of an area may have less need of this capability than a set of vehicles tasked with recognizing and monitoring certain types of events.

Current State of the Technology:
Varies widely. A broad range of Contingency Management techniques have been proposed or investigated for 1) increasing the robustness of plans and schedules to uncertainty, and 2) allowing rapid replanning and recovery when plans and schedules fail. The first category includes techniques that a) produce “flexible” plans and schedules (tolerant of minor variations in activity duration and resource consumption), b) produce “conformant” plans guaranteed to work over a broader range of uncertainty or faults, and c) produce “conditional” plans, which contain one or more alternative courses of action which may or may not be executed depending on the actual course of execution.

There is wide variation in the level of development and TRL levels of these different techniques. Generation of temporally flexible plans and schedules (1a) is currently fielded in the MAPGEN planning system being used for the generation of daily activity plans for the Spirit and Opportunity rovers. This technology should therefore be considered to be at TRL 6 or above. In contrast, conformant and contingent planning methods (1b and 1c) have only been shown in limited "proof of concept" demonstrations in structured settings. In addition, the methods being demonstrated have some significant weaknesses and limitations. A realistic assessment of readiness for these methods is probably TRL 2-3. Rapid replanning (2) has been demonstrated in software for the EO-1 satellite, and the DS1 spacecraft although the replanning and optimization capabilities are still somewhat limited. Overall TRL assessment for this technology is therefore probably in the 6-7 range.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?
A small amount of legacy funding (~300K) from the NASA Intelligent Systems NRA program is supporting low TRL work on methods for planning under uncertainty. This funding will expire at the end of FY06. A small amount of funding ($150K/year) is being devoted to this area in Exploration Systems through the ESRT program. The current focus of this work is on producing more robust crew schedules for the CEV. This work is therefore probably more relevant to contingency management for IMM than for IVHM. The current funding commitment to these areas is not enough to significantly push the TRL level in this area.

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Development of conformant and contingency planning techniques has been hampered by the fact that the basic probabilistic planning methods developed within the academic research community have difficulty coping with domains and problems involving concurrent activities, activities with differing durations, and rich temporal constraints among activities. Significant breakthroughs are still needed in this area before these techniques are widely applicable to the planning of and control of UAVs. Improvements in plan quality are still needed for replanning technology. This technology can benefit significantly from needed improvements in plan optimization techniques discussed in ???

Forecast of enabling technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast. What is the time estimate for this enabling technology to be ready to support the capability for the mission?*

Identify and articulate any technology gaps discovered:

Enabling Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

A limited form of rapid replanning has been demonstrated for autonomous rotorcraft.

<u>Technology Assessment – Resource & Research Summary</u>

No information provided

- USRA Analysis

1. Technology Description

Very good summary of the demands on a contingency management system, especially distinguishing changing mission objectives from unforeseen events (which should include both impending collisions with terrain or other aircraft and weather phenomena).

ISHM and IMM systems development may be as important as collision avoidance technology in the quest for certification and operational efficacy. The “unforeseen events” category is one of the major elements driving the FAA’s need for data to support a safety case for the safe operation of UAS's in the NAS. Anticipating and mitigating system failure at any level is critical to safe operations.

Taking evasive action to avoid a mid-air collision or having to maneuver to avoid an impact with terrain would be categorized as a “contingency” activity as one would not expect this to be normative behavior on every flight. Additionally, having the ability to gather sufficient data to make a determination that a particular part of the system is about to fail is in its infancy with UAVs.

2. State of the Technology

Good general description of emerging technologies. Agree with TRL of 2-3, but question whether that standard applies when transferring manned aircraft technology to UAVs..

Lack of discussion of regulations [or lack thereof] that may drive or impede technology development. No discussion of “unforeseen events” such as lost communications, aberrant weather, security breaches, and the like. Seems to be focused on flexible Mission Management to the exclusion of the “real world” situations that pilots of manned aircraft face and mitigate as a fundamental part of their training and operational experience. Equivalent Level of Safety is the current standard.

There is no “conventional wisdom” in the UAS industry on where this sector of the larger technological challenges is going or should go. As noted, there is a wide variety of strategies under development or contemplation, and without standards or regulations to guide the industry, the prospects for a “one size fits all” solution that the FAA can comfortably impose upon the companies developing these technologies. Are “proof of concept” demonstrations in the space and satellite world truly relevant to operation of unmanned low and medium altitude vehicles? RTCA SC-203 has particular bias for “UA-specific regulations” regarding the proper implementation of Contingency Management protocols as they do for all other areas of UAV activities. Current state of the Technology is, as was stated in the report, very difficult to generalize due mostly to the wide variation in concept and application. Additionally, the specific need for a large number of sensors coupled with the relatively small size of most UAVs makes the incorporation of a sufficiently robust contingency management system in UAVs extremely difficult

Additionally, applications of technology for platforms other than UAVs may or may not be suitable for UAS use.

Applying TRLs in that manner seem to have little bearing on the task at hand – civil UAVs.

3. Enabling Technology Development	Accurate assessment of negative impact of lack of funding in this area. Answered the question quite literally. May be beyond the scope of the question, but an estimate of needed funding to achieve TRL 6 and above would be helpful.
4. Technology Dependencies	Good, concise start on a complex problem. Full description of issues and proposed solutions would consume several pages (or volumes). Could have provided more information. What technologies? Where are the gaps? Define the problem with greater detail. Breakthroughs needed in hardware, software, algorithms? Where to focus?
5. Technology Forecast	Not addressed; a ready source for industry and government's take on this would be the proceedings from the various conference events that have taken place over the last year in the US and elsewhere. The TAAC conference in Albuquerque, NM last October, the FAA conference in Washington D.C. last December, the Canadian conference in Banff early this year, the conference in France last January, and another one this month, meetings sponsored by AUV International come to mind. The TAAC presentations are all available [for a price, of course] and are quite comprehensive.
6. Technology Gaps	Not addressed; RTCA SC-203 committee report is a good description (copy available). The gaps are better described as "canyons" because there is no regulatory scheme that specifically addresses UAS.
7. Technology Cost Drivers	Not addressed; involves a comprehensive regulation study to determine what the minimum standards for technology development in the Sense and Avoid area would be, which in turn requires an understanding of the entire architecture of an integrated system. The industry currently is very fragmented, and the contractors and R&D players are not particularly forthcoming regarding still proprietary technological developments and/or costs [for obvious reasons]. This analysis would have to focus on a macro and micro level, since each system has its unique characteristics, and there is no common standard other than "Equivalent Level of Safety."
8. Competing Technologies	Not addressed; UAVs represent the embodiment of "disruptive and competing technologies." The entire aviation environment (manned aircraft, ATC, airports, the NAS, etc.) is competing with UASs. Various organizations such as AOPA vigorously oppose UAVs in the NAS until they can demonstrate ELOS with manned aircraft.
9. UAV Application Demonstrations	Not addressed.
10. Sources of Information	Not addressed; see comment to #5 above. FAA, DoD, RTCA SC-203, US Congress, hundreds of websites devoted to UAS.
11. Technology Capabilities	Not addressed; Detect Sense and Avoid systems that satisfy the Equivalent Level of Safety requirement. Solve that one, and the industry begins to mature.
12. Current Research	Not addressed; See comment to #5 above. Abundant conference proceedings and materials available.

13. Regulatory Issues	Not addressed; the entire body of Federal Aviation Regulations apply to UAS until such time as the FAA promulgates new rules specific UASs or otherwise providing for an exemption. Security of the communications architecture is a looming issue that is under vigorous scrutiny by the industry and the military.

3.7 Open Architecture

3.7.1 Overview

- TWG Output

Enabling Technology:__________________ *Date:*

Specific Technology: Open Architectures
Contributing Editor: Don Sullivan
Phone: +1 650 604 0526 Fax: +1 650 604 4680 Email: Donald.v.sullivan@nasa.gov

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Specific Technology Description:
Current "Open Architectures" are systems, or, systems of systems, that enable, or facilitate, data or information exchange between elements that subscribe to the specific "Open Architecture". The overriding problem is, and has been, that these "Open Architectures" have been developed inside specific communities to address specific needs or problems, within that community, and, as such, actually instantiate the problem, not the solution. Each "Open Architecture" is, in reality, just another "stovepipe". The "Open Architecture" developed for the Predator does not interoperate with the "Open Architecture" developed for the Global Hawk or the "Open Architecture" developed for the NASA Pathfinder. And on, and on, …

Current State of the Technology:
Current "Open Architectures" include protocols and standard services for notification, retrieval, scheduling and planning data/information from a wide range of sources, including water, ground and air mobile platforms.

Currently used protocols and services include*:*
COP format notifications, CBRM Hazard Prediction Model
CAP format notifications, FEMA, California Office of Emergency Services.
NASA/OGC Web Service Standards
Sensor Planning Service
Sensor Model Language
Transducer Markup Language
FGDC Z39.50
NGA Aircraft Collection Tasking Message (ACTM)
DTRA Chemical and Biological Archival Information Management System (CBAIMS)
NONE of which interoperate*.*

Identify funded programs that contribute to the development of this specific technology
Numerous commercial and government entities fund these developments, all independently, and without significant efforts at harmonization

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Architecture "bridges" are absolutely critical to amalgamate, or harmonize, "Open Architectures" of many flavors.
An interoperable security framework for OpenGIS Web Services based Spatial Data Infrastructures to enable business with protected geospatial information is currently in progress.

Authentication (proof of identification) is a pre-requirement for establishing either Role Based Access Control or the Licensing of geospatial information.

Sensitive payload elements/blocks/modules (e.g., sensor location information) must be encrypted separately from the rest of message payload in many cases.

Identify funded programs that contribute to the development of the critical supporting technology:

OGC Sensor Standards Harmonization Working Group, (mainly concerned with OGC/NIST harmonization)

Forecast of specific technology:
Lacking a cohesive approach, this is impossible to predict.

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:
The problem is, simply stated: they are **ALL** competing, and mutually disruptive**.**

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					
Demonstrated?: (text)					

Technology Assessment – Resource & Research Summary

No information provided

- USRA Analysis

1. Technology Description States the challenge, but is not descriptive of what OA is. It is not clear whether the promise is to have an open architecture for general needs, or the goal is to build on existing OAs addressing UAV capabilities specifically.

2. State of the Technology Better defines Open Architecture and cites example; illustrates lack of inter-operability among OA systems.

The Navy has adopted the "ARCI-like" process to facilitate the OA introduction in surface combat systems. Interoperability is the key. Quantum 3D makes and markets COTS open-architecture IG solutions and embedded visual computing systems for the embedded military and aerospace visual computing systems. Again, no interoperability with other systems.

3. Enabling Technology Development Identifies need for harmonization; does not identify programs, only that they exist. There is a conference module called 'Open Architectures and Systems for Command and Control' that is all about the technology behind open architectures and systems for command and control applications.

4. Technology Dependencies Interoperability is seen as the major challenge. Four supporting technologies identified, but not discussed

5. Technology Forecast Encryption is a relatively mature technology and can be readily adopted. Interoperability takes a while to mature. Efforts need to bring together progress in existing technologies.

6. Technology Gaps	Not addressed
7. Technology Cost Drivers	Not addressed; software development mainly.
8. Competing Technologies	Not addressed.
9. UAV Application Demonstrations	Not addressed; Open-Architecture Technology is several years away from maturity.
10. Sources of Information	Not addressed: additional sources… http://www.military-aerospace-technology.com/department.cfm?id=14 http://www.defenseworld.net/html/Graphical%20Reports/ Unmanned%20Combat%20Air%20Vehicles.htm
11. Technology Capabilities	Not addressed.
12. Current Research	Not addressed; activities are going on in France (Dassault), Sukhoi (Russia) and Boeing (DARPA), USA.
13. Regulatory Issues	Not addressed.

3.8 Payload Sensors

3.8.1 Active Optical: LIDAR

- TWG Output

Enabling Technology:_Sensors_ *Date: January 20.2006*
Specific Technology: Active Optical (Lidar)
Contributing Editor: Grady Koch
Phone: 757-864-3850 Fax: 757-864-8828 Email: grady.j.koch@nasa.gov

Specific Technology Description:
Active optical remote sensing (also known as lidar), uses an optical source, typically a laser, to sense targets. The targets can be hard objects (terrain, other vehicles, obstacles) or the atmosphere via scattering of light from molecules and aerosols. Hard target measurement is useful for altimetry, geographical information systems, ice sheet/pack changes, vegetation canopy studies, and target designation for payload delivery. Atmospheric parameters that can be measured include aerosol density, trace gas concentration (H_2O*,* O_3*,* CO_2*, hydrocarbons, pollutants, or chemical weapons), wind, and cloud composition. An advantage of lidar-based techniques is that the spatial and temporal resolution is typically much higher than other sensor methods.*

Current State of the Technology:
A lidar has yet to have been demonstrated on board a UAV (at least as described in un-classified literature), but such deployment is feasible and likely within a few years for larger UAVs (Altair or Global Hawk). Lidars have been flown on aircraft for decades, including autonomous designs, and these instruments could be adapted to a payload of a large UAV. Deployment in smaller UAVs requires further research and development, primarily in reducing the size, weight, and power consumption of the laser transmitter.

Identify funded programs that contribute to the development of this specific technology
The NASA Science Mission Directorate has funded, with a start in FY 06, an Instrument Incubator Program called the Global Ozone Lidar Demonstrator (PI at NASA LaRC) to demonstrate ozone and aerosol profiling from a UAV. Previously funded programs have made progress in developing a water vapor profiling instrument at NASA LaRC for use in a UAV. Other Federal Government agencies are looking into UAV programs, but in the realm of feasibility studies rather than aggressive development of technology.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
For large UAVs the lidar designs now in use and under development for manned aircraft based on solid-state lasers are likely sufficient for a wide range of beneficial Earth Science applications. But further payoff could be found in miniaturizing lidar systems as a payload for smaller UAVs. The critical limiting technology is the size, weight, and power consumption of lasers. Fiber lasers and new diode laser designs have emerged in the past few years are promising toward this goal. Lidars for atmospheric measurements, regardless of UAV size, would benefit from a reduction in size of gas cells used as frequency reference. These cells are typically a pressurized vessel used to give an optical path in the meter to 10s of meters length and currently (in configurations such as the White cell or Herriot cell) are rather bulky. A recent invention worthy of more research is to use a hollow core optical fiber as a gas cell.

Identify funded programs that contribute to the development of the critical supporting technology:
The NASA Science Mission Directorate has funded, with a start in FY 06, an Instrument Incubator Program "Development of Miniaturized Intra-Cavity DFG, Fiber-Optics, and Quantum Cascade Laser Systems in Conjunction with Integrated Electronics for Global Studies of Climate Forcing and Response Using UAVs as a Partner with Satellite and Adaptive Models" (PI at Harvard University) to address laser technology needs. Small investments have been made at NASA GSFC and NASA LaRC from internal discretionary funds for

UAV lidar technologies. The Department of Defense, Department of Energy, and NOAA are also investing in small amounts toward UAV lidar technologies.

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

A TRL assessment for the use of lidar as a payload is perhaps best linked to the type of UAV, with a classification of UAVs into large and small. For large UAVs, lidar as a payload is currently at a TRL of 6. For small UAVs there are remaining challenges in component technology representing a TRL of 4 for the lidar.

The complexity of small-size laser transmitters for small UAVs seems to require a more focused research program with larger funding than is now seen. For example, a program such as the NASA Laser Risk Reduction Program (which is aimed at large scale transmitters for orbital or space instruments) should be considered toward UAV applications.

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:
Lidar is recognized in its benefit and as yet largely unexploited potential over passive instruments. There are no alternate technologies known to become disruptive. A potential limitation of lidar is that some implementations may be problematic in posing a safety hazard for ocular viewing,

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?: (text)

Technology Assessment – Resource & Research Summary

Known sources of information:

Research being done:

Regulatory/security issues? ITAR:
Lidars or components thereof to be used in flight instruments are typically subject to ITAR restrictions.

Non-US efforts:
European nations and Australia are considering lidars for UAV deployment, but such work seems to be currently limited to feasibility studies, simulations, and designs. A program in which flight hardware is being developed outside the United States could not be found in the published literature.

List Any Assumptions:

- USRA Analysis

1. Technology Description

Strengths: Lidar and more importantly DIAL (differential absorption lidar) are key for measuring the vertical and horizontal distributions of atmospheric aerosols and primary chemicals (e.g., H2O, O3, CO2). The major strength of lidar is its ability to profile and range with very high resolution. Further, because of its very specific wavelength, its signals can be discriminated with respect to background noise using interference or Fabry-Perot filters. It can be made eye-safe, or not visible to the eye, e.g. using 1.5 micrometer lasers. From high altitudes, it can profile the troposphere between optically thick clouds and through optically thin clouds. Raman and Differential Absorption Lidar (DIAL) allows for unique inversion of gas concentrations like water vapor and ozone.

Weaknesses: All lidar (and of course DIAL) techniques require pulsed lasers and large aperture telescopes. For simple lidar applications (i.e., aerosol mapping), systems may be relatively small (few Kg) and may require modest energy (~100W) and alignment. However, DIAL techniques require pulsed monochromatic and often tunable lasers. Furthermore, these lasers must also provide high-level spectral purity and when tuned repeatedly on and off-line must have high level of reproducibility (i.e., both the wavelength at line center and bandwidth must be well reproduced). These requirements tend to make the transmitter extremely complex thereby requiring high level of maintenance and operating expertise.

For elastic backscatter, its measurements are relative and must be normalized or ratioed to molecular backscattering with a priori information. Aerosol density can not be retrieved without information on composition, shape and size distribution. Long range applications or ones having small cross-sections for scatter or absorption usually require lasers of higher energy output and, therefore, lasers that would probably exceed the power available on a UAV.

For airborne applications, the narrow field of view of the lasers makes mapping difficult. In addition, for DIAL applications, tuning on and off-line while in motion implies that the on line and off line signal bins are scattered from different samples thereby reducing the correlation between the two measurements. Finally, the high rate of data stream (vertical and horizontal resolution combined with spectral tuning) puts serious demands on onboard data processing and down link bandwidth.

2. State of the Technology

Strengths: There is a significant experience in airborne and space based applications of lidars and.DIALs. Several DIAL systems (e.g., H2O and O3) are now routinely being flown on manned missions. Small, portable lidar systems are commercially available (e.g., SESI) and could be adapted for UAV applications. Important issues such as eye safety, airworthiness, and autonomous operation have already been addressed and will accelerate UAV deployment.

Weaknesses: UAV deployment has not been demonstrated yet. Reduction in lidar size, mass, and power consumption are necessary before they can be used in smaller UAVs. Hwever, since lidars are significantly simpler than DIALs they are more likely to be deployed on UAVs and could provide topographic mapping capabilities, aerosol distribution measurements, tree canopy analysis, etc. Although quasi-autonomous deployment of a DIAL on the ER-2 has

occurred several years ago, the stringent requirements that the laser system must meet may delay fully autonomous UAV deployments.
The power needed depends on its application and measurement distance from the UAV. There are very lightweight, small and autonomous lidars now being built for space applications, mainly planetary. For example, in NASA's Mars Scout program, Phoenix has a 5-Kgm lidar being built by the Canadians for measuring aerosols and clouds from the surface of Mars. Phoenix will be launched in 2007. In addition there are a few laser altimeters that have flown in space (two Shuttle flights, one lunar flight and the very successful Mars Orbiting Laser Altimeter) and one that is on its way to Mercury (Messenger Program). Albeit heavy and fairly large, an autonomous lidar (the NASA GSFC Cloud Physics Lidar) has been flown for at least 20 years in a WB-57 or ER-2. Its elastic backscatter measurements are of aerosols and clouds.

3. Enabling Technology Development

Strong interest on the part of the Army (Edgewood) to develop portable and airborne DIALs for the detection of chemical weapon agents (CWA) may result in a sufficiently robust agile frequency CO2 laser that could be deployed on UAVs. If successful, that laser may be used in DIAL systems for the detection and mapping of hydrocarbons, CO2 and H2O DIAL.

The NASA Science Mission Directorate is currently funding an Instrument Incubator Program to demonstrate ozone and aerosol profiling using UAVs. A lidar for water vapor profiling for UAVs has already been developed by NASA. An effort by LaRC to develop a UAV based H2O DIAL resulted in a prototype that was only preliminarily tested on ground. A previous DIAL flown on the ER-2 was nearly autonomous and should be a good prototype for a UAV based system.

Usually, the development of a remote sensor for a particular platform happens when a funding opportunity becomes a reality. A good example is the Phoenix lidar. A trade study for an application will determine if there are limiting technologies, e.g. amount of power available on a particular UAV.
There are some very new capabilities for laser altimeters that are impressive based on micro-joule kilohertz lasers and single photon detectors.
Data from aircraft show a very good capability for exceedingly good ranging and spatial coverage. Adding optical gratings at the output and 2-dimensional array single-photon detectors allow multiple laser beams to 'paint' a picture below the aircraft.

4. Technology Dependencies

Strengths: The most critical development for UAV lidar/DIAL applications are miniaturized, pulsed solid-state lasers. Currently, dye, Ti:Sapphire and Cr:LiSAF lasers have demonstrated such capabilities and cover the spectral range of interests for H2O and O3 detection. The Army's effort to develop agile frequency CO2 lasers is also encouraging. In addition, new technologies such as hollow optical fibers show promises as replacement for bulk gas cells such as the Herriot cell.

Weaknesses: The proposed lasers have relatively low efficiency thereby requiring high power and extensive cooling. In addition, the stringent spectral requirements require sensitive alignments and controls. Unaware of any new technology that will replace any of these lasers or that will simplify the tuning and control methods.

5. Technology Forecast

Good description of limiting technologies and NASA-funding for UAV lidars. Systems for deployment on large UAVs are at a high TRL level (6 or higher) and may benefit from many years of experience in manned flights. The Aerospace Corporation has been developing a wind lidar for UAVs and NASA LaRC has been developing a water vapor profiling lidar also for use in UAVs. In addition, NASA Science Mission Directorate has been funding the development of ozone and aerosol lidars for UAVs.

There exist small lidar systems (e.g., SESI) that may be deployed on small UAVs. Unaware of DIAL technology that is now ready for deployment on small UAVs.

Perhaps, discussion of lidars and laser altimeters for NASA's planetary program could have been mentioned.

6. Technology Gaps

The laser transmitter must meet strict requirements to provide accurate and reproducible measurements (see #3 above). This combination of requirements is unique to this application. Only a few lasers can meet all these requirements thereby limiting the number of molecules that can be studied and the progress towards UAV deployment.

Strengths:
The effort for the development of UAV based DIAL systems may benefit from synergy with the Army's effort to develop CWA DIALs (Edgewood Chemical and Biological Center, Aberdeen Proving Ground, MD). There, the motivator is the development of simple and robust system for military applications. Clearly, the drivers of such application are similar to the drivers of UAV deployment. Agree with the write-up and the separation into large and small UAV which will then create TRLs for each.

The miniaturization and increase in the reliability of various lidar systems, and in particular lasers are necessary for wide application on UAVs. Fiber lasers and hollow core optical fibers are emerging technologies that can expand the use of lidars by UAVs.
Weaknesses:
Lidar lasers are still power hungry and not as reliable as other remote sensing techniques. Owing to the small commercial market of this application there is relatively little drive by industry to develop such lasers and consequently most of the development cost must be borne by the government. Currently, the industry is investing heavily in laser technologies that benefit communication, computing and medicine. Some of these lasers may be useful for lidar applications (e.g., sealed Ar ion or Nd:YAG lasers). However, do not see any industrial application that could provide the necessary drive for the development of technologies that benefit lasers for DIALs.

If the application is laser altimetry, the measurement of the PBL, cloud tops, or the determination of whether a cloud has ice particles in it, then the TRL is probably higher than 6 for the larger UAVs. If the application is a DIAL measurement of water vapor, then the TRL might be lower than 6, again depending on power available from the UAV.

7. Technology Cost Drivers

Not addressed; Cost of the technology other than lasers is moderate (it includes receivers, detectors, computing, down links). Lasers are the primary cost drivers, as lasers and reference cells are still too bulk and power hungry for UAV applications.

8. Competing Technologies

No known competing technology. Lidars are the best remote sensing instruments for measurements of aerosols and trace species.
The potential of eye damage for a particular application where high energies and small fields of view are needed in order to make the measurement is a real threat to this technique. However, applications at eye-safe spectral regions may in most cases mitigate this threat.

The size and power consumption of current lidars are still not small enough for UAV applications. Passive remote sensing techniques are currently more suitable for these applications.

9. UAV Application Demonstrations

Not addressed; NASA Langley made in the past an effort to develop a UAV based water vapor DIAL. A Diode pumped Cr:LiSAF laser was developed for the transmitter and integrated with the receiver. The system underwent ground based preliminary tests. However, the laser failed to meet power and spectral specifications. Not aware of other UAV demonstrations.

NASA has demonstrated numerous airborne DIAL applications including a semiautonomous system flown on the ER-2.

The Air Force demonstrated an airborne agile frequency CO2 DIAL for the detection of SF6 – a simulant of nerve agents. Unaware of any, but nothing precludes putting a lidar on a UAV depending on UAV size and lidar application.

10. Sources of Information

Not addressed; see below...

1. D. B. Cohn, J.A. Fox and C. R. Swim, “Wavelength agile CO2 laser for chemical sensing”, SPIE Proceedings. 2118, pp. 72-82, (1994).
2. R. Highland et al., “Laser long-range remote sensing program experimental results”, SPIE Proceedings, 2580, pp. 30-37, (1995).
3. N. S. Higdon et al., “Air Force research laboratory long-range airborne CO2 DIAL chemical detection system”, Proc. 19th International Laser Radar Conference, 651-654, (1998).
4. N. Hoang, R. J. De Young, C. R. Prasad, and G. Laufer, Differential Absorption Lidar (DIAL) Measurements of Atmospheric Water Vapor Utilizing Robotic Aircraft, 19th International Laser Radar Conference, Annapolis, MD, July 1998.

11. Technology Capabilities

Not addressed; Thermal and mechanical stability required but this and resultant weight needs should be overcome with good engineering.

12. Current Research

Not addressed; see below...

Extensive research effort in sensor development for atmospheric science applications and airborne deployment is undergoing at NASA LaRC (e.g., Ed Browell). Development of portable or vehicle mounted DIAL sensors for the detection of CWAs is undergoing at Edgewood Chemical and Biological Center, Aberdeen Proving Ground, MD. (e.g., Cynthia Swim)

Small portable lidars are developed by SESI. Europeans are very involved in space lidar and will soon fly a winds lidar called ALADIN on Aeolus that should be launched in 2008. This development will obviously produce new technologies for the French and ESA.

13. Regulatory Issues

As stated in the write-up, ITAR issues will have to be considered for any non-US joint lidar program. This shouldn't be a problem however based on the experience of the recently launched CALIPSO lidar on a French spacecraft.

In addition, there are the flight restrictions imposed by the FAA.

3.8.2 Passive Optical: Overview

- TWG Output

Enabling Technology: Passive Optical Sensors

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Enabling Technology Description:
Passive optical sensors form the majority of the Earth imaging devices found on satellites and aircraft. They essentially capture reflected or direct solar energy, or emitted infrared radiation, and project them onto photosensitive detectors via some system of imaging optics. Some passive optical sensors are non-imaging, collecting spectral and/or radiometric data from a single point; these are typically used to measure the up-welling radiation from the Earth or down-welling radiation from the Sun, and are often used to optically characterize the intervening atmosphere. Systems of both types are highly appropriate for deployment on UAVs, however few have been adapted for this application. Some of the technologies involved are necessarily large, making then compatible with only the larger platforms, however several are more clearly candidates for miniaturization. Also relevant to the UAV mission are digital tracking cameras, which are used to document the scenes being recorded by the science instruments.

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Current State of the Technology:
Passive optical imagers typically fall into one of three categories of technology:

1. "Pushbroom" multi- or hyper-spectral sensors, which acquire all pixels for a single scan line underneath the aircraft simultaneously, with the motion of the platform then being used to complete the imaging of a scene. The spectral dispersion of the energy is accomplished by various combinations of diffraction gratings, dichroic filters, or in some cases, an interferometer. These sensors generally have few moving parts, can be made relatively small, and would lend themselves to the UAV application. Absolute calibration of these instruments can be problematic however, unless this is a fundamental design criterion for the system. Several compact commercial pushbroom hyper-spectral sensors have been flown on small UAVs, however they have inherent limitations which would reduce their utility for most scientific applications. The overall TRL is 8 – 9 for commercial systems, with several known science-quality government instruments at TRL 6 - 7 (none believed to be intended for UAV use, however.)

2. "Whisk-broom" or "line-scanning" multi- or hyper-spectral sensors, which sequentially scan each pixel for a given scan line, sweeping from one side of the flight path to the other, and again using the forward motion of the aircraft to complete the image. Spectral dispersion is accomplished as above. This is the most mature of the scientific imaging technologies, and is widely used in current satellite and airborne systems. The sensors themselves tend to large and heavy however, requiring sizeable input optics and a mechanical scanning mirror. TRL 8 - 9

3. "Framing Devices" which acquire an entire image at once (e.g. a digital camera.) These are typically COTS camera systems, which may be modified for airborne use. Some infrared cameras have also been adapted for this role. They have varying numbers of pixels on a single 2-doimensional array,

behind a single imaging lens. The visible-light systems are not generally calibrated, and are used in a qualitative mode, for scene documentation. Several types of infrared cameras are commercially available, some using the newer micro-bolometer or QWIPS detector technologies. Any framing camera can be fitted with rotating filter wheel, to produce multi-spectral or multi-polarization images (with varying degrees of success.) The visible-light framing cameras are at TRL 9, with the IR devices ranging from TRL 6 – 9.

Non imaging optical sensors include broad-band, radiometers, spectro-radiometers, and photometers. They generally use the same detector and spectral dispersion techniques found in the imaging sensors above, but can support a very high level of absolute calibration. There are many designs currently in use, including atmospheric profilers on satellites and aircraft, and airborne tracking sun photometers, which monitor down-welling solar radiation through the atmospheric column. These instruments tend to relatively small, and should be readily adaptable for UAV use. They are generally at TRLs of 7 – 9.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?
DoD has funded numerous hyper-spectral imaging (HIS) projects, both in the visible and infrared, almost all of which pertain to classified programs. The technologies in use however fall into the descriptions listed above, and are not generally classified themselves. Other federal agencies, such as DHS, may also invest in imaging technology R&D, however this is as yet TBD. Several commercial companies have built HSIs of varying levels of sophistication. Typically their markets are for mineral exploration, commercial farming, or forestry applications, which lack the data quality requirements necessary for most scientific research. There does not appear to be much, if any, funded development of science-grade optical sensors specifically designed for the UAV application.

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Although the technologies involved are mostly at high TRLs, these sensors would need to be adapted or re-designed for UAV operations. Many of the existing imaging systems are large, heavy, and require onboard operators. In most cases the instrument packaging would need to be downsized, and autonomous control systems implemented.

Forecast of enabling technology:
Enabling technologies mainly include miniaturization of electronics and packaging. Fundamental physical limitations preclude the miniaturization of most optical components; however there are several innovative spectrometer designs (e.g. the Offner design) for hyper-spectral sensors, which are very attractive for UAV use. These are currently at a TRL of about 6, and could be produced for NASA in about two-three years.

Identify and articulate any technology gaps discovered:
No fundamental technology gaps have been identified. The requirements are mainly for down-sizing and automating existing technologies.

Enabling Technology Cost Drivers: *Operating and development costs.*
The development cost of a small science-grade Offner hyper-spectral imager for a UAV could be as high as $10M. The costs for re-engineering of existing systems for UAV compatibility would vary widely, depending on the system, but would most likely range from $20 – 300K.

Known competing or disruptive technologies:

None noted.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					
Demonstrated?:					

Technology Assessment – Resource & Research Summary

No information provided

- USRA Analysis

1. Technology Description

Strengths:
Passive optical sensors have been extremely successful in terrestrial and planetary multi-spectral imaging. Small and lower power sensors such as the MiniTES employed by the MER rovers are ideal for UAV applications.
- Robust – avoiding the need for a light source removes many of the complexities of systems like DIAL (e.g., power, tenability, wavelength stability, spectral purity, etc.).
- Multi chemical – passive techniques can in principle detect any chemical with sufficiently strong absorption in the far or mid IR ranges.
- Depending on the application, sensors can be made, small, low-cost, low-energy (e.g., DAR, TOVA, GFCR).
- Some techniques (e.g., FTS or GFCR) can provide high specificity and sufficient spectral resolution to provide vertical mapping of species based on pressure broadening effects.
- Lends itself to imaging applications (e.g., hyperspectral techniques), or even GFCR that can provide images of the distribution of certain species.
Weaknesses:
- Line of sight absorption – Signal results from absorption of radiation along the line of sight between the source and the sensor and consequently it represents the integrated value of C•L. Some range resolution can be obtained in nadir looking space applications (e.g., FTS).
- Cryogenic cooling – High sensitivity sensors (e.g., FTS) require low noise HgCdTe detectors that must be cryogenically cooled thereby adding to cost and power demand.
- Strongly affected by the emission characteristics of the source (e.g., temperature, spectral emissivity)
- With passive IR absorption, chemical detection is possible only if the temperature of the target gas is sufficiently different (at least 1 – 2 degrees C) from the temperature of the emitting source. Detection sensitivity is affected by that temperature differential.
- With solar scattering and occultation, detection is limited to the availability of sun light (day and clear sky)
- Strongly affected by temperature fluctuations at the source and along the line of sight.
- Hyperspectral techniques are data extensive thereby requiring either large onboard digital storage and processing capabilities or broadband high speed down links
- The most sophisticated instruments are bulky and power hungry.
Passive sensors are typically limited by vertical resolution, but are much more capable than active sensors of measuring many more gases, and for providing more spectral, angular, and polarization information for characterization of aerosols.

2. State of the Technology

Strengths:
Very good overview of passive-type remote sensors.
There is a strong push by DoD (Army, DTRA) to develop robust FTS system for

the detection of chemical weapon agents (CWAs) with a specific requirement to provide detection from at least 5 km with a low rate of false positive and false negative alarms. That requirement translates to high detection specificity. Consequently, available FTS sensors are quite robust. If successfully deployed by the Army, similar systems can be readily deployed on UAVs.

The simplest framing instruments or cameras have TRL 8-9 for visible or infrared images. The pushbroom multi-spectral instruments have TRL 7-8 and are almost ready for use by UAVs. The more sophisticated line-framing instruments are bulkier and consume more power and therefore require more development to get ready for UAV applications.
Weaknesses:
The more sophisticated instruments have many moving parts and sensitive optical systems that might need regular calibration and alignment. Despite the strong support, not a single FTS system was fielded yet thereby suggesting that some of the target specs were not met. There is relatively low support (government and private) for the development of low-end passive sensors. Hyperspectral techniques are complex and expensive and may not be immediately applicable to UAV applications.

3. Enabling Technology Development

Strengths:
The DoD, NOAA, and NASA have been supporting the development of a large number of passive optical instruments. Many instruments require only modest investments to become ready for UAV applications. Microbolometer arrays are available commercially and are being used extensively in uncooled IR imaging cameras.

Weaknesses:
Much of the IR technology is in the hands of few manufacturers. Consequently there are significant delays in the delivery of detectors (e.g., pyroelectric), bandpass filters, and other IR components. In addition, the costs of many of these components are high relative to the costs of their counterparts in the visible and near IR range. The more sophisticated multi-spectral instruments are less mature.

This write-up concentrated on hyper-spectral sensors, yet most passive remote sensors do not use high spectral resolution for their application. Furthermore, the word 'hyper-spectral' is a relative term, describing sensors with any number of wavelength bands or channels. A myriad of companies build high-quality camera imaging systems for aircraft use, and others build interferometers and radiometers. NASA satellite and research aircraft missions use a myriad of sophisticated passive sensors.

4. Technology Dependencies

IR technology is basis to most passive remote sensing techniques. Until recently it had little commercial applications and thus development was funded mostly by DoD and NASA.

Strengths:
New applications create significant commercial needs; e.g., thermal imaging cameras for luxury cars and for first responders, sensitive IR motion sensors for home alarm systems. Consequently cost of key IR components (e.g., detectors) is being rapidly driven down and their availability is increasing.
DoD, NOAA, NASA, and private industry such as Lockheed Martin Advanced Technology Center have been investing in the development of passive optical systems for decades. This technology has been used in civilian and military satellites and airplanes.

Weaknesses:
Most current instruments are not ready for use in small UAVs because they are heavy and power hungry. Despite its growth, the market is still limited thereby generating bottlenecks and often high prices. For example, while an ordinary CCD camera with excellent performance characteristics costs <$200, a thermal imager costs ~$10,000. The cost of other IR components is comparatively high and delivery times can be as long as six months.
Additional Comments:
Obviously miniaturization of the passive remote sensor will have to be accomplished for a number of UAV applications. This would also include a reduction in mass and power consumption, and development of autonomous operation, yet there are some remote sensors that could be easily adapted to UAV flight, e.g. radiometers, sun photometers, and various cameras.

5. Technology Forecast

Strengths:
Most of the remote sensing technology has been available for at least 30 years and thus is mature and can be readily deployed in UAV applications. Of course advances discussed above will lead to reduced cost, increased availability and improved performance. A large number of passive optical sensors have TRL ranging from 7-8 for UAV applications. They only need to be adapted and test flow on UAVs to reach TRL 9.

Weaknesses:
The most sophisticated instruments have moving parts, cryogenic cooling systems, and are power hungry. They will need larger investments to reach TRL 9.

The write-up is probably targeted at the very small UAVs, where it will be very difficult to use the more sophisticated passive sensors.

6. Technology Gaps

Strengths:
Many passive optical systems can be easily adaptable for UAV applications.

Weaknesses:
Techniques requiring sensing in both atmospheric windows (3-5 microm and 8-12 microm), require at least two sets of detectors and when using transmission optical elements (e.g. lenses) may require two sets of optics to overcome non-uniform transmission characteristics.
Many of the most advanced instruments need to be miniaturized for UAV applications. It will be difficult to reduce the size of their optical sub-systems

Additional Comments:
Agree that there are no fundamental gaps in technology depending on the size and capability of the particular UAV.

7. Technology Cost Drivers

Strengths:
The adaptation of many existing instruments for UAV applications will require only modest investments.

Weaknesses:
For passive sensors of chemicals, the major cost drivers are, detectors, cryogenic cooling devices (e.g., Stirling engines), and interferometers (for FTS)
For hyperspectral imagers the cost drivers are the spectral analysis elements (e.g., bandpass filters, etalons, etc.). The design and fabrication of robust and compact instruments for UAVs will require serious funding.

Additional Comments:
Agree that the development costs will depend on the sophistication of the passive sensor required, and the range could be as little as 10s of $K to 1000s of $K.

8. Competing Technologies

The main competing technology is lidar/DIAL

Strengths:
Lidar/DIAL techniques can provide longitudinal resolution and higher chemical specificity. Lidar techniques can also be used for topographic mapping with centimeter level resolution, tree canopy mapping and to map aerosol distribution (e.g., clouds). Active systems are more precise.

Weaknesses:
Lidar/DIAL are complex, expensive, can be used to detect only a few chemicals (most notably, H_2O, O_3, CO_2) have very narrow field of view and thus require numerous passes to provide full imaging. Active systems are in general bulkier, heavier and consume more power.

9. UAV Application Demonstrations

Not addressed;

Strengths:
Avir is supported by ONR to deploy its multi-spectral TOVA sensor on an expendable UAV. Initial flight tests were successful and demonstrated in-flight operation and communication. Flight tests scheduled for July-August 2006 expected to demonstrate detection of chemicals. FTS, GFCR and hyperspectral sensors were deployed on manned aircrafts and therefore are likely to be successful in UAV deployments

Weaknesses:
Unaware of other efforts to deploy passive remote sensors on UAVs.

Additional Comments:
Assume that any flights to date have included a passive sensor and/or an in situ sensor as a minimum.

10. Sources of Information

Not addressed.

11. Technology Capabilities

Not addressed; Many sub-systems need to be adapted for UAV environments.

12. Current Research

Not addressed;

Passive FTS techniques for the detection of CWAs and TICS: Research Development & Engineering (RDECOM), Edgewood Chemical Biological Center, Aberdeen Proving Ground, Maryland.
Passive multispectral techniques for the detection of CWA and TIC: University of Virginia and Avir, LLC
GFCR techniques – NASA LaRC
FTS techniques - NASA LaRC

13. Regulatory Issues

Not addressed; the primary regulatory issue needed to be addressed is FAA imposed UAV flight restrictions.

3.8.3 Active Microwave: SAR & IFSAR

- TWG Output

Enabling Technology: Sensors *Date: Jan 17, 2006*

Specific Technology: SAR and IFSAR Systems
Contributing Editor: Scott Hensley
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Specific Technology Description:
SAR and IFSAR system are imaging radar that emit microwave radiation and record the echoes returned from the scene under observation. SAR system have wavelengths that vary depending on application from

less than a centimeter to greater than 3 meters. To achieve fine resolution in range and azimuth SAR system transmit a chirp waveform (a linear frequency ramp) with bandwidth depending on the desired resolution (1 – 3000 MHz) a collect many pulses in azimuth that are combined through signal processing to achieve the desired resolution. SAR systems may require, again depending on system, large data bandwidth and DC power levels up to the 10 KW range. IFSAR system collect data from two or more antenna that may be on the same platform or for certain applications collected in using repeat passes.

Current State of the Technology:
SAR systems have been developed for UAV systems by the military. NASA's ESTO office is currently funding a civilian SAR designed for mapping surface using an L-band radar. First flight is expected in November 2006. Thus the TRL level for this technology is 6-7.

Identify funded programs that contribute to the development of this specific technology
See above.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Yes. Some of these are under development for this program. To have similar capabilities for higher frequency SARs additional antenna technology development would be needed. Electronically scanned arrays at C-band, X-band, Ku-band and Ka-band would be needed to have a robust SAR mapping capability at these frequencies. Precision trajectory control (better than 5 m) is required a number of repeat pass interferometric applications. For single pass systems precise in flight measurement of the interferometric baseline may be required for certain frequencies if antennas can not be mounted to the platform with sufficient relative position accuracy (sub-millimeter typically) similar the laser baseline metrology system developed for the GeoSAR system.

Identify funded programs that contribute to the development of the critical supporting technology:
The UAVSAR program is funding precision trajectory control for the Gulfstream III aircraft. Additional technology development for precision trajectory control is required as the system is migrated to different UAV platforms.

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*
TRL progress is directly linked to funding. L-band repeat pass technology should reach TRL 8 by July 2008 based on the UAVSAR development effort. Too difficult to project a TRL level for the other technologies.

Specific Technology Cost Drivers: *Operating and development costs.*
This question can not be readily answered without some either a priori operating assumptions, e.g. what aircraft are we discussing, where will it fly, does it have access to standard airports, what level of crew support is required, it the platform operated by NASA or an outside contractor, who will process the data, how many flight hours per year will the system operate, etc.. It seems this question might best be approached from several directions – what is maximal amount the science community will be willing to spend to support various types of data collection – which in turn affects the design of platform and sensors.

Known competing or disruptive technologies:
None.

Major Events/Milestones:

Event:	2006	2007	2008	2009	2010
UAVSAR CDR	11/04/05				
UAVSAR First Flight	11/20/06				
UAVSAR Science Demo	07/15/08				

Demonstrated for UAV application?:
L-band repeat pass interferometry demonstrated on Gulfstream III by July 08. Possible migration and test flight on Predator in same time frame.

<u>Technology Assessment – Resource & Research Summary</u>

No information provided

- USRA Analysis

1. Technology Description

Strengths:
SAR and IFSAR systems are imaging radars with wavelengths that vary depending on application from less than a centimeter to greater than 3 meters. Thus, these are all weather imaging system extremely useful for civilian and, in particular military UAV applications. IFSAR systems can achieve great resolution and accuracy by combining data from two or more antenna from the same platform or using repeat passes from quasi-static scenes.

Weaknesses:
SAR systems may require high-precision antenna placement, high-precision formation flights, large data bandwidth and large DC power (10 KW range). SAR is much more mature and simpler that IFSAR but does not provide images of high resolution.

Additional Comments:
SAR and IFSAR have wider application in military than civilian systems.

2. State of the Technology

Strengths:
The military has been making considerable investments on SAR technology. NASA is currently funding a civilian SAR designed for mapping surface with an L-band radar. First flight test is expected in November 2006. The current TRL level of SAR technology is around 6.

Weaknesses:
The technology for antennas and scanned arrays at C-band, X-band, Ku-band and Ka-band needs development for imaging at these frequencies. Either antennas have to be mounted to the platform with sub-milimiter relative position accuracy or in-flight measurement of the interferometric baseline may be required. Precision trajectory control with accuracy better than 5 m is required for repeat pass interferometric applications to be possible.

3. Enabling Technology Development

Strengths:
The military has been investing in this SAR technology. Currently, the UAVSAR program is funding precision trajectory control for the Gulfstream III aircraft. Additional technology development for precision trajectory control is required for SAR technology to migrate to UAV platforms. The L-band repeat-pass technology is the most mature. It could reach TRL 8 by the end of 2008 if funded tests are succesful.

Weaknesses:
Except for L-band repeat-pass systems, it is difficult to project the TRL level of other SAR technologies because of the lack of current investments on them.

Additional Comments:
Large funding is necessary for maturation of all SAR technologies except for L-band repeat pass systems.

4. Technology Dependencies	Strengths: Currently, the UAVSAR program is funding precision trajectory control for the Gulfstream III aircraft. This could lead to considerable maturation of L-band repeat-pass systems. Weaknesses: Currently, there are no investments on other SAR technologies. Thus, there are large uncertainties on the performance and cost of these systems.
5. Technology Forecast	Strengths: L-band repeat-pass technology might reach TRL 8 in two years. Weaknesses: The maturation of the SAR technology for UAV application is uncertain because of the lack of investiment on them.
6. Technology Gaps	Weaknesses: Antenna and precision technology control needs substantial amount of work.
7. Technology Cost Drivers	The cost drivers are highly uncertain.
8. Competing Technologies	Strengths: The only know technology for imaging on all types of weather.
9. UAV Application Demonstrations	Very immature technology.
10. Sources of Information	Not addressed
11. Technology Capabilities	Not addressed
12. Current Research	Not addressed
13. Regulatory Issues	Not addressed

3.8.4 Active Microwave: Wind Measurements in Precipitation

- TWG Output

Enabling Technology: Sensors - Active Microwave *Date: 1/25/2006*

Specific Technology: **Wind Measurements in Precipitation and Cloud Regions**
Contributing Editor: **Gerald Heymsfield**
Phone: **(301)-614-6369** **Fax:** **(301)-614-6356** **Email:** **Gerald.Heymsfield@nasa.gov**

Specific Technology Description:
Current radar transmitters and receivers/processors required for measurement of clouds and precipitation are too large and power consuming for use in payloads on smaller UAVs. In addition, operation in HUAVs at high altitudes and low temperatures requires special considerations such instrument cooling. New radars employing low power solid state transmitters and low power high-speed digital receivers are being developed but are in their infancy. This development is required for compact, low power systems that will be useful for weather forecasting and climate applications.

Current State of the Technology:
Components necessary for UAV radars are at a relatively high level (TRL-5) but the technology at the system level is significantly lower (TRL-3). Only a few precipitation/cloud radar systems have been developed employing solid-state power amplifiers and pulse compression and there is significant work required in the area of processing (e.g. pulse compression) algorithms to maximize system performance (sensitivity, range side-lobes, etc) without compromising the derived parameters.

Identify funded programs that contribute to the development of this specific technology
IIP: High Altitude Imaging Wind and Precipitation Profiler
ACT: FPGA-based dual-frequency radar & processor.
HQ Science Discipline Managers and satellite validation programs have funded aircraft instrumentation R&D that have resulted in instruments suitable for UAVs.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Development of radar digital receivers and processing systems with the most recent FPGA chips in order to reduce size, weight, and power consumption of current radar processors. This work is being done by industry but has not been tailored to cloud and precipitation radars and UAVs.
Development of low cost active antennas for reduction in size and weight of systems; this is being used in military radars at X-band.
Development of high power and compact solid state RF power amplifiers. This has been advanced significantly by the communication industry, but improvements in power level and cost reduction are still required.

Identify funded programs that contribute to the development of the critical supporting technology:
IIP, SBIR/STTR, Center-level R&D

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*
The forecast for the TRL progress in the radar are is quite positive. The component technology is very suitable for basic cloud and precipitation radars. What is needed is development of radar systems that demonstrate the current technologies in terms of reliability, low-power consumption, small size in the UAV environment. Better component technology is desired to meet more stringent science and platform requirements, but much can be demonstrated with existing technology in the near term. Some of the technologies such as active antennas are desired but still too expensive for the UAV platform given that the radars can be developed with less expensive technologies.

Specific Technology Cost Drivers: *Operating and development costs.*
More conventional radar systems are expensive but affordable. Active systems are currently affordable by the military for airborne radars and for spaceborne radars. This technology is trickling down to the civilian

world but it is not necessarily better performance than currently available technology for wind and precipitation/cloud measurements.

Known competing or disruptive technologies:
none

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:			X		

Demonstrated for UAV application?:
An NASA IIP project is funded that will develop a UAV-based radar that will measure tropospheric winds in precipitation regions using a solid state transmitter. This radar will be dual frequency, dual beam, and conical scaning for the measurement of winds. It will be demonstrated on a manned aircraft.

Technology Assessment – Resource & Research Summary

No information provided

- USRA Analysis

1. Technology Description

Strengths:
Clouds and precipitation radars are extremely useful for weather forecasting and climate related studies. Low-power solid-state radar transmitters and low-power high-speed digital receivers are current being developed.

Weaknesses:
Lightweight low-power cloud/precipitation radars for UAV applications are not yet available. Indeed, current radars are too large and require too much power and therefore are not suitable for UAV applications.

2. State of the Technology

Strengths:
Individual lightweight/low-power cloud/precipitation radar components have a relatively high TRL level (TRL 5).

Weaknesses:
At the system level cloud/precipitation radars are not mature yet (TRL 3). Solid-state power amplifiers and pulse compression hardware are not available for these systems.

3. Enabling Technology Development

Strengths:
Various military and civilian programs, as well as the communications industry, have developed many sub-systems suitable for lightweight low-power cloud/precipitation radars.

Weaknesses:
Lightweight low-power digital receivers, solid-state RF power amplifiers and lightweight antennas suitable for UAV applications do not exist yet.

4. Technology Dependencies	Strengths: X-band radars for UAV applications have already been developed by the military. Moreover, lightweight, low-power digital receivers, processing units, and RF power amplifiers suitable for UAV applications are being developed by the communications industry. Weaknesses: Lightweight/low-power digital receivers and processing units must be developed for cloud/precipitation radars to become suitable for UAV applications. Lightweight/low-mass and small active antennas must also be developed. The power level and cost of the systems being developed by the communication industry still need to be reduced for them to become suitable for UAV applications.
5. Technology Forecast	Development of radar systems that demonstrate the current technologies in terms of reliability, low-power consumption, small size in the UAV environment. Better component technology is rneeded to meet more stringent science and platform requirements, but much can be demonstrated with existing technology in the near term. Some of the technologies such as active antennas are desired but still too expensive for the UAV platform given that the radars can be developed with less expensive technologies. Weaknesses: The reliability of lightweight/low-power subsystems suitable for UAV applications must be demonstrated. More robust systems than those currently being developed by the communications industry are also necessary for UAV applications. A major challenge will be the improvement of existing sub-system reliability while reducing mass and cost.
6. Technology Gaps	Strengths: Active radar systems exist but have high cost that only the military can afford to pay for airborne and for spaceborne radars. Weaknesses: The performance of current must be improved to allow precipitation/cloud and wind measurements.
7. Technology Cost Drivers	Strengths: Improvements in the performance and reliability of existing systems are the main cost drivers. Thus, major surprises should not occur. Weaknesses: Current activity system do not meet the performance requirement for wind measurements.
8. Competing Technologies	Strengths: Radars are necessary for in-cloud wind and precipitation measurements. Weaknesses: Lidars might be more suitable for wind measurements in cloudless environments.

9. UAV Application Demonstrations	Strengths: Portable radars for clouds are precipitation measurements currently exist. Weaknesses: Reducing the power, size and mass of current systems enough to make them suitable for UAV applications is a challenge and will require large investments on technology maturation.
10. Sources of Information	Not addressed
11. Technology Capabilities	Not addressed
12. Current Research	Not addressed; The military and communication industry have been investing in various systems and sub-system suitable for UAV applications. These systems might not be as reliable as desirable.
13. Regulatory Issues	Not addressed; The relatively long wavelengths of radars signals make safety concerns relatively small when compared with other active systems such as lidars.

3.8.5 Passive Microwave: Light Weight, Low Loss, Antenna Technology

- TWG Output

Enabling Technology: <u>Sensors_Passive Microwave</u> *Date:*

Specific Technology: Lightweight low loss antenna technology
Contributing Editor:
Phone: **Fax:** **Email:**

Specific Technology Description:
The measurement of geophysical parameters important for Earth remote sensing including climate or regional studies often require multiple sensors. These sensors typically include both active (Radar) and Passive (Radiometer) measurements. Microwave measurements have been used successfully for both atmospheric measurements (including rain) and surface imaging. The interaction of liquid water and the sensitivity of the reflections/emissions at microwave frequencies to the state of water (frozen or thawed) make surface imaging at microwave frequencies extremely important for existing and future science missions. An important challenge for these sensors is the spatial resolution required. Cold Land Processes for example may required spatial resolutions of 100's of meters at microwave frequencies, spatial resolution requirements for Soil Moisture measurements (1.4 GHz) of 1 km are also a technology challenge from Low Earth Orbit (LEO). The longer wavelengths of these measurements have limited the available spatial resolution from LEO. SSM/I for example has a spatial resolution of approximately 30 km at 19 GHz. The resolution for spacecraft concepts at lower frequencies (L-band!) have remained a formidable challenge for decades.

The use of UAVs for microwave remote sensing may enable incredible improvements in spatial resolution and provide new views of Earth processes albeit on a region scale. However, to enable these improvements UAVs must accommodate these low-loss (for radiometry) antenna systems. These antennas many require integration or at least substantial accommodation of the UAV to provide the desired spatial resolution from a moderate UAV.

Current State of the Technology: Currently Microwave Radiometer systems are developed for large manned aircraft. While some instruments have been developed specifically for ER2 or specific “specialty” aircraft microwave instruments are developed as “payloads” and, unlike DoD missions, arrays are usually not optimize take best advantage of the vehicle. There has been substantial investment in the development of conformal array technology for “heavily loaded Structures” such and high performance fighter aircraft or transports. Smaller efforts focused on developing array technology consistent with the lightweight highly flexible structures likely required for future long duration vehicles. The TRL is difficult to summarize in a single number. Since clearly arrays at these arrays exist for these applications (TRL=9), if we define the technology as ultra light weigh (near zero parasitic mass) elements that also enable the structural deformation (wing flexure) to be accommodated there remain technology issues. Several concepts for lower frequencies (L-band) have be developed and tested in the laboratory at GSFC as part of a radiometric system (TRL=?). Other approaches that minimize impact of structural deformation on the antenna performance have been have been developed at LaRC and analyzed and minimum testing has been performed (TRL = ?). Finally, GSFC plans to test the array concept as a radiometer with an integrated array within the next year.

Identify funded programs that contribute to the development of this specific technology
GSFC Internal Research funding, ESTO does provide some funding of space antenna concepts some of this may be applicable, however, in my view the needs of the UAV remote sensing community for microwave low loss light weight antenna technology are very different and not well supported by ESTO technology programs.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Development of advanced materials, coatings, and films to enable “spray on” or appliqué antenna elements and low loss surface wave control.

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:
“meta materials” (EM composites): these concepts could created new broadband small antenna elements. Hybrid Right/Left material concepts may provide extremely small antenna structures. These concepts may also enable antenna elements that are tunable or may operate with very wide bandwidth.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Technology Assessment – Resource & Research Summary

Known sources of information:

SPIE 2005 Infotech symposium

Research being done:
Thin film antenna array development (JPL)
Multi band resonant element (GSFC –L-band) (LaRC- C- band)
Reduced Surface Wave and materials (LaRC)

- USRA Analysis

1. Technology Description

Strengths:
Microwave radiometers are useful for atmospheric and surface imaging. The various available wavelengths have different sensitivity to water vapor, liquid water, ice, and surface properties. Microwave radiometers would have excellent spatial resolutions when flown on UAVs.

Weaknesses:
Large radiometer antennas need to be accommodated on UAVs to provide the desired spatial resolution.

2. State of the Technology

Strengths:
Complete radiometers have been flown on manned aircrafts such as the ER-2. These systems need to be adapted and tested on UVAs. The currently TRL level for simple UAV systems is probably around 7. The University of Michigan has been test flying an innovative radiometer with a compact antenna on NASA airplanes. This system cold be easily adapted to large UAVs.

Weaknesses:
Antennas must be incorporated to UAV's structure. The impact of structural deformation on antenna's performance must be understood.

3. Enabling Technology Development

Strengths:
DoD, NASA, and NOAA have been funding the development of passive radiometer systems.

Weaknesses:
Current systems are power hungry and have large antennas.

4. Technology Dependencies

Strengths:
Innovate antennas such as the one developed at the University of Michigan and flight tested on NASA's airplanes could simplify the integration of radiometers on UAVs.

Weaknesses:
Antennas made of advanced materials could be excellent for UAV applications but are not yet mature enough.

5. Technology Forecast

Strengths:
Most of the technology that would enable the use of passive microwave radiometers on UAVs are already available.

Weaknesses:
Unaware of any technology development targeting passive radiometers for UAV applications.

6. Technology Gaps

Not addressed; No new technologies are necessary.

7. Technology Cost Drivers	Not addressed; Currently technology is enough for microwave radiometers for large UAVs. However, the integration of antennas to UAVs structure is not available yet and would benefit from the development of advanced materials.
8. Competing Technologies	Strengths: Passive optical systems are as mature as microwave sensors. These systems could be more compact. Weaknesses: Optical sensor needs more maintenance to maintain performance.
9. UAV Application Demonstrations	Not addressed.
10. Sources of Information	Very limited.
11. Technology Capabilities	Not addressed
12. Current Research	Strengths: There is large amount of activity in the development of microwave radiometers and innovative antennas both in US and abroad. Weaknesses: NASA new focus on Lunar and Mars exploration caused a substantial reduction in the funding available for the maturation of new technologies.
13. Regulatory Issues	Not addressed

3.8.6 In-situ Sensors: Chem. Detection using Laser Diode Spectroscopy

- TWG Output

Enabling Technology: Sensors - Atmospheric Research Date: 24 Feb 2006

Specific Technology: Argus instrument: *in situ* chemical detection using diode laser spectroscopy
Contributing Editor: Dr. Max Loewenstein**,** NASA Ames Research Center
Phone: 650.604.5504 Fax: 650.604.3625 Email: max.loewenstein-1@nasa.gov

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Specific Technology Description:
Advanced electro-optical techniques applied to detection of atmospheric chemical species; the measurement is a key element of any atmospheric or meterological research system deployed on UAVs, has been deployed on ozone layer and cloud/climate studies on conventional aircraft

Current State of the Technology:

The Argus instrument, a tunable diode laser based infra-red spectrometer, is a fully operational instrument currently deployed on the B-57 high altitude research aircraft based at Johnson Space Center. The instrument is small and lightweight and was designed to be deployed on a UAV or a light payload balloon platform.

Identify funded programs that contribute to the development of this specific technology
This technology is fully developed; field deployment is funded by the Upper Atmosphere Research Program at NASA Headquarters

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
N/A

Identify funded programs that contribute to the development of the critical supporting technology:
N/A

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*
The Argus instrument is currently at a TRL 9 level

Specific Technology Cost Drivers: *Operating and development costs.*
Currently costs are limited to specific integration costs on a candidate UAV platform; operational costs are limited to staff (2 field qualified scientists) travel, salary and per diem

Known competing or disruptive technologies:
Advanced electro-optical techniques; currently the cavity ringdown technology is being developed and could be suitable for UAV deployment in the near future

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:	deploy on B 57	deploy on B 57 Possibly deploy on Altair	no plans yet		

Demonstrated for UAV application?:
The Argus instrument is field tested and is technically and size and weight wise ready for UAV deployment. Its current limitation is endurance, which is limited to 6 hours of flight measurement time by the LN2 cryogen required to operate lasers and detectors. An enlarged dewar could easily extend endurance to 18 hours, the current flight time of a typical Altair flight operation.

Integration of Argus onto a UAV is not viewed as a problem and would be a fairly simple modification of its current B 57 integration hardware.

Technology Assessment – Resource & Research Summary

Known sources of information:
NASA Crystal-Face web site: http://cloud1.arc.nasa.gov/crystalface/WB57_files/argus2.pdf

Research being done:
Argus is active in the NASA cloud and climate research program

List Any Assumptions: Easy integration to UAV, operations not radically different from conventional aircraft; extended flight endurance requirements are well understood from point of view of technology and personnel stress

- USRA Analysis

1. Technology Description	Strengths: A system exists, namely Argus, that can measure two gases from an aircraft platform, CO and CH4. Weaknesses: No comment on uniqueness. All comments specific to Argus, and this write-up is not an overview or state of the art discussion.
2. State of the Technology	Strengths: Argus is at the TRL of 9, and is flying on high-altitude aircraft. Weaknesses: No comment on other diode laser spectrometers that are flying on aircraft.
3. Enabling Technology Development	Strengths: The Argus is fully developed. Weaknesses: Argus requires a UAV that can accommodate 21 kg, and a 40x30x30cm volume instrument. Power and weight were not discussed but could be critical for a UAV. The WB 57 can provide large amounts of power to a payload unlike a UAV.
4. Technology Dependencies	Strengths: Since it is flying and requires moderate resources, it appears that no new technologies are needed. Weaknesses: Argus is a two-channel instrument. For applications that require more gases to be measured the instrument would have to be miniaturized for a given UAV.
5. Technology Forecast	Not addressed.
6. Technology Gaps	Not addressed; need to discuss what improvements in technology would do for the next generation Argus or other laser diode systems.
7. Technology Cost Drivers	Since they feel they are ready to fly Argus, all they need are integration and operator field costs.
8. Competing Technologies	Mention a cavity ringdown technology without being specific on its importance or use.

9. UAV Application Demonstrations	Strengths: Good discussion on endurance of Argus due to cryogen depletion in 6 hours. Weaknesses: They mention that the Altair can fly for 18 hours and imply that Argus could fly aboard it for 18 hours by increasing the size of their dewar. No mention of weight or power accommodation for Argus on Altair was mentioned.
10. Sources of Information	Limited.
11. Technology Capabilities	No mention of improving Argus for smaller UAV deployment was given and no mention of how Argus could become more capable.
12. Current Research	Not addressed; NASA's LaRC has been involved in tunable laser diode spectroscopy research and aircraft flight missions for decades. This is a mature field and has many applications from medical research to atmospheric research. It is a disappointment that this technology write-up did not do more of a survey of the field.
13. Regulatory Issues	Not addressed; Access to the laser diode spectrometer would have to be carefully controlled if involved in an international program. ITAR regulations would have to be carefully followed.

3.8.7 In-situ Sensors: Meteorological Data

- TWG Output

Enabling Technology: Sensors - Met Data (P, T, 3D-winds, turbulence) Date:

Specific Technology:
Contributing Editor:
Phone: **Fax:** **Email:**

Specific Technology Description:
Because there are so many kinds of UAVs, designed and developed world wide for specific application, for our discussion here, let us narrow the focus to basically 3 classes of UAV for science application: small and light-weight such as Aerosonde, medium performance such as the Altus, and high performance such as the Global Hawk. The classification can also be categorized by duration and altitude performance.

At the present time, none of these UAV classes are equipped with Met instrumentation to make science quality data. There are nominal thermodynamic measurements for flight operation, which can tolerate a wider error uncertainty than for scientific studies. Take static temperature for example, in general both pressure and temperature are measured to determined air speed and the accuracy can tolerate +- 5 K in static temperature for navigation purpose. For scientific studies, an accuracy to 0.3 K is typically required. Accurate wind field and turbulence require even higher measurement accuracy for velocities, attitudes and the correction for aerodynamic disturbance surrounding the fuselage.

Current State of the Technology:
The current demonstrated technique makes accurate measurements of the air speed, angle of attack, angle of sideslip, and ground velocity. These measurements are combined to produce winds. This technique has

been used and documented on the instrumentation of the NCAR P3, NOAA P3, NASA ER2/DC8/WB57F. Similar technique and developments are also on board lower altitude and lower speed aircraft such as the Twin Otter, Cessna, LongEZ etc... There are commercially available sensors to make all the basic measurements (true air speed, angle of attack, angle of sideslip and ground velocity) to sufficient accuracy so that science quality 3-D winds, pressure, and temperature can be derived using established mathematical techniques. Temperature sensors include platinum resistance thermometers as well as thin films for turbulence (100 hz) measurements. Air velocity sensors use either vanes, or differential pressure approaches (up to 100 hz response). Ground velocity measurements are made with inertial navigation systems updated using GPS methods.

These sensors could also be used on UAVs, though very light INS/GPS equipment will need to be developed for the smallest UAVs.

The basic technique is to derive 3D wind field by differencing the air speed velocity relative to the airframe from the ground speed velocity. The calibration is typically the result of eliminating induced aircraft maneuver in the wind field data. Pressure and temperature corrections are derived from the air velocity vector for improved accuracy.

Another technology with some potential (but not yet demonstrated) is the use of aerosol laser scattering/reflectivity to determine the wind field.

Identify funded programs that contribute to the development of this specific technology
I can only speak to the NASA funded program for the development of the Met system on the ER2/DC8 and WB57. The Upper Atmospheric Research Program (UARP) provided the initial and continuing sensor research and development of the Met measurement capability. It started in the early 1980s on the high altitude ER2 aircraft. The DC-8 system was later funded by SASS (super sonic assessment ?) and the WB-57 was supported by the Radiation Program. The later two development benefited significantly in term of development cost and time from the early research on the high altitude platform.

NCAR has an established capability for installing and maintaining facility meteorological measurement instrumentation aboard all the NSF aircraft.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
A number of supporting technologies already exist, namely the Micro-Electro-Mechanical-System (MEMS) which fabricate complicated system in miniaturized scale and extensive usage of micro machining and electronics. An example of such system would be a quartz gyro inertial navigational system, such as the MMQ-G from Systron. It weights less than 1-lb.

Further miniaturization of air sampling probes is needed however. I believe that it is a matter of scaling of existing probe design. There are probes already available for smart guided arsenals which can be utilized for UAV application.

Identify funded programs that contribute to the development of the critical supporting technology:
The ERAST program had in the past provided funding support for UAV instrumentation.

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*
In general, sensor technology to support UAV application is available or at least can be designed and developed.

Specific Technology Cost Drivers: *Operating and development costs.*
For Met package specifically, sensor and hardware development costs are not the major hurdle. It is the knowledge base which is derived from labor personnel which are the main cost. There is also operational time required to mature the instrumentation and to calibrate the final data for scientific quality. For example, various micro parts and components are available, but until they are flown on an UAV and tested, the combined performance is not determined.

Known competing or disruptive technologies:
Optical and laser using both Raleigh and Mie scattering technique is very promising, although their performance are yet to be quantified.

I think the two main hurdles at this point are: the funding commitment to support UAV development, and to converge to a specific accessible UAV platform for science application. While the Global Hawk and the Altus/Predator have demonstrated military operation, albeit barely, the platforms and their operational support are generally not accessible to the scientific community.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

It is premature to do a milestone chart for this activity.

Demonstrated for UAV application?:
This depends on appropriate funding for UAV development for civilian science uses. Right now known active
civilian science uses of UAVs include Aerosonde for a number of NASA global hydrology and weather experiments, and a NOAA UAS demonstration project based at NASA Dryden. Neither of these has science quality meteorological capabilities.

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:
Indicated in text

Research being done:
As mentioned, above, research has been done on the laser reflectivity/scattering technology.

Regulatory/security issues? ITAR:
Possible DOD “dithering” of GPS signal by the military can affect the accuracy of
Measured ground speeds.

Non-US efforts:
Not known

List Any Assumptions:
Implicit in the text

- USRA Analysis

1. Technology Description

Strengths:
NASA, NSF, NOAA and a few private and university research aircrafts are capable of making accurate meteorological measurements. The technique developed for these research aircrafts could be easily adapted to medium size and large UAVs. Small UAVs such as the Aerosonde could use radiosonde packages such as that used in a simple RPV by Renno and Williams (Journal of the Atmospheric Sciences, 1995).

Weaknesses:
Current UAVs do not have sensor packages to make science quality meteorological measurements of quantities such as static pressure, air temperature, humidity, 3-dimensional wind and turbulence.

2. State of the Technology	Strengths: Sensors for high quality measurements of pressure and temperature in cloudless air are commercially available for all classes of UAVs. Sensors for high quality measurements of 3-dimensional wind and turbulence are available for medium size and large UAVs. Weaknesses: Sensors for research quality measurements in clouds and precipitation are not yet available. Sensor packages for high quality measurements of wind and turbulence with small UAVs are not yet available.
3. Enabling Technology Development	Strengths: NASA, NSF, and NOAA have funded the development of the technology for meteorological measurements from aerial platforms. In addition private industry such as Vaisala Inc has developed some sensors. These sensors have TRL 7-8. Weaknesses: In-cloud temperature measurements are still problematic. Wind sensor packages for small UAVs should be developed.
4. Technology Dependencies	Strengths: The technology for measurements in clear air is currently available. Weaknesses: The technology for the miniaturization of meteorological sensors packages exists but is not fully developed yet.
5. Technology Forecast	Strengths: The technology for the development of lightweight low power sensor packages exists. Weaknesses: The reviewer is not aware of any program specifically targeting the development of meteorological sensor packages for UAVs.
6. Technology Gaps	Weaknesses: Sensors for accurate in-cloud measurements are not well developed yet.
7. Technology Cost Drivers	Strengths: No major investments in technology development are necessary. Weaknesses: Investments in sensor development, their integration of small packages, calibration and tests are necessary.
8. Competing Technologies	
9. UAV Application Demonstrations	Strengths: Current sensor packages developed for manned aircraft are ready to be integrated in mid to large UAVs. Weaknesses: Small sensor packages need to be developed for small UAVs.

10. Sources of Information	
11. Technology Capabilities	
12. Current Research	Strengths: NASA and NSF have been funding research in this area, but not particularly for UAVs. ESA has been supporting the development of small sensor packages for planetary exploration. Weaknesses: The reviewer is not aware of the activities in other parts of the world.
13. Regulatory Issues	Strengths: In-situ meteorological sensor may be a subject to regulatory or security issues.

3.8.8 In-situ Sensors: CO_2 Detection Using Non-dispersing IR Analyzer

- TWG Output

Enabling Technology: Sensors CO2 *Date:03 March 2006*

Specific Technology: Non-dispersed Infrared Analyzer
Contributing Editor: S Wofsy
Phone: 617 495 4566 Fax: 617 495 4551 Email: swofsy@deas.harvard.edu

Specific Technology Description:
The sensor uses a non-dispersed infrared analyzer in a flight configuration with very effective isolation from the environment, to measure CO2 to better than 0.1 ppm long term precision and better than 0.2 ppm absolute accuracy—as required for all major atmospheric applications.

Current State of the Technology:
This techology has **Level 9** readiness, with more than 350 flights on the ER-2, WB-57F, and many other platoforms. It was orginally developed under the ERAST program and cofigured for UAV use, although it has not yet has a flight on a UAV.

Identify funded programs that contribute to the development of this specific technology
Developed with NASA funding under ERAST.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
No.

Identify funded programs that contribute to the development of the critical supporting technology:
NA

Forecast of specific technology:
It will stay at Level 9.

Specific Technology Cost Drivers: *Operating and development costs.* The sensor requires 2 persons in the field to perform pre-flight and post-mission activities.

Known competing or disruptive technologies:
None

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
Yes, has run automated without human intervention on hundreds of flights.

Technology Assessment – Resource & Research Summary

Other information: The sensor specifications are as follows.

CO_2 / Harvard	inches	lbs	Power peak/average	inlet	hazmat
Main Instrument	27.1 x 17.4 x 10.5	77	280W/ 170W	0.250" / SS / AFT	
Pump Box Assy.	20.0 x 9.5 x 8.25	33		can be shared	4 - 0.7L gas cylinders
Pre-Water Trap	23.0 x 2.6 x 3.5	2			
Dewar (incl. dry ice)	8.0 OD x 12.0 H	18			relief valve where req.

Total weight is 130 lbs. This can be reduced by investing funds at a rate of $1000-$2000 per lb. to about 100 lbs.
Volume can be reduced with modest investment.
Integration cost onto a UAV $50-100k depending on requirements.

- USRA Analysis

1. Technology Description

Strengths:
The proposed sensor uses a non-dispersed infrared analyzer to measure CO2 concentration to precision better than 0.1 and absolute accuracy better than 0.2 ppm.

Weaknesses:
The proposed sensor has not been integrated into an UAV instrument package yet

2. State of the Technology	Strengths: The sensor has TRL 8 with more than 350 flights on the ER-2, WB-57F, as well as other platforms. It was originally developed under the ERAST program and has been configured for UAV use. Weaknesses: The sensor has not been test flown on UAVs yete.
3. Enabling Technology Development	Strengths: NASA's ERAST program has been funding the development of the non-dispersive CO2 analyzer. Weaknesses: None.
4. Technology Dependencies	Strengths: The sensor does not depend on the development of other technologies. Weaknesses: None.
5. Technology Forecast	Strengths: The sensor will reach TRL 9 as soon as it is integrated and flight tested in a UAV. Weaknesses: The sensor is not integrated into a UAV yet.
6. Technology Gaps	Strengths: No technology gaps were identified. Weaknesses: None.
7. Technology Cost Drivers	Strengths: The technology has already been developed. Weaknesses: None.
8. Competing Technologies	Strengths: No competing or disruptive technologies exist. Weaknesses: None.
9. UAV Application Demonstrations	Strengths: The instrument has run automated without human intervention on hundreds of flights on manned aircrafts. Weaknesses: None.

10. Sources of Information	Not addressed.
11. Technology Capabilities	Strengths: No additional required technology was identified. The sensor is already integrated into an autonomous instrument package suitable to a large UAV. Weaknesses: The current instrument is not suitable to medium or small UAVs.
12. Current Research	Not addressed
13. Regulatory Issues	Strengths: No any known or potential regulatory or security issues exist. Weaknesses: None.

3.8.9 In-situ Sensors: CO_2 Detection Using a Quantum Cascade Laser Spectrometer

- TWG Output

Enabling Technology: Sensors CO2 *Date: 03 March 2006*

Specific Technology: Quantum Cascade Laser Spectrometer
Contributing Editor: S Wofsy
Phone: 617 495 4566 Fax: 617 495 4551 Email: swofsy@deas.harvard.edu

Specific Technology Description:
The sensor uses a quantum cascade laser spectrometer in a flight configuration to measure CO2 to better than 0.05 ppm long term precision and better than 0.1 ppm absolute accuracy—as required for all major atmospheric applications.

Current State of the Technology:
This technology occupies **Level 6** readiness, with many hours of testing of flight-ready hardware in the laboratory. It is awaiting its first opportunity for flight testing.

Identify funded programs that contribute to the development of this specific technology:
NSF Major Research Instrumentation/Development and DoE STTR..

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
No.

Identify funded programs that contribute to the development of the critical supporting technology:
NA

Forecast of specific technology:
It will reach Level 8/9 within 12 months, after initial testing in flight.

Specific Technology Cost Drivers: *Operating and development costs.*
The sensor requires 2 persons in the field to perform pre-flight and post-mission activities.

Known competing or disruptive technologies:
None

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:	Flight tests				

Demonstrated for UAV application?:

<u>Technology Assessment – Resource & Research Summary</u>

Other information: The sensor specifications are as follows.

CO_2 QCL /	inches		Power max/mean	inlet	hazmat
Optical Assy.	25x10x10	30	600/300	0.250" / SS / AFT	
Gas Deck Assy.	9.75 x 17.28 x 5.4	16		cannot be shared	3 - 1.1L gas cylinders
Pump Assy.	TBD	10			relief valve as req.
Laser Chiller	TBD	5			
Press./flow control	TBD	10			
Misc.	TBD	9			
total		**80**			

Total weight is 80 lbs. Volumes of flight-hardware listed as “TBD” are compable to the main instrument
Integration cost onto a UAV $100k , will need a flight test series.

- USRA Analysis

No USRA review and analysis of this topic was provided.

3.8.10 In-situ Sensors: Trace Gas Detection Using Difference Frequency Generation Lasers

- TWG Output

Enabling Technology: Sensors Date: 7 March 2006

Specific Technology: In-situ detection of trace gases using difference frequency generation lasers
Contributing Editor: Dr. Hans-Jürg (H.J) Jost, Director of Atmospheric Research, Novawave Technologies

Phone: 650 610 0956 x126 **Fax:** 650 610 0986 **Email:** hjjost@novawavetech.com

Specific Technology Description:
Difference frequency generation (DFG) lasers can be used for advanced in-situ detection of trace gases and their isotopic composition in the mid-infrared and can be combined with cavity enhanced absorption spectroscopy. DFG based sensors are very small, non-cryogenic and allow accurate trace gas detection; these measurements are a key element of atmospheric or meterological research missions on UAVs.

Current State of the Technology:
DFG laser based prototype instrument has been flown aboard NSF C-130. Commercial development of small, ultra-sensitive laboratory trace gas sensors based on DFG technology is underway. TRL 6-7 for UAV application.

Identify funded programs that contribute to the development of this specific technology
Commercial development is funded by NASA and DoE SBIRs. NSF funded DFG prototype on C-130.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Novel optical materials (non-linear crystals) currently being developed, but not broadly available, could extend the frequency range beyond 5□m and make many more trace gases accessible.

Identify funded programs that contribute to the development of the critical supporting technology:
NSF, NASA SBIR, DoE SBIR

Forecast of specific technology:.
DFG based laboratory sensors will be commercially available within 12 months. Currently no funding is allocated to develop this technology for UAV application, but it could be reached within 12-24 months by making the commercial sensors more rugged. This is a very straight forward engineering task.

Specific Technology Cost Drivers: *Operating and development costs.*
Field operation of a DFG sensor can generally be achieved by 1 person. Development costs are driven by engineering of commercial sensor for UAV application.

Known competing or disruptive technologies:
Other electro-optical techniques.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:	commercial sensor development		(no UAV specific projects)		

Demonstrated for UAV application?:
DFG laser based sensors have not been deployed on UAVs, but certainly offer the potential due to low weight and size, non-cryogenic operation, long endurance (limited by on board data storage), and ultra-high sensitivity for trace gas detection.

Technology Assessment – Resource & Research Summary

Known sources of information:
http://www.atd.ucar.edu/~dr/research.htm
http://www.ece.rice.edu/lasersci/midirsensors.htm
http://www.novawavetech.com

and papers listed on these sites.

Research being done:
See links above

- USRA Analysis

No USRA review and analysis of this topic was provided.

3.8.11 In-situ Sensors: Trace Gas Detection Using Cavity-enhanced Absorption Spectroscopy

- TWG Output

Enabling Technology: Sensors Date: 7 March 2006

Specific Technology: Iris: In-situ cavity-enhanced detection of water isotopes and other trace gases
Contributing Editor: Dr. Hans-Jürg (H.J) Jost, Director of Atmospheric Research, Novawave Technologies
Phone: 650 610 0956 x126 **Fax:** 650 610 0986 **Email:** hjjost@novawavetech.com

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Specific Technology Description:
Advanced in-situ detection of trace gases and their isotopic composition in the near-infrared using optical feedback, cavity enhanced absorption spectroscopy; very small, non-cryogenic and accurate trace gas detection; these measurements are a key element of atmospheric or meterological research missions on UAVs.

Current State of the Technology:
The Iris instrument has been built for the detection of water vapor isotopic composition for atmospheric and climate change research. Two prototypes have flown on the NASA DC-8 measuring water isotopes and methane and it is now being adapted to the WB-57 and Geophysika. TRL is 7-8. Further size and weight reductions can easily be achieved.

Identify funded programs that contribute to the development of this specific technology
Original funding comes from the Dutch Foundation for Fundamental Research (FOM) and the Royal Netherlands Academy of Arts and Sciences (KNAW), as well as a University of Groningen Competitive Strategic Grant, NASA Ames DDF, NASA Upper Atmosphere Research Program and Radiation Sciences Program.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
N/A

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology:
We expect to reach TRL 9 in the next 9 months as integration on high altitude aircraft Geophysika and WB-57 proceeds and further test flights are occurring.

Specific Technology Cost Drivers: *Operating and development costs.*
For UAV application, further weight and size reduction (currently 45 kg, <50 liters) is desirable and will be driven by engineering cost. Field operation can generally be achieved by 1-2 persons.

Known competing or disruptive technologies:

Other electro-optical techniques. Difference frequency generation of mid-IR radiation to access stronger absorption features of trace gases

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:	deploy on Geophysika	deploy on WB-57	no plans yet		

Demonstrated for UAV application?:
Iris has not been deployed on UAVs, but certainly offeres the potential due to its low weight and size, further potential for weight and size reduction, non-cryogenic operation, long endurance (limited by on board data storage), and ultra-high sensitivity.

Technology Assessment – Resource & Research Summary

Known sources of information: Paper in press by Romanini et al in Applied Physics B describing DC-8 results. Morville, J., S. Kassi, M. Chenevier, and D. Romanini, Fast, low-noise, mode-by-mode, cavity-enhanced absorption spectroscopy by diode-laser self-locking, Applied Physics B: Lasers and Optics, 80 (8), 1027-1038, 2005.

Research being done:
Development of water isotope device by Dr. Kerstel and co-workers at University of Groningen, The Netherlands, and Dr. Romanini and co-workers at University Joseph Fourier, Grenoble, France

Non-US efforts:
See above

- USRA Analysis

No USRA review and analysis of this topic was provided.

3.8.12 In-situ Sensors: Microsystems-based Chemical Sensor Arrays

- TWG Output

Enabling Technology: **Payload Sensors** Date: March 22, 2006

Specific Technology: In-situ Sensors: Microsystems-based Chemical Sensor Arrays
Contributing Editor: Gary Hunter
Phone: 216.433.6459 **Fax: 216.433.8643** **Email: ghunter@grc.nasa.gov**

Specific Technology Description:
The characterization of chemical species onboard UAV is often done with large and cumbersome equipment. In contrast, there is ongoing development in microfabricated chemical sensor technology that allows measurement of a range of chemical species of possible application to UAV. These microsensors are smaller and less power consumptive than standard instrumentation and can be integrated with hardware and software to form intelligent Microsystems. These microsensors have been developed using base platform technology which can be tailored for the needs of the application. Unlike standard electronic nose technology, which tends to be based on a single sensor type, the approach discussed here uses orthogonal

technology, i.e. very different sensor types each of which provide different types of information about the environment, and attempts to minimize cross interference between the sensors. These Microsystems may be deployed to allow more accurate assessment of the immediate environment surrounding the UAV.

For example, UAV systems have previously been deployed in forest fire situations to map out forest fire fronts to aid of ground personnel. Rather than carrying complex, large instrumentation as has been done in the past, it is proposed that a Microsystem based chemical sensor array be integrated into the UAV allowing local characterization of the chemical species. This particular Microsystem array is based on ongoing development to address the needs of the aerospace industry for more accurate and reliable fire detection. Species measured include CO, CO2, hydrogen/hydrocarbons, and humidity as well as particulates. By recording the local chemical and particulate environment, the UAV can characterize the fire front and aid ground personnel in firefighting activities.

The microsensor systems can be tailored for the application; for other applications a different array may be required. Thus, for atmospheric characterization applications, measurement of CO2 and trace gases may be required, where for environmental safety applications toxic species may be of higher interest. Some of the technology available from NASA GRC and its collaborators, at varying levels of maturity and selectivity, are sensors to detect CO2, O2, NOx, H2S, hydrocarbons, CO, pH, hydrazine, and even nerve gas agent.

Current State of the Technology:
The NASA Aviation Safety and Security Program has identified false fire alarms as one of the national problems hindering safe expansion of the U.S. air transportation system. Federal Aviation Administration (FAA) surveys of air carriers found that for fire detection systems in remote cargo compartments, there were 100-200 false alarms for every warning of an actual fire. False alarms negatively impact safety by causing aircrews and air traffic controllers to needlessly employ emergency procedures to affect fire mitigation and perform the required priority landing to the nearest suitable airfield. Safety is also affected in that aircrews subjected to repeated false alarms may be less likely to quickly and aggressively respond to a warning of an actual fire.

To address this problem, a multi-parameter, microsensor-based low false alarm fire detection system (MMFDS) has been developed and demonstrated. The primary function of this sensor system is to detect the onset of aircraft fires with high sensitivity, but with a very low rate of false alarms. Testing was conducted at the FAA cargo compartment testing facility in Atlantic City, NJ achieving a TRL 6. Under false alarm and actual fire conditions, the new technology demonstrated a zero false alarm rate in contrast to a conventional system which consistently false alarmed, while both systems consistently detected fires. This task produced a new commercial product, “Multi-Parameter, MicroSensor-Based Low False Alarm Fire Detection System” (MMFDS), which has been bestowed a 2005 R&D 100 Award as one of the 100 most significant inventions of the year as well as a 2005 Turning Goals into Reality Associate Administrators Choice Award.

Identify funded programs that contribute to the development of this specific technology
The NASA Aviation Safety and Security Program Phase I has completed. In Aviation Safety Program Phase II work is presently ongoing to decrease the power consumption of the fire detection sensor array by the use of nanotechnology. The objective is to enable a fire detection system with the same low false alarm rate but the size of a postage stamp with signal conditioning, power and telemetry which can be placed in inaccessible areas to detect the presence of hidden fires on aircraft. It has been proposed to continue these activities in FY07 in the IVHM program. Other funding contributes to improved fire detection sensor technology by, for example, encouraging the development of lower power CO2 sensors as is occurring in the EVA program.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
The present low false alarm rate fire detection system is a product that can be deployed in the near term for UAV applications. However, repackaging of the system would be necessary for UAV, and testing would be necessary to ensure proper interpretation of the sensor data. There may be a need for sensor redesign depending on the conditions associated with sampling of the UAV.

Identify funded programs that contribute to the development of the critical supporting technology:
The base technology is available for use in, for example, fire detection applications; the program that would apply the technology would likely be responsible for tailoring the sensor for that application. However, if other applications besides fire detection are envisioned for which the sensor technology does not exist or is not as mature, then further development would be necessary.

Forecast of specific technology:
Without major redesign, for the fire detection applications the packaging and tailoring the system to be ready for flight testing could take place in roughly a year depending on funding. This assumes use of the present technology for this application

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:
For fire detection, we consider this technology state-of-the-art.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
No

Technology Assessment – Resource & Research Summary

Known sources of information:
Papers and presentations related to fire detection research and development at GRC. This includes a Con-Ops presentation given to industry in May 2005.

Research being done:
See above.

Regulatory/security issues? ITAR:
None

Non-US efforts:

List Any Assumptions:
Assumptions discussed above. They significantly include a fire front mapping application using recently developed fire detection technology

- USRA Analysis

1. Technology Description

Very good overview given.

Strengths:
Microsensors are smaller and consume less power than standard instruments used for airborne in-situ measurements of chemical species.

2. State of the Technology

Strengths:
Very good discussion of the current technology for aircraft Met measurements. NASA, DoD, NSF and a few other federal agencies have been funding the development of MEMS sensors. Funding for this important area is expected to continue growing during the next decade.

Weaknesses:
The ER-2 system also provided turbulence information. Most instruments based on microsensors currently have TRL < 6.

3. Enabling Technology Development	Familiar with the funding programs mentioned, although NASA supports a technology/instrument program that is used to increase the TRL of components and instruments for planetary flight programs. Various sensors based on nanotechnology are already available, but most are not ready for integration on flight instruments based on similar technology.
4. Technology Dependencies	Strengths: MEMS is mentioned as is a miniaturized quartz gyro as examples for supporting technologies. In addition the military uses sensors on their projectiles for providing met and other data to help them improve accuracies. These technologies could be used for UAV met instruments. Scaling of existing met probes/instruments should suffice. Weaknesses: More information on critical technologies is needed. UAV sensor packages require other sensors besides those employed in fire protection.
5. Technology Forecast	Met probes are of sufficient TRL that they can be available when needed. Trade studies for a particular UAV could now be accomplished without new technology developments. Specific sensors for must be developed for UAV applications. A few sensors for meteorological measurements are available.
6. Technology Gaps	Agree that sensor technology to support UAV application is available; however, micro- or nano-sensors for specific measurements must be developed.
7. Technology Cost Drivers	Costs are in people with the appropriate experience. Hardware costs are a minimum. Test flights for calibration are a must. Adaptation to UAV system ?
8. Competing Technologies	None apparent
9. UAV Application Demonstrations	Not aware of any. The author of the write-up is but claims the quality is lacking that needed for science studies.
10. Sources of Information	Not addressed.
11. Technology Capabilities	Don't know of any. Not sure a lidar would provide more precise or accurate met information than an in-situ measurement.
12. Current Research	
13. Regulatory Issues	None apparent.

3.8.13 Drop Sondes: Meteorological Sondes

- TWG Output

Enabling Technology: Sensors Date: March 21, 2006

Specific Technology: meteorological sondes
Contributing Editor: Melody Avery
Phone: 757-864-5522 Fax: Email: melody.a.avery@nasa.gov

Specific Technology Description:

Copied from the attached memo:
Accurate thermodynamic and kinematic atmospheric profile measurements are probably the most basic type of data needed for any type of meteorological forecasting. Therefore, sensor and sonde (carrier) development has been evolving for many years. Whether sondes are elevated through the atmosphere on balloons, or dropped from a moving platform, the basic technology for sensors is essentially the same. There are four basic measurements needed for forecast model data assimilation, and for assessing the basic atmospheric state. These are: Pressure, temperature, humidity (moisture) and winds. Sondes also being may include sensors for icing, and sea surface temperature sensors.

Listed here are the basic four measurements, with associated accuracy and precision achieved by Vaisala Inc., for their model RS90 sonde, which is currently in wide usage:

	Range	Accuracy	Resolution
Pressure	1080-100 hPa	± 1.0 hPa	0.1 hPa
Temperature	-90 to +60 C	± 0.2 C	0.1 C
Humidity	0-100%	± 5%	1.0%
Horizontal Wind	0-200 m/s	± 0.5 m/s	0.1 m/s

In consultation with engineers at the National and University Centers for Atmospheric Research (NCAR and UCAR, respectively), these Vaisala sondes have been adapted for use from the NOAA G-IV, NASA ER-2, ballon-borne and many other government and university-sponsored research platforms. A description of the NCAR GPS dropsonde provided by the principal Investigator, Terry Hock at NCAR, is attached to this memo.

<u>Sonde Size:</u>

The NCAR GPS dropsonde in widespread current use is 10” x 12”, and weighs 390 g. NCAR is developing a smaller sonde for their drifting balloon-borne platform, available during the summer of 2006, and these sondes will be 2” x 6”, and weigh 225 g.

<u>Measurement Considerations:</u>

Temperature, pressure and moisture are generally measured using a thermistor and thin-film polymer package. Temperature and pressure measurements provide the accuracy needed by NOAA forecast model assimilation requirements, and are not a technical challenge. However, humidity measurements have been the subject of some research and debate. A small capacitor or thin-film polymer has limited accuracy and dynamic range for moisture measurements, and there have been several recent comparisons made between water vapor soundings and other water vapor measurement techniques, such as lidar.
Winds are now typically measured using GPS receivers, which may be either codeless or true GPS “engines”. These receivers are now made into small, low cost chips that are easily incorporated into sondes, although they require power, and the smallest sondes (20 g) may not be able to accommodate GPS, and may instead use radio frequency technology. With GPS winds the descent rate needs consideration because the receiver needs to lock on to the satellite signal quickly in order to start measuring

the winds. Calibration of sonde sensors is generally done at the factory with each sonde transmitting this information when it is turned on.

Current State of the Technology: *Provide a short summary including current TRL and basis for this assessment.*
TheVaisala RS90 / NCAR GPS dropsonde is a commercial product.

Identify funded programs that contribute to the development of this specific technology
Given a potentially limited payload size and weight, there are also other efforts to develop a smaller and lighter sonde. Yankee Environmental Systems (Northhampton, MA) has developed a 3"x12" sonde weighing only 80 g through phase two of an SBIR program. This sonde includes an IR pyrometer to measure surface emissivity, providing sea surface temperature information, and has a true, coded GPS chip for calculating winds. Recently a posting on the NOAA federal business opportunities website called for procurement of 20 g sonde technology, although this link is no longer active on the website. Given these and other efforts to reduce sonde size and weight, this is not likely to limit sonde utility, although sonde descent rate and horizontal transport will need to be considered with science requirements for a specific science mission.

Sondes that are dropped from high-altitude platforms have specific technology needs for slowing their descent through the atmosphere; Vaisala has patented a square-parachute technology to slow the initial descent, but there are other companies working on descent-rate control, including adding plastic "maple leaf" wings to slow sonde descent. There are at least two considerations for descent rate: one is that any sonde will fall more quickly at higher altitudes because there is less air available for resistance to the fall; the other is that vertical measurement resolution will depend on measurement speed as well as fall rate through the atmosphere. A typical measurement reporting rate is 2 Hz for these sondes. Fall rate depends upon altitude.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Technology development for sensors that are transported (either upwards or downwards) through the atmosphere for soundings or for more horizontal wind-borne (Lagrangian) measurements has a rich heritage and is also ongoing. Pressure and temperature measurements are reliable and have developed to provide the accuracy needed for most meteorological applications. Moisture (or humidity) measurements from a very small sensor do not yet have the desired dynamic range or accuracy needed, but this is a known problem that is being extensively worked on by a wide community of scientists and engineers. The best technique for making horizontal wind measurements are also a matter of debate and ongoing engineering. The addition of icing sensors and pyrometers for surface temperature measurements adds weight and size to sonde packages, but also adds value. Some sensor technology, such as particle and liquid water content, is currently too large for inclusion on a small, disposable sensor package. However, meteorologists, operational forecasters and forecast model developers are familiar with sensor limitations and typically rely on sonde-based measurements, so they are likely to remain a "staple" commodity for any atmospheric forecasting or research effort. In a general sense there are many sensor packages available, and ongoing engineering development occurring, so in situ, sonde-based sensor technology is not likely to limit the potential usefulness of AAOS-based missions.

The selection of sensor and carrier packages for an autonomous platform should be based on careful consideration of the science requirements and observation strategy needed for a particular application. This applies also to the selection of the autonomous platform, and current technology offers a variety of choices. The following paragraph is meant to briefly illustrate and summarize some of these considerations.

A very small UAV might itself act as a sensor carrier, in which case it is almost like a sonde itself, with the advantages of being maneuverable and recoverable. In most cases, however, sondes will be an expendable part of a UAV payload, and in this respect can be considered in the same way one considers fuel – the UAV will start a mission heavy with both sondes and fuel, and will end a mission light. Clearly the duration of a useful mission that relies on sondes will be limited by the number of sondes that can be carried at the beginning, therefore favoring sensor and carrier technology that is very small and light. One could create an engineering specification that is similar to miles per gallon for fuel – measurements per gram of sonde weight, for example. However, particularly from a high-altitude platform, the descent rate and horizontal travel of a sonde also need to be considered, because a very small and light sonde will travel horizontally as well as fall vertically. Lagrangian measurements following horizontal advection are very desirable for some applications, but may not be as useful for forecast model assimilation to an Eulerian grid, in which case a heavier sonde might be needed to provide a more geographically vertical profile. In a simple way, smaller and lighter may not always be better for the science application, although it has obvious benefits for saving payload space and for mission duration. A final systems engineering consideration is that in a UAV-based application that requires telemetry, data reporting at a temporal resolution corresponding to a spatial resolution that is much higher than forecast models can assimilate may have an unjustified associated receiver “cost”. However, since data streams for point measurements are much smaller than for imaging or for remote sensing applications, real-time telemetry and data reporting are not a technical “tall-pole”, except in the sense that receivers must fit within available UAV payload “space”, or that over-the horizon communications are necessary for real-time ground station data collection.

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

Specific Technology Cost Drivers: *Operating and development costs.*
NCAR GPS dropsondes cost between $600-$750 per sonde, which could potentially add significant expense to a long-duration mission requiring high-frequency continuous measurements. The Yankee Envirnomental Systems sonde is supposed to be available at $200 per sonde, and a smaller sonde using radio technology to derive winds might cost even less.

Known competing or disruptive technologies:
Lidar is recognized in its benefit and as yet largely unexploited potential over passive instruments. There are no alternate technologies known to become disruptive. A potential limitation of lidar is that some implementations may be problematic in posing a safety hazard for ocular viewing,

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:

In Situ Measurements from Sondes

Melody A. Avery
Research Scientist
NASA Langley Research Center
Hampton, VA 23681
757-864-5522

February 20, 2006

Overview:

This memo is not meant to be a complete survey of all sonde technology that is available, as time does not permit a thorough inventory of what is offered by all sonde technology providers, but it is meant to be a start at gathering some of the specifications necessary for assessing the technology as it could be applied to an Automated Aerial Observing System (AAOS), or Unpiloted Aerial Vehicle (UAV). In particular, the selection of commercial vendors for inclusion in this technical memo does not represent a preferential endorsement of those vendors.

Accurate thermodynamic and kinematic atmospheric profile measurements are probably the most basic type of data needed for any type of meteorological forecasting. Therefore, sensor and sonde (carrier) development has been evolving for many years. Whether sondes are elevated through the atmosphere on balloons, or dropped from a moving platform, the basic technology for sensors is essentially the same. There are four basic measurements needed for forecast model data assimilation, and for assessing the basic atmospheric state. These are: Pressure, temperature, humidity (moisture) and winds. Sondes also being may include sensors for icing, and sea surface temperature sensors.

Listed here are the basic four measurements, with associated accuracy and precision achieved by Vaisala Inc., for their model RS90 sonde, which is currently in wide usage:

	Range	Accuracy	Resolution
Pressure	1080-100 hPa	± 1.0 hPa	0.1 hPa
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Humidity	0-100%	± 5%	1.0%
Horizontal Wind	0-200 m/s	± 0.5 m/s	0.1 m/s

In consultation with engineers at the National and University Centers for Atmospheric Research (NCAR and UCAR, respectively), these Vaisala sondes have been adapted for use from the NOAA G-IV, NASA ER-2, ballon-borne and many other government and university-sponsored research platforms. A description of the NCAR GPS dropsonde provided by the principal Investigator, Terry Hock at NCAR, is attached to this memo.

Sonde Size:

The NCAR GPS dropsonde in widespread current use is 10" x 12", and weighs 390 g. NCAR is developing a smaller sonde for their drifting balloon-borne platform, available during the summer of 2006, and these sondes will be 2" x 6", and weigh 225 g. Given a potentially limited payload size and weight, there are also other efforts to develop a smaller and lighter sonde. Yankee Environmental Systems (Northhampton, MA) has developed a 3"x12" sonde weighing only 80 g through phase two of an SBIR program. This sonde includes an IR pyrometer to measure surface emissivity, providing sea surface temperature information, and has a true, coded GPS chip for calculating winds. Recently a posting on the NOAA federal business opportunities website called for procurement of 20 g sonde technology, although this link is no longer active on the website. Given these and other efforts to reduce sonde size and weight, this is not likely to limit sonde utility, although sonde descent rate and horizontal transport will need to be considered with science requirements for a specific science mission.

Measurement Considerations:

Temperature, pressure and moisture are generally measured using a thermistor and thin-film polymer package. Temperature and pressure measurements provide the accuracy needed by NOAA forecast model assimilation requirements, and are not a technical challenge. However, humidity measurements have been the subject of some research and debate. A small capacitor or thin-film polymer has limited accuracy and dynamic range for moisture measurements, and there have been several recent comparisons made between water vapor soundings and other water vapor measurement techniques, such as lidar. This topic is too detailed and controversial for this memo, but the reader is referred, for example to the recent IHOP campaigns at the DOE ARM site in Oklahoma for a more detailed discussion.

Winds are now typically measured using GPS receivers, which may be either codeless or true GPS "engines". These receivers are now made into small, low cost chips that are easily incorporated into sondes, although they require power, and the smallest sondes (20 g) may not be able to accommodate GPS, and may instead use radio frequency technology. With GPS winds the descent rate needs consideration because the receiver needs to lock on to the satellite signal quickly in order to start measuring the winds. Calibration of sonde sensors is generally done at the factory with each sonde transmitting this information when it is turned on.

Descent Rate:

Sondes that are dropped from high-altitude platforms have specific technology needs for slowing their descent through the atmosphere; Vaisala has patented a square-parachute technology to slow the initial descent, but there are other companies working on descent-rate control, including adding plastic "maple leaf" wings to slow sonde descent. There are at least two considerations for descent rate: one is that any sonde will fall more quickly at higher altitudes because there is less air available for resistance to the fall; the other is that vertical measurement resolution will depend on measurement speed as well as fall rate through the atmosphere. A typical measurement reporting rate is 2 Hz for these sondes. Fall rate depends upon altitude.

Cost:

NCAR GPS dropsondes cost between $600-$750 per sonde, which could potentially add significant expense to a long-duration mission requiring high-frequency continuous measurements. The Yankee Envirnomental Systems sonde is supposed to be available at $200 per sonde, and a smaller sonde using radio technology to derive winds might cost even less.

Brief Summary:

Technology development for sensors that are transported (either upwards or downwards) through the atmosphere for soundings or for more horizontal wind-borne (Lagrangian) measurements has a rich heritage and is also ongoing. Pressure and temperature measurements are reliable and have developed to provide the accuracy needed for most meteorological applications. Moisture (or humidity) measurements from a very small sensor do not yet have the desired dynamic range or accuracy needed, but this is a known problem that is being extensively worked on by a wide community of scientists and engineers. The best technique for making horizontal wind measurements are also a matter of debate and ongoing engineering. The addition of icing sensors and pyrometers for surface temperature measurements adds weight and size to sonde packages, but also adds value. Some sensor technology, such as particle and liquid water content, is currently too large for inclusion on a small, disposable sensor package. However, meteorologists, operational forecasters and forecast model developers are familiar with sensor limitations and typically rely on sonde-based measurements, so they are likely to remain a "staple" commodity for any atmospheric forecasting or research effort. In a general sense there are many sensor packages available, and ongoing engineering development occurring, so in situ, sonde-based sensor technology is not likely to limit the potential usefulness of AAOS-based missions.

The selection of sensor and carrier packages for an autonomous platform should be based on careful consideration of the science requirements and observation strategy needed for a particular application. This applies also to the selection of the autonomous platform, and current technology offers a variety of choices. The following paragraph is meant to briefly illustrate and summarize some of these considerations.

A very small UAV might itself act as a sensor carrier, in which case it is almost like a sonde itself, with the advantages of being maneuverable and recoverable. In most cases, however, sondes will be an expendable part of a UAV payload, and in this respect can be considered in the same way one considers fuel – the UAV will start a mission heavy with both sondes and fuel, and will end a mission light. Clearly the duration of a useful mission that relies on sondes will be limited by the number of sondes that can be carried at the beginning, therefore favoring sensor and carrier technology that is very small and light. One could create an engineering specification that is similar to miles per gallon for fuel – measurements per gram of sonde weight, for example. However, particularly from a high-altitude platform, the descent rate and horizontal travel of a sonde also need to be considered, because a very small and light sonde will travel horizontally as well as fall vertically. Lagrangian measurements following horizontal advection are very desirable for some applications, but may not be as useful for forecast model assimilation to an Eulerian grid, in which case a heavier sonde might be needed to provide a more geographically vertical profile. In a simple way, smaller and lighter may not always be better for the science application, although it has obvious benefits for saving payload space and for mission duration. A final systems engineering consideration is that in a UAV-based application that requires telemetry, data reporting at a temporal resolution corresponding to a spatial resolution that is much higher than forecast models can assimilate may have an unjustified associated receiver "cost". However, since data streams for point measurements are much smaller than for imaging or for remote sensing applications, real-time telemetry and data reporting are not a technical "tall-pole", except in the sense that receivers must fit within available UAV payload "space", or that over-the horizon communications are necessary for real-time ground station data collection.

Description of the NCAR GPS Dropsonde

The dropsonde incorporates a new pressure, temperature, humidity sensor module (RSS903) and a new GPS receiver module (GPS111), both designed by Vaisala, Inc., for their RS90 radiosonde. The sensor specifications are shown in the following table:

Dropsonde Sensor Specifications

	Range	Accuracy	Resolution
Pressure	1080-100 hPa	± 1.0 hPa	0.1 hPa
Temperature	-90 to +60 C	± 0.2 C	0.1 C
Humidity	0-100%	± 5%	1.0%
Horiz Wind	0-200 m/s	± 0.5 m/s	0.1 m/s

The winds are derived using a low-cost codeless 8-channel GPS receiver in the dropsonde that tracks the relative Doppler frequency from the RF carrier of the GPS satellite signals containing the satellite and the dropsonde motion. These Doppler frequencies (8 maximum) are digitized and sent back to the aircraft data system as a 1200 baud Frequency Shift Key modulation on the 400 MHz sonde telemetry transmitter. The aircraft data system has a Vaisala winds processing card (MWG201) which contains a high-quality 12-channel GPS commercial full-up receiver (GPS engine) that measures the local carrier phase Doppler frequencies, which are then compared to the telemetered sonde Doppler frequencies. The GPS engine also generates GPS time and the satellite ephemeredes data, and identifies the satellites and their Doppler frequencies so that the Doppler frequencies sent back from the sonde can be identified as coming from a particular satellite to make the wind calculations. The MWG201 card uses this data to compute independent velocity measurements every 0.5 seconds.

In addition to the RSS903 sensor module and the GPS111 receiver module, the dropsonde electronics board includes a microprocessor for measuring and controlling the sensor module and sending the measured data to the 100 milliwatt 400 MHz telemetry transmitter, and an 18-volt lithium battery pack for power. Surface mount technology is used on the electronics board to reduce size and increase the ease of manufacture. In addition, the electronics board contains a connector that serves as an RS-232 link with the aircraft data system for test and checkout and for setting the telemetry transmitter frequency prior to deployment. The transmitter can be set anywhere in the 400-406 MHz meteorological band in 20 kHz steps, creating about 300 separate channels.

A unique square-cone parachute is used to reduce the initial shock load and slow and stabilize the sonde. The parachute is immediately deployed on exit from the launch chute and streamers for about five seconds until filled by ram-air. The stability of the square cone parachute is very good during the sonde's descent and reduces or eliminates any pendulum motion of the sonde.

UCAR/Intellectual Property and NCAR/SSSF have licensed Vaisala Inc. of Woburn, Massachusetts to build the NCAR GPS Dropsonde, as Vaisala model RD93.

- USRA Analysis

1. Technology Description

Strengths: A good overview of the basic technology of dropsondes was provided, with some detail about level of accuracy and precision. The issue of sonde drop velocity (vertical velocity), which can influence the utility of the measurements provided, was raised.

Weaknesses: Although inferred, the technology overview doesn't discuss UAV applications. The required capabilities for dropsondes were not discussed, unless it is assumed that those provided by the currently available products are sufficient. Although mentioned, the limitation of the sonde's humidity measurement capabilities is a potentially severe one that could have been explored more. Certainly the community of data users (especially those who typically work with rawinsonde data) will be familiar with the potential weaknesses of capacitive humidity sensors, but that limitation may impact the desirability of using dropsondes on many UAV missions.

A technical memo was attached to the technology description document, but this did not provide much information beyond that provided in the original document.

2. State of the Technology

Strengths: Dropsonde systems currently exist and have been fairly widely used from a number of high altitude aircraft platforms. The NCAR/Vaisala collaboration has yielded smaller, lighter sondes recently; these will be tested during the upcoming summer on high-altitude Lagrangian balloons. This is perhaps the closest environment to a UAV platform in terms of weight and power constraints.

Weaknesses: While the TRL is quite high as a result of the long heritage of dropsonde systems, issues specific to UAVs have yet to be addressed. There was little basis for assessment of the UAV-specific readiness provided in this document.

3. Enabling Technology Development

Strengths: The development of a dropsonde system for use on Lagrangian (super-pressure) balloons is likely to make substantial contributions to the readiness of the technology for UAV deployment. To the best of my knowledge, the new NCAR lightweight dropsonde system is ready and will be tested this summer (July 2006).

Weaknesses: The biggest weaknesses in the technology are the shortcomings of the humidity and horizontal wind (GPS) sensors. However, these are issues faced by the community at large and are not specific to the use of dropsonde systems on UAV platforms.

4. Technology Dependencies

Strengths: As noted above, the dropsonde technology itself is relatively mature and there are a number of ongoing developments cited by the author that are likely to further reduce the weight of individual sonde sensor packages.

Weaknesses: There does not seem to be much activity in the area of improving the capabilities of the sensor package itself, particularly the humidity and horizontal wind measurement capabilities. While this will not necessarily limit the utility of dropsonde measurements from a UAV, it does limit their utility overall (regardless of launch platform).

5. Technology Forecast

Not addressed;
Strengths: Testing of a new, lighter-weight dropsonde system is occurring within a few months' time, which will aid the development of a UAV-specific system.

Weaknesses: No information in this category was provided in the document, so it is difficult to assess the likely trajectory of sensor and system development.

6. Technology Gaps

Can't really cast this as strengths/weaknesses – There are gaps in sensor technology as noted above, but these do not specifically impact deployment of dropsonde systems on UAVs. The author notes that the problems that affect dropsonde systems on other platforms will still be issues on UAVs – the accuracy of humidity measurements, the ability to measure horizontal winds using a GPS sensor on a rapidly dropping package, the tradeoff between weight and number (e.g., horizontal spacing) of sondes. It is not clear from the information provided to what extent these issues are being addressed by the community at large.

7. Technology Cost Drivers

Strengths: The widespread use of rawinsondes has made the basic sensor technology of dropsondes relatively inexpensive. Likewise, the variety of airborne platforms on which dropsondes are used and the range of research areas in which they are desirable has provided impetus for the creation of low-cost technology.

Weaknesses: It is difficult to assess the cost drivers for improved sensor technology. Certainly more accurate measurements of humidity are not only desirable, but perhaps critical, to the improvement of forecast models. Although there are numerous development efforts to create smaller, lighter sensors for water vapor, none has yet reached the desired intersection of accuracy and low cost suitable for a “throw-away” device.

8. Competing Technologies

Strengths: There are no known directly competing or disruptive technologies for dropsonde systems. They are unique methods for obtaining the types of information they provide.

Weaknesses: The author mentions the potential of competition from LIDAR. While LIDAR may provide higher resolution and more accurate vertical and horizontal “curtains” of water vapor and temperature, it seems unlikely that it will replace the simplicity of dropsonde systems in the near future.

9. UAV Application Demonstrations

Not addressed;

Strengths: Virtually identical technology is in use on other aircraft and shortly on Lagrangian balloons. No complications of transfer to UAV platforms would be anticipated.

Weaknesses: Not yet demonstrated on a UAV platform.

10. Sources of Information

Not addressed.

11. Technology Capabilities

Not addressed.

12. Current Research

Not addressed; Briefly – balloon-borne very lightweight dropsonde systems will be tested shortly. Research will still be needed to improve the basic sensors for humidity and horizontal winds. The details of research efforts in these areas were not addressed in the document, and are likely too numerous to review in such a short format.

13. Regulatory Issues	Not addressed; Strengths: Given the widespread use of rawinsondes, it seems unlikely that there would be any significant regulatory or security issues associated with dropsonde systems. There are certainly issues related to the actual dropping of sondes over certain areas, including flight lanes and perhaps over sensitive environments. Weaknesses: Improvements to the horizontal wind measurement capabilities of dropsonde systems may require use of advanced GPS technology that could have ITAR restrictions.

3.9 Power & Propulsion

3.9.1 Regenerative Energy Storage: Lightweight Energy Storage Using Regenerative Fuel Cells

- TWG Output

Enabling Technology: Lightweight Energy Storage *Date: 3/13/06*

Specific Technology: Regenerative Fuel Cells

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Specific Technology Description:
Solar powered UAVs coupled with lightweight energy storage can enable long endurance UAV missions. Closed loop H2-O2 regenerative fuel cells (RFC) have the potential to offer higher specific energy (Wh/kg) than state-of-the-art batteries (>400 Wh/kg vs. ~100 Wh/kg), especially for long discharge times. An RFC consists of a fuel cell, electrolyzer, reactant tanks, and supporting ancillary equipment. During sunlight hours, the solar array provides power both to the aircraft and to the electrolyzer to break down water into hydrogen and oxygen which is stored in tanks. At night, the hydrogen and oxygen is fed to the fuel cell, which produces power to the aircraft in lieu of the solar array. A byproduct of the fuel cell reaction is water, which is recovered and stored in a tank to send to the electrolyzer to repeat the cycle. The RFC can use either discreet fuel cell and electrolyzer stacks or a unitized stack which can operate as both a fuel cell and electrolyzer.

Current State of the Technology:
The technology is currently at TRL 4. A ground-based test bed was built and demonstrated under the ERAST/Fundamental Aeronautics programs. The unit has demonstrated 5 back-to-back day/night cycles.

Identify funded programs that contribute to the development of this specific technology
The closed loop RFC system development was initially funded by NASA under the ERAST program. Funding has continued through FY06 under the Fundamental Aeronautics program. Funding to continue testing of existing hardware at a reduced level has been proposed under the Subsonic Fixed Wing thrust area for FY07. An open-loop H2-air RFC is being developed by TARDEC/TACOM for military vehicle applications. Lockheed-Martin is pursuing RFC technology as a risk reduction activity through a contract with the Missile Defense Agency (MDA). NASA's Exploration Systems Mission Directorate is funding some RFC technology and system concept development as part of its Exploration Program which would be applicable to aeronautics missions.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain: The critical technology required for the system to reach maturity is the development of lightweight fuel cell and electrolyzer stacks capable of demonstrating reliable operation and life on pure oxygen. Additional benefits (reduced weight) would result from the development of unitized stacks, lightweight balance-of-plant components, and passive concepts that would eliminate the need for mechanical components.

Identify funded programs that contribute to the development of the critical supporting technology
Lightweight stack development was supported under the NASA aeronautics program through FY06. No additional aeronautics funding is anticipated for component development. Unitized stack development has been funded through the NASA SBIR program and a stack delivered from the program will be tested through the Energy Storage Project funded by the Exploration Systems Mission Directorate. Exploration is also providing a low level of funding for passive ancillary component development.

Forecast of specific technology:
Based on the projected funding levels, it is unlikely that the technology will progress past TRL 4 in the near future. With adequate funding (estimated $10-15 M), the technology (using discrete stacks) could demonstrate 600 Wh/kg and achieve TRL 6 by 2011.

Specific Technology Cost Drivers: Unknown at this time.

Known competing or disruptive technologies:
Lithium-sulfur batteries may be a competing technology. While these batteries are still at a very low TRL, they are projected to achieve 400 Wh/kg when mature.

Major Events/Milestones:

2009- Demonstrate closed loop operation with 20-30 contiguous day/night cycles with less than 2% degradation in power output (Based on milestone submitted for Subsonic Fixed Wing thrust area proposal.)

2011- Could achieve TRL 6 at 600 Wh/kg with adequate funding (~$10-15M)

Demonstrated for UAV application?:
The RFC system has not been demonstrated on a UAV. Development began under the ERAST program with the intention of flying a closed loop system on Helios. As part of the program, a system was designed, preliminary packaging was completed, and component development was initiated. A breadboard system was demonstrated at NASA GRC and is currently still in operation.

Technology Assessment – Resource & Research Summary

Known sources of information:

Bents, David J.; Scullin, Vincent J.; Chang, Bei-Jiann; Johnson, Donald W.; Garcia, Christopher P.; et al.**, Hydrogen-Oxygen PEM Regenerative Fuel Cell Energy Storage System,** NASA/TM-2005-213381, 2005.

Bents, David J.(Technical Monitor), **Light Weight 5 kWw Hydrogen-Oxygen PEM Fuel Cell Stacks and Light Weight 15 kWe Hydrogen-Oxygen PEM Electrolyser Stacks,** NASA contract report - NNC04CB37C, 2004.

Research being done:
Testing of closed loop H2-O2 RFC (NASA GRC)
Testing of unitized RFC stack (NASA GRC)
Development of passive ancillary components (NASA JSC/GRC)
Development of open loop H2-air RFC (U.S. Army TACOM/TARDEC
Development of closed loop RFC system (Lockheed-Martin through MDA contract)

- USRA Analysis

1. Technology Description	Adequate description of solar cell/RFC power generation system.
2. State of the Technology	Limited description of state of technology based on NASA project. No discussion of efforts outside of Agency. Basis for estimate of TRL ?
3. Enabling Technology Development	Better effort at address initiatives by federal government, but no direct mention of solar cell applications.
4. Technology Dependencies	Somewhat limited discussion as to supporting technology development…need to include RFC tank & plumping components to weight discussion. Solar cells ? Other government initiatives, outside of NASA ?

5. Technology Forecast	Assumptions ? Rationale ?
6. Technology Gaps	Not addressed
7. Technology Cost Drivers	Unknown ?
8. Competing Technologies	Not necessarily 'competing' if coupld with solar cells.
9. UAV Application Demonstrations	Other than limited NASA efforts ?
10. Sources of Information	Two references/sources identified.
11. Technology Capabilities	Not addressed.
12. Current Research	Appears complete, but listing of only US activities. Why isn't this reflects in other sections ?
13. Regulatory Issues	Not addressed.

3.9.2 Regenerative Energy Storage: Low Volume, High Power Density Solid Oxide Fuel Cells

- TWG Output

Enabling Technology: low volume, high power density SOFC Date: 3/3/06
Specific Technology:
Contributing Editor:
Phone: **Fax:** **Email:**

Specific Technology Description:
Low volume, high power density SOFC system operated on hydrogen in fuel consumption and regenerative mode to supply 100 day flight capability.

Current State of the Technology: Solid oxide fuel cells (SOFC)
SOFC are high temperature devices that offer greater power output and the highest efficiencies of all conventional fuel cell types. If fuel cells are used in a regenerative manner, both consuming and generating H2, the potential gain in efficiency compared to a PEM fuel cell can be 1.5 to 2 times. The system weight is also significantly lower. SOFC technology, however, is five to ten years behind PEM technology and SOFC

costs remain relatively high. As a high temperature device, SOFC are limited in practice by technological issues relating to materials and to design. Mechanical reliability and materials and system stability over long lifetimes require further development. Major challenges to the SOFC community are hermetic sealing of planar designs, development of light weight interconnects with needed electrical/chemical compatibility properties, and durable operation.

For application, technology challenges and gaps unique to flight systems must be addressed: power to weight, altitude operations, system durability. Aviation applications require large magnitude improvements in specific power density over current SOA land-based solid oxide fuel cells and impose stringent volumetric requirements. New materials and alternative designs optimized for aerospace requirements need be investigated. Novel low weight, low volume concept of SOFC systems which can provide an order of magnitude increase in specific energy density have been developed. Simplified stack configurations and fabrication procedures designed to decrease area specific resistance and improve mechanical integrity require further development. Cell-level heat, mass, and electrochemical transport models to help evaluate the thermal, electrochemical, and transport phenomenon are needed to guide the design and development of the high specific power cell, stack and balance of plant.

Materials issues: Selection of materials for SOFC components presents technical challenges. Each cell component must have the electrical properties to perform its function and the proper chemical and structural stability to survive fabrication and operating conditions. Material sets for anode, cathode, electrolyte and interconnect must be developed such that the microstructure, chemical reactivity, catalytic behavior, electronic/ionic conduction and thermal expansion properties are compatible with the atmosphere of operation and with the adjoining materials.

NASA-GRC has developed both a novel cell design and a novel ceramic fabrication technique that is unique within the SOFC community and uses an established material set. The design and fabrication techniques address the key hurdles to SOA technology of seals and interconnects, and has a predicted specific power density to meet 1.0 kW/kg.

Identify funded programs that contribute to the development of this specific technology
DOE through SECA and HITEC and other SOFC development programs
DOD through UAV, Portable Power an other defense programs

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Hydrogen storage and handling for flight applications.

Identify funded programs that contribute to the development of the critical supporting technology:
DOD is funding some hydrogen storage work.

Forecast of specific technology:
Progress is largely dependent on long term funding and political will. U.S. programs may also benefit from advances in Europe and Japan. Japan is introducing SOFC units for home power and heating in 2005/2006.

Specific Technology Cost Drivers: *Operating and development costs.*
Material, materials fabrication costs and system investment costs remain high relative to competing land-based power sources.

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?: Micro-SOFC have been demonstrated for military applications as part of the DOD Portable Power initiative.

<u>Technology Assessment – Resource & Research Summary</u>

Non-US efforts:
SOFC programs in Japan and Northern Europe.

- USRA Analysis

1. Technology Description	General nature of technology addressed in #2. No discussion of how support to UAV capabilities provided. Uniqueness?
2. State of the Technology	Nice discussion, failry comprehensive, although some of this bleeds over to other areas.
3. Enabling Technology Development	R&D efforts listed, including NASA, DOD, and DOE.
4. Technology Dependencies	Of course, hydrogen storage and handling issues…
5. Technology Forecast	Assumptions/rational for 'political will' ?
6. Technology Gaps	Addressed throughout report
7. Technology Cost Drivers	Brief…no direct mention development or operating costs
8. Competing Technologies	Not addressed/
9. UAV Application Demonstrations	DOD Portable Power Initiative.
10. Sources of Information	Not addressed; although awareness is apparent.
11. Technology Capabilities	Not specifically addressed.
12. Current Research	Not specifically addressed.
13. Regulatory Issues	Not addressed.

3.9.3 Battery Technology: Long-life Rechargeable Batteries Using Li-S Technology

- TWG Output

Enabling Technology: Long-life Rechargeable batteries Date: 3/17/06

Specific Technology: Li-S Batteries
Contributing Editor: Michelle Manzo
Phone: 216-433-5261 Fax: 216-433-6160 Email: manzo@nasa.gov

Specific Technology Description:
Li-S batteries offer one of the highest energy densities of secondary (rechargeable) battery systems currently under development. Coupled with solar arrays, they can provide an efficient power system for UAV missions. Li-S batteries are projected to have an achievable specific energy of 600 Wh/kg and an energy density of 700 Wh/l at the cell level. As such, they have the potential to serve as a simple, lightweight system for storage of energy produced via solar arrays during sunlit portions of the mission. The batteries would become the prime power source during eclipse periods. The recharge efficiency of this battery systems is relatively high, >85%, which can effect the solar array size and thermal rejection requirements for the overall system.

Current State of the Technology:
The technology is currently at TRL 4. The leading manufacturer of this technology, Sion Power, has built and demonstrated prototype batteries in lap top computers.

Identify funded programs that contribute to the development of this specific technology
NASA currently has a Phase 1 SBIR with Sion Energy for the development of this technology.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
No, successful development of the cells should be sufficient for the UAV application. Specific battery designs would need to be addressed to meet the UAV requirements.

Identify funded programs that contribute to the development of the critical supporting technology

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

Specific Technology Cost Drivers:

Known competing or disruptive technologies:
Regenerative fuel cells

Major Events/Milestones:

Demonstrated for UAV application?:
Li-S is not at a high enough TRL level to have been demonstrated for UAV applications. Prototype Li-S batteries have been built and demonstrated in laptop computers.

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:

Sion Technology papers and presentations

Research being done:
Evaluation of Li-S technology to verify vendor claims is being pursued NASA Phase I SBIR

- USRA Analysis

1. Technology Description	Strengths: This appears to be an interesting technology. It is proposed to use it with solar arrays. Weaknesses: There are many competing technologies that have advantages over this.
2. State of the Technology	Good but not that innovative.
3. Enabling Technology Development	Limited - NASA Phase I SBIR
4. Technology Dependencies	Not addressed
5. Technology Forecast	Not addressed.
6. Technology Gaps	Not addressed.
7. Technology Cost Drivers	Not addressed.
8. Competing Technologies	Weaknesses: This is an area where there are many competing technologies. Battery Technology research is heavily funded by DoD for soldier portable power. Zinc-air batteries, sodium-sulfur batteries and advanced iron based batteries may be better choices.
9. UAV Application Demonstrations	Not addresses.
10. Sources of Information	Limited
11. Technology Capabilities	Not addressed.
12. Current Research	Limited
13. Regulatory Issues	Not addressed.

3.9.4 Consumable Fuel Cell: Electric Propulsion Using H_2-Air PEM Fuel Cells

- TWG Output

Enabling Technology: Fuel cells for electric propulsion Date: 3/13/06

Specific Technology: H2-Air PEM fuel cells
Contributing Editor: Lisa Kohout
Phone: 216-433-8004 **Fax: 216-433-6160** **Email: Lisa.L.Kohout@nasa.gov**

Specific Technology Description:
Because of their high conversion efficiency, fuel cells offer lower specific fuel consumption than internal combustion engines and, therefore, can increase UAV mission endurance when used in an electric propulsion system. Due to the significant investment for automotive applications, H2-air PEM fuel cell technology is at a higher TRL than either H2-O2 PEM or SOFC technology, making it a candidate for near-term UAV systems. However, since most of this development has taken place on the commercial side, very little published data is available regarding performance, life, and reliability, making it difficult to assess the state of technology development. Current H2-air PEM stacks typically operate at ambient (14.7 psi) pressure, requiring either compression for operation at altitude or de-rating of the stack power. Also, the life and reliability of these systems is unknown and would need to be assessed for UAV applications.

Current State of the Technology:
An H2-air PEM fuel cell was flown on the Aerovironment Global Observer in November 2005. Details of the fuel cell technology (power level, operating pressure, etc.) are not available. Based on the information presented in the open literature, it is estimated that the technology is at a TRL 7. It is assumed that the system that flew is a prototype used to test the concept/vehicle. In addition, smaller PEM systems (10-500 W) have been demonstrated on micro UAVs. There is also work being done toward a flight demonstration of an all-electric PEM fuel-cell powered general aviation aircraft being done by Boeing Madrid in conjunction with their European partners.

Identify funded programs that contribute to the development of this specific technology
NASA has not been involved in H2-air PEM development. Significant commercial investment for transportation and portable power applications exists. The DoE is also contributing to the development of the technology for stationary and transportation applications at both the component and stack level. The DoD is investing in the technology for military vehicle and portable soldier applications.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Lightweight, high specific power stacks that can operate at low ambient pressures without significant power degradation would reduce the weight and power penalty associated with compression and cooling of reactant air. Lightweight balance of plant components would also improve specific power. Operational lifetime and reliability for PEM stacks and systems needs to be demonstrated.

Identify funded programs that contribute to the development of the critical supporting technology:
Since operation at low pressure is a concern limited to altitude operation, it is unlikely that any of the aforementioned sources is addressing this area. A low level investment by NASA has been made in this area through the SBIR program. Stack and component life is being addressed through some of the DoE work and most likely through some of the commercial work, as well. NASA is currently funded to look at lightweight, passive balance of plant concepts through the Exploration Program. While the systems targeted under this program are H2-O2, there may be some spin-off benefit for H2-air systems in terms of passive component and system design which would reduce weight and improve reliability.

Forecast of specific technology:
According to the Aerovironment website, they are targeting a 2-year window to the commercial availability of their fuel cell-powered UAV. Limited information is available to assess the state of development and the likelihood that this will happen in the given timeframe.

Specific Technology Cost Drivers: *Operating and development costs.*
Unknown.

Known competing or disruptive technologies:
Competing technologies would be traditional combustion engine technologies. There are no known disruptive technologies.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
H2-Air PEM fuel cell UAV was flown by Aerovironment on the Global Observer in November 2005. Small PEM fuel cells have also been demonstrated on micro UAVs developed under military funding (Spider-Lion UAV).

Technology Assessment – Resource & Research Summary

Known sources of information:

"Protonex Awarded USAF Contract for Fuel Cell UAV", Jan 2006. Link at http://www.evworld.com/view.cfm?section=communique&newsid=10705

Aerovironment Global Observer – The First Hydrogen-Powered Unmanned Flight", Nov 2005. Link at http://www.popsci.com/popsci/bown2005/aviationspace/4eb21d15cc827010vgnvcm1000004eecbccdrcrd.html

Department of Energy Multi-Year R&D plan for Hydrogen, Fuel Cells & Infrastructure Technologies Fuel. Link at http://www.eere.energy.gov/hydrogenandfuelcells/mypp/

Research being done:
Commercial R&D (both U.S. and foreign) for automotive and portable power applications (e.g. Ballard, General Motors, Hydrogenics, Giner)
Government investments by DoE and DoD for stationary and portable power applications

- USRA Analysis

No USRA review and analysis of this topic was provided.

3.9.5 Propellant Storage & Feed System: Storage Using Layered Silicate Clay Noncomposites

- TWG Output

Enabling Technology: Propellant Storage & Feed Systems: Date:

Specific Technology: Layered Silicate Clay Nanocomposites for Propellant Storage
Contributing Editor: Sandi Miller
Phone: (216) 433-8489 Fax: (216) 977-7132 Email: Sandi.G.Miller@grc.nasa.gov

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Specific Technology Description:
This technology utilizes the dispersion of layered silicate clays throughout the matrix of a polymer-carbon fiber composite tank. The dimension of the clay platelets are 1 nm thick and 100nm to 1 μm in the lateral direction. The high aspect ratio of the nano-particle contributes to enhanced material properties such as increased strength and barrier performance. The work is unique in that a low loading of the nano-filler (2-5 wt%) results in significant improvements in material performance. There has been limited work utilizing layered silicate nanocomposites in traditional polymer matrix composites. Most work to date has been done by NASA or the Air Force, with outstanding results. Decreased gas permeability and improved mechanical properties of polymer matrix composites are consistently demonstrated. This technology will contribute to UAV capabilities by improving the performance and lifetime of lightweight composite tankage for propellant storage.

Current State of the Technology:
TRL 4 – Composite tanks, with a nanocomposite matrix, have been prepared and tested in a laboratory environment. The results show five fold reduction in gas permeation through the nanocomposite tank. Coupon testing shows increases of up to 30 percent in composite coupon flexural tests. The dispersion of clay in an epoxy resin lowers the resin coefficient of thermal expansion by up to 30%. This should reduce the mismatch in CTE between resin and carbon fiber, thereby reducing microcracking of the matrix with temperature changes. However, microcracking is also dependent on material toughness.

Identify funded programs that contribute to the development of this specific technology
Supersonics, Subsonics, Fixed Wing

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
No

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology:
TRL 6 can be reached in 5 years assuming funds are available. A system/subsystem model or prototype demonstration in a relevant environment (ground or space) is a reasonable next step to the progress that has already been made with nanocomposite tank materials.

Specific Technology Cost Drivers: *Operating and development costs.*
The necessary operating and development costs include the cost of scale-up and tank manufacturing. Additionally, test costs such as long term durability in appropriate conditions are needed.

Known competing or disruptive technologies:
None. There are other types of polymer nanocomposites being developed at NASA as well as in industry and academia. These include exfoliated graphite nanocomposites and polysilsesquioxane nanocomposites. Neither has reached the advanced level of development that has been achieved with layered silicate clay nanocomposites.

Major Events/Milestones:

	2006	2007	2008	2009	2010

Event:

2007- Identify appropriate resin/ silicate system
2008- Scale up Nanocomposite Preparation
2009- Manufacture a subscale component
2010- Test component in relevant environment

Demonstrated for UAV application?:
This technology has been proven to reduce the leak rate of gaseous helium through a linerless composite tank. The helium leak rate in the nanocomposite tank is five times slower than that of a traditional polymer composite tank. Additional testing needs to be to determine the mechanical performance of these materials. However, coupon tests show increased composite strength, which will allow higher stresses to be placed on a nanocomposite tank compared to a neat epoxy-carbon fiber tanks.

The nanocomposite tanks do not require special tooling to manufacture and offer significant weight savings compared to metallic tanks.

Technology Assessment – Resource & Research Summary

Known sources of information:

S. Campbell, J.C. Johnston, L. Inghram, L. McCorkle, and E. Silverman, "Analysis of the Barrier Properties of Polyimide-Silicate Nanocomposites", *48th Intl SAMPE Symposium*, May 11-15, **2003**, 1124.

S. Miller, N. Leventis, J. Chris Johnston, and M. Meador, "Clay Nanocomposite/Aerogel Sandwich Structures for Cryotanks", National Space and Missile Materials Symposium (NSMMS) June 27- July 1, 2005, Summerlin NV

S. Burnside and E.P. Giannelis, Chem. Mater., **9**, (7), 1597 (1995).

P. Messersmith and E.P. Giannelis, J. Polym. Sci. A: Polym. Chem., **33,** 1047 (1995).

K. Yano, *et. al*., J. of Poly. Sci., Part A., Poly. Chem.**, 31,** 2493 (1993).

H.L. Tyan, K.H. Wei and T.E. Hsieh, J. of Poly. Sci., Part B., Poly. Phys.**, 32,** 2873 (2000).

H.L. Tyan, Y.C. Liu and K.H. Wei, Chem. Mater., **11,** (7), 1942 (1999).

T. Lan and T.J. Pinnavaia, Chem. Mater., **6,** 2216 (1994).

Z. Wang, T. Lan, and T.J. Pinnavaia, Chem. Mater., **8,** 2200 (1996).

T. Lan, D. Kaviratna and T.J. Pinnavaia, Chem. Mater., **7,** 2144 (1995).

Research being done:
Current research is focusing on the development of methods to achieve greater control over the placement of the nanometer sized particles. Alignment of the dispersed sheet results in optimized barrier and mechanical performance.

Regulatory/security issues? ITAR:
No

Non-US efforts:
Layered-silicate nanocomposites are being investigated worldwide, for numerous applications. Japanese researchers, specifically Toyota, continue to research these materials for automotive applications.

- USRA Analysis

1. Technology Description	Strengths: Appears to be a viable enabling technology. Weaknesses: Presents data for helium, it is not clear which propellant is the objective for UAV applications.
2. State of the Technology	The layer silicate clay composite tanks have shown improved behavior in laboratory tests. TRL 4 is a reasonable level from which to begin a development.
3. Enabling Technology Development	NASA providing funding through the supersonics and subsonic fixed wing programs.
4. Technology Dependencies	No technology dependencies are identified.
5. Technology Forecast	Weakness: TRL 6 attainable in five years - little detailed information to justify.
6. Technology Gaps	Not addressed; but don't appear to be any.
7. Technology Cost Drivers	Costs of scale-up and manufacturing ar enoted, bu tno estimates are provided.
8. Competing Technologies	"Advanced level of development" in comparison with other technologies ? Test environment (TRL 4) would not seem to indicate this.
9. UAV Application Demonstrations	Apparently lab environment only; none other cited.
10. Sources of Information	
11. Technology Capabilities	TRL 4 has been demonstrated and supporting research is on-going.
12. Current Research	Significant current work is on-going.
13. Regulatory Issues	None apparent.

3.9.6 Propellant Storage & Feed System: Cryogenic Storage Using Densified Liquid Hydrogen

- TWG Output

Enabling Technology: Propellant Storage & Feed System Date: 3/6/2006

Specific Technology: Cryogenic Storage Using Densified Liquid Hydrogen

Contributing Editor: Thomas M. Tomsik
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Specific Technology Description:
Densified liquid hydrogen (DLH2) may be able to provide a 9.3 % increase in propellant density by sub-cooling to 27°R. Results will be a smaller, lighter hydrogen storage tank and associated propellant storage systems. The propellants low vapor pressure (1.1 psia) reduces leakage rates while at altitude and allows the designer use of thinner walled tank materials of construction. A number of secondary impacts such as more volume become available for new equipment (ie. increased payload) or smaller airframe for reduced drag are possible. Using subcooled (densified) liquid hydrogen would also eliminate propellant boil-off losses during a significant portion of a UAV mission; thereby further improving vehicle performance and mission duration.

Current State of the Technology:
Production of DLH2 has been demonstrated at low flow rates and with unit performance characterized in the range of 29 – 30 °R. To achieve maximum benefits, the sub-cooled fluid temperature goal is 26.5 – 27 °R. Utilization of DLH2 including the storage, handling, pumping and pre-conditioning of this propellant while onboard a UAV has never been demonstrated. The production technology is currently rated at TRL-4 while aircraft system component technologies needed for implementing DLH2 for UAV flight service is nearer to TRL-3.

Identify funded programs that contribute to the development of this specific technology
None. There are no funded government programs for developing DLH2 technology for UAV platforms.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Densified propellants have no known critical dependencies on support technologies.

Identify funded programs that contribute to the development of the critical supporting technology:
Not applicable.

Forecast of specific technology:

Production Technology Level 5 - FY2006 Level 6 - FY2008 Level 7 - FY2010

UAV Feed Systems Level 4 - FY2006 Level 5 - FY2008 Level 6 - FY2009 Level 7 - FY2010

Specific Technology Cost Drivers: *Operating and development costs.*
$ 15 – 20 M

Known competing or disruptive technologies:
Slush hydrogen, solid hydrogen, or gelled hydrogen. All are at a lower development levels than densified propellants or require more complex support systems.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:	System Trades & Performance	Component Testing	Production Tests Ground Demo	Integrated Feed Systems Demo	UAV Flight Demo

Demonstrated for UAV application?:
Densified propellant technology has never been flight demonstration tested in either a space or aeronautics application

Technology Assessment – Resource & Research Summary

Known sources of information:

- **Brewer, "Hydrogen Aircraft Technology", CRC Press, 1991**
- **"Guide to Safety of Hydrogen and Hydrogen Systems, ANSI/AIAA G-095-2004, Reston Va., 2005.**
- Tomsik, T. M., "*Recent Advances and Applications in Cryogenic Propellant Densification Technology*", NASA TM 2000-209941, March 2000.

Research being done:

- **1988-1994: NASP Slush H2 Technology Program. >200,000 gallons of SLH2 produced.**
- **1995-1997:LH2 densification (subcooling) prototype system – 2 lbm/sec rig tested at K-site.**
- **1996: Hot fire ignition test of RL10B-2 engine with DLH2 at Plum Brook SPRF.**
- **1998: Demonstrated thermal stratification in composite dual lobe tank at K-site.**
- **1997-2001: Design, fabrication, and test of full scale LO2 (30 lbm/sec) and LH2 (8 lbm/sec) densification units for X-33/RLV.**
- 1995 – 2004: Boeing (Phantoms Works & Commercial) - Have investigated DLH2 production technologies and conducted studies for STS, CEV and UAV mission applications.

Regulatory/security issues? ITAR:
None

Non-US efforts:
There no known or current non-US efforts to investigate/develop this technology.

List Any Assumptions:
No assumptions made.

- USRA Analysis

1. Technology Description

Strengths: Very useful to have densified liquid hydrogen for propulsion.

Weaknesses: The proposal addresses the storage of densified liquid hydrogen: however, hydrogen is an impractical fuel for the UAV mission. The infrastructure to implement this and the design of a multitude of components to use this will have to be done. Cost, long term storage, auxiliary equipment, etc. will have to be worked out. 27 degrees R is a real challenge.

2. State of the Technology

Strengths: TRL 3 is a reasonable technology level for further development into a flight system.

Weaknesses: As is the case with most hydrogen propulsion proposals: New fuel systems have to be designed. New combustion chambers have to be designed. And the heat exchangers have to designed almost from scratch.

3. Enabling Technology Development	None, no current programs are concurrently developing this technology.
4. Technology Dependencies	None identified.
5. Technology Forecast	Rationale not provided; densified hydrogen has been under consideration for space missions for decades, and has much value. Yet it has not been put into place, presumably because of the difficulty in developing the technology. It is therefore assumed that the proposers underestimate the cost and difficulty.
6. Technology Gaps	Not addresses (or at least identified).
7. Technology Cost Drivers	It is speculated that the proposers underestimate the cost of technology development (see #5)
8. Competing Technologies	Other technologies for improving the volumetric energy efficiency of hydrogen are less well developed.
9. UAV Application Demonstrations	No denonstrations on aerospace systems were recognized.
10. Sources of Information	Sources of information were provided but not described.
11. Technology Capabilities	Not addressed; TRL 4-5 is indeicyaed. Studies should have been made.
12. Current Research	No current non-US research is underway.
13. Regulatory Issues	None.

3.9.7 Propellant Storage & Feed System: Hydrogen Feed Systems

- TWG Output

Enabling Technology: Propellant Storage & Feed System Date: 3/3/2006

Specific Technology: Hydrogen Feed Systems

Contributing Editor: Marc G. Millis
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Enabling Technology Description:
To support longer duration aloft, liquid hydrogen offers an energy/mass advantage of 2.8 compared to conventional aviation fuels. The challenge is that the energy/volume is 4.2 times greater and additional techniques are required to safely handle and store hydrogen as a cryogenic liquid (T≈-400 ˚F) over the flight duration.

Current State of the Technology:
Liquid hydrogen storage systems are a well-developed mainstay of spacecraft, but their use in longer-duration aeronautic applications is still in its early stages. For spacecraft, the TRL is 9. In the case of UAVs, TRLs range between 3 and 7 depending upon how strictly the definitions are applied. Component and subsystem design tools are relatively mature, but their combination into a generic package that could design the whole aircraft systems is only at the level of TRL-2 (Technology concept and/or application formulated).

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?
Unknown.

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
The most general challenge is to reduce storage tank mass (Sullivan).

The next technical challenge tends to be more application specific, namely to design the thermal management and control strategies to match the fuel delivery system to the mission profile and power plant requirements. If the objective is to develop the tools for design optimizations for any such systems, then further development work is needed on such tools. The system design depends on the choice of the aircraft's power plant (internal combustion or fuel cell). Since many of the fuel cell technologies are still evolving, a fair degree of modeling flexibility is required. Since there have been minimal precedents, it would be prudent to also create and operate flexible bench-testing rigs to assess various approaches.

Forecast of enabling technology:
To produce a simple baseline flight demonstrator (TRL-7) could proceed very rapidly (less than a year), in large part because such was already demonstrated in 2005 by AeroVironment (Dornheim).

On the other hand, if the objective is to develop system design optimization tools available for the general community (as opposed to having proprietary tools remain within the companies contracted to deliver the vehicles), then this would extend the development time into years. The exact timeline depends on the desired fidelity and flexibility of the tools to accommodate ever-evolving technologies, such as fuel cells. Since the hydrogen storage and delivery system is affected by, and affects, the design of the airframe and power plant, this is a *system* design issue and one that deals with evolving technology.

This issue of time is really a program management trade: If the program wants a demonstrator soon, something with limited capabilities could be produced rapidly. If the program wants to meet ambitious performance goals that would require an optimized design, then it would take longer. If the program wants ambitious performance, plus the added benefit of having publicly available design tools, then the development time gets longer still.

Identify and articulate any technology gaps discovered:
Various technology options exist for lowering the mass of storage tanks (including the requisite insulation), but deciding which of these is best requires system design trades contrasted with performance goals.

Likewise, the technology options to provide the thermal and pressure management of the storage and delivery system exist, but depend on the choice of power plant. This also requires system design trades to determine which combinations are optimum, choices that are also affected by the level of performance sought.

Lastly, the design tools have so far been at the component or subsystem level, with little work on integrating the airframe, power plant, thermal management, control strategies, and hydrogen storage system into a single design tool.

Enabling Technology Cost Drivers: *Operating and development costs.*
As evidenced by the AeroVironment demonstrator flights on May 27 and June 2, 2005, (Dornheim) entry-level approaches already exist. The largest cost driver is in the fidelity of the performance goals sought, specifically the required time aloft and payload capacity that affects the size of the tanks and correspondingly their mass and long-duration insulation requirements. The choice of the power plant (which is its own technology subject) affects the fidelity and hence, cost, of the thermal management system. The higher the temperature of the power plant, the more challenging the thermal management issues become. Lastly, increasing the fidelity or flexibility of the system design tools will increase upfront costs, but with a reciprocal lowering of the hardware development costs later.

Known competing or disruptive technologies:
Metal-hydrides have advantages for automotive applications, but when weight is of paramount importance as with aircraft, then liquid hydrogen storages systems have advantage.

Major Events/Milestones:

	2006	**2007**	**2008**	**2009**	**2010**
Event:					

Demonstrated for UAV application?:
In 1988 the first aircraft fueled solely by liquid hydrogen was flown (Brewer, p405).

On May 27 and June 2, 2005, AeroVironment conducted flight demonstrations of a liquid hydrogen fueled drone where the hydrogen was fed to fuel cells, whose electrical power was then fed to motor driven propellers (Dornheim).

Technology Assessment – Resource & Research Summary

Known sources of information:
- ***Brewer, Hydrogen Aircraft Technology, CRC Press, 1991***
- Dornheim, M.A, "Fuel-Cell Flier: Global Observer to stay aloft 7-10 days at 65,000 ft. using liquid hydrogen," Av. Wk. & Sp. Tech. June 27, 2005, p52.
- Millis, et al, "Design trades for Hydrogen Fueled Remotely Operated Aircraft, NASA TM in progress.
- Sullivan, Roy, et al, "Engineering Analysis Studies for Preliminary Design of Lightweight Cryogenic Hydrogen Tanks in UAV Applications" NASA TP in progress.

Capabilities (must have, etc.):
Depends on aircraft and power plant system requirements.

Research being done:
- AeroVironment

Regulatory/security issues? ITAR:
Unknown

- USRA Analysis

1. Technology Description	Strengths: This is a very realistic and well thought out engineering approach to the problem of hydrogen propulsion. Weaknesses: However, poor addresses applicability to the UAV mission.
2. State of the Technology	Weaknesses: The proposers provide a perfunctory description of TRL. As stated in the report, current subsystem TRL's range from 3-7 - depending upon how strictly the definitions are applied. (???) . From a UAS basis, a TRL of 2 seems appropriate.
3. Enabling Technology Development	Weaknesses No funded programs are identified, although there is substantial work ongoing in hydrogen systems for other applications; e.g., automotive applications.
4. Technology Dependencies	Strengths: The proposer describes the need for a systems-level model. Weaknesses: The parameters of the system level model are undefined.
5. Technology Forecast	Weaknesses: The proposers offer that by spending more resources on the technology development it could be done faster…
6. Technology Gaps	Weaknesses: The proposer indicates that studies are required to identify the most pressing technology gaps.
7. Technology Cost Drivers	Does not completely address the question…
8. Competing Technologies	
9. UAV Application Demonstrations	Strengths: Refers to the Baseline Flight Demonstrator [TRL-7]. The author cites two examples where UAV's fueled by hydrogen were demonstrated
10. Sources of Information	Four sources cited.
11. Technology Capabilities	Weak…
12. Current Research	Th eauthor does not provide any information on the research being done, only the sponsoring organization.
13. Regulatory Issues	None known.

3.9.8 Propellant Storage & Feed System: H_2 Gas Storage Using Composite Overwrapped Pressure Vessels

- TWG Output

Enabling Technology: Regenerative Energy Storage *Date:*

Specific Technology: Composite Overwrapped Pressure Vessels for Hydrogen Gas Storage
Contributing Editor: Pappu L.N. Murthy
Phone: 216 433 3332 Fax: 216 433 8300 Email: Pappu.L.Murthy@nasa.gov

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Specific Technology Description:
Light weight composite overwrapped pressure vessels (COPV) can be utilized to store hydrogen gasses at pressure for the long duration, high-flying UAV's. Technological advances in the design and manufacturing of fiber wrapped pressure vessels are enabling highly-efficient pressure-volume to weight ratios. However, to operate safely and reliably over long durations, lifing methods, damage tolerance and standard repair issues need to be addressed. In the past glass, kevlar, carbon and PBO fibers were utilized to build composite overwrapped pressure vessels. Current thinking is to move away from Kevlar vessels to carbon, PBO or other types of fibers due to the poorly understood process of stress rupture in Kevlar fibers as well as the fact that kevlar is known to be adversely affected by UV radiation. Developments in advancing carbon or other fiber based COPV technology is therefore a key necessity for achieving light weight long duration pressurized tanks on board UAVs.

Current State of the Technology:
Currently, COPVs made of both kevlar and carbon are on the ISS and Shuttle Orbiter as well as many other commercial applications. In order to achieve optimum weight and safety, the carbon COPV technology needs to be developed and a design database of carbon vessels stress rupture and aging characteristics as well as life and reliability prediction models for these vessels need to be developed. Currently the carbon fiber design database is incomplete. A systematic building block approach backed up by design of experiments needs to be developed. Substantial theoretical work has been conducted at the micro and macro-scopic level but the adaptation and distillation of fundamental design procedures for full scale pressure vessels has not been accomplished. Limited data and models are currently available for Kevlar fiber overwrapped vessels which provides an opportunity to expand the technology to carbon or other fibers. The research effort should focus on developing models, test plans for generating design database and sub-element and small scale vessel level test plans to lead the UAV fleet. Operational issues such as damage tolerance and standard repair procedures will also be addressed.

Identify funded programs that contribute to the development of this specific technology
Recently, the NASA Engineering Safety Center (NESC) sponsored a safety investigation of COPVs on board the Shuttle and the ISS. The NESC board identified many gaps in the current COPV technology and made several recommendations. There are currently no programs that are funding the COPV activity.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
The most critical need is to develop a validated life prediction methodology for carbon and other fiber overwrapped pressure vessels. This involves a systematic development of testing, material characterization, analytical modeling and FEM-based analysis techniques.

Identify funded programs that contribute to the development of the critical supporting technology:
Very limited funding is currently provided by the Orbiter Project Office. This is limited to only kevlar vessels which are on board the Space Shuttle. No funding has yet to be secured for advancing the technology to carbon vessels even though these are the vessels of choice for many current and future space and aero applications (For e.g. ISS, CEVs, CLVs etc…)

Forecast of specific technology:
Experimental testing and characterization: current TRLS 1-2 range
Analytical Model development: current TRLS 1-2 range

FEM based analysis current TRLS 2

Specific Technology Cost Drivers: *Operating and development costs.*
Testing and Characterization: Major cost drivers
Modeling and analysis: somewhat minor cost driver.

Known competing or disruptive technologies:

This technology is needed in many space and aero applications as mentioned above for e.g. CEVs and CLVs are currently planning to use Carbon fiber overwrapped vessels. Lots of synergy is expected. No competing technology has been identified for these types of applications.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
It is being contemplated to utilize regenerative energy technology for powering UAVs over long durations (100 days or more). Keeping the propulsion power system at an optimum weight is another overall requirement. Light weight composite overwrapped pressure vessels are therefore obvious choices for such applications. However, since these are under high pressure over long durations, such issues like stress rupture etc. must be addressed thoroughly and the reliability of operation over the duration of flight has to be established with analysis validated by testing in order to successfully advocate and advance the technology. Currently, although these vessels are in use in space applications, many issues are still unresolved (as evidenced by the recent NESC COPV safety investigation).

Technology Assessment – Resource & Research Summary

Known sources of information:
NESC COPV ITA assessment reports for Kevlar and carbon vessels.

Research being done:
Currently not much in this area is being done other than the NESC sponsored independent assessment activity.

Regulatory/security issues? ITAR:
None.

Non-US efforts:
None.

- USRA Analysis

1. Technology Description

Strengths: This involves composite pressure vessels for hydrogen storage. The research will have applications to many areas. The research proposed here is to develop models of carbon fiber behavior in pressure vessels.

Weaknesses: The technology using carbon nanotubes in structures is not yet at the point where macroscopic models will have any utility. The models for carbon fibers already exist are being used extensively and successfully in the aerospace industry. Hydrogen is not a feasible fuel for long term missions. Weak argument to justify a project on improving our understanding of carbon fiber composite failure mechanisms by stating that we need to move away from Kevlar fibers because they are poorly understood.

2. State of the Technology	Strengths: Good ideas on testing, and lifetime predictions. Evidently there are only Kevlar tests, and no carbon testing Weaknesses: It is not clear that they have a carbon pressure vessel to test. No TRL is provided in this section, although in the forecast of enabling technology development the TRLs are listed as1-2. This is inconsistent. Lacking an adequate description of the SOT.
3. Enabling Technology Development	
4. Technology Dependencies	Strengths: The authors propose the development of lifing methods. Lifing is an important and valuable technology for most lightweight aerospace components Weaknesses: Carbon overwrapped tanks are used in many applications. The proposers do not provide the state of the art in lifing technology.
5. Technology Forecast	Weaknesses: The authors state a technology forecast for components of the analysis to be in the 1-2 range. This is inconsistent with their statements that COPD's are the vessel of choice for many current and future space applications.
6. Technology Gaps	Strengths: The proposal for a systematic investigation of failure modes and lifing methods is valuable for most aerospace components.
7. Technology Cost Drivers	Incomplete.
8. Competing Technologies	Strengths: Carbon COPVs are clearly to be developed and investigated. They are presently the best choice for lightweight tank applications.
9. UAV Application Demonstrations	No demonstrations, just concepts.
10. Sources of Information	NASA documentation only…
11. Technology Capabilities	Synergy with many other applications is noted.
12. Current Research	Strengths: The proposers claim synergy is likely because of the large amount of work being done for other applications. Weaknesses: The large amount of other applications noted by the proposers is not consistent with the low TRL stated.
13. Regulatory Issues	None.

3.9.9 Propellant Storage & Feed System: Lightweight Cryo Insulation Using Polymer Crosslinked Aerogels

- TWG Output

Enabling Technology: Lightweight insulation Date: March 8, 2006

Specific Technology: Polymer crosslinked aerogels
Contributing Editor: Mary Ann Meador and Chris Johnston
Phone: 216 433-3221 Fax: 216 977-7132 Email: maryann.meador@nasa.gov

Specific Technology Description:
Polymer crosslinking provides a means of strengthening the otherwise extremely fragile silica aerogels to create a light weight multifunctional insulation material (support structure as well as insulation, low dielectric, acoustic damping, etc.)

Current State of the Technology:
The polymer crosslinked aerogels have been demonstrated in the laboratory and optimized for strength at minimal densities (TRL 3); properties are dependent on particular polymer used for crosslinking as well as density of underlying silica, amount of polymer used and processing conditions. So far, polymer crosslinking has been carried out and optimized with isocyanates, and epoxies which limit the temperature stability of the material. Cross-linking with higher temperature polyimides has been demonstrated but not optimized (TRL2). Crosslinking with polystyrenes which could improve hydrophobicity has been demonstrated but not optimized (TRL2). In addition, manufacturing needs to be streamlined for all polymer systems.

Identify funded programs that contribute to the development of this specific technology:
Past funding has been provided under LEAP and ESR&T. Current funding includes AEVA, subsonics rotory wing (acoustic testing) and AAP.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
None

Identify funded programs that contribute to the development of the critical supporting technology:
NA

Forecast of specific technology:
Demonstration project with MSFC--X-aerogel composite cryogenic tank (XACCT) project will raise TRL of isocyanate crosslinked aerogels to TRL 4 by end of FY06. Project is to build and test 6 small cryotanks with polymer crosslinked aerogel insulation. In addition, optimization study of polyimide and polystyrene aerogel are in progress and will advance to TRL 3 by end of FY07. Development of process to make aerogels in greatly shortened time (one-pot aerogels) will improve manufacturing capabilities.

Specific Technology Cost Drivers:
No comment

Known competing or disruptive technologies:
Multilayer insulation (MLI) is main competitor for thermal tank insulation, but it is by no means multifunctional. Requires a hard vacuum for insulation performance, provides no structural support, no acoustic insulation.

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:		X		X	X

Demonstrated for UAV application?:
No specific UAV demonstrations to date, but insulation and structural capabilities are relevant to UAV and are being demonstrated in other programs.

Technology Assessment – Resource & Research Summary

Known sources of information:

- Meador, M. A. B.; Fabrizio, E. F.; Ilhan, F.; Dass, A.; Zhang, G. H.; Vassilaras, P.; Johnston, J. C.; Leventis, N., *Chem. Mater.* 2005, *17*, 1085-1098.
- Katti, A.; Shimpi, N.; Roy, S.; Lu, H.; Fabrizio, E. F.; Dass, A.; Capadona, L. A.; Leventis, N. *Chem. Mater*. 2006, 18, 285-296.
- Zhang, G. H.; Dass, A.; Rawashdeh, A. M. M.; Thomas, J.; Counsil, J. A.; Sotiriou-Leventis, C.; Fabrizio, E. F.; Ilhan, F.; Vassilaras, P.; Scheiman, D. A.; McCorkle, L.; Palczer, A.; Johnston, J. C.; Meador, M. A.; Leventis, N., *J. Non-cryst. Solids* 2004, *350*, 152-164.

Research being done:
Refinement of existing polymer crosslinked aerogel materials and the development of new materials are ongoing. Refinement and optimization of the processing conditions is also under way with the goal of minimizing time / cost for the production of polymer reinforced aerogels.

Regulatory/security issues? ITAR:
None, to date.

Non-US efforts:
None known. These are primarily GRC-developed materials

List Any Assumptions:
We assume that all goals are nebulous, all schedules are flexible, and all budgets are inadequate.

- USRA Analysis

1. Technology Description

Strengths: Aerogels make great lightweight insulators.

Weaknesses: Must study the weight-volume relationships to optimize any given configuration.

2. State of the Technology

Strengths: Good.

Weaknesses: Non-polymer areogels, such as silica, may be a better choice for UAV applications.

3. Enabling Technology Development

Brief

4. Technology Dependencies

None given - no explanation.

5. Technology

Brief overview through 2007

Forecast

6. Technology Gaps	Not addressed.
7. Technology Cost Drivers	Not addressed. (Huh ?)
8. Competing Technologies	Brief mention of MLI.
9. UAV Application Demonstrations	What 'other programs' ?
10. Sources of Information	
11. Technology Capabilities	Not addressed.
12. Current Research	Topical, but no attribution
13. Regulatory Issues	None identified

3.9.10 Propulsion System: Internal Combustion

- TWG Output

Enabling Technology: <u>Propulsion</u> Date:

Specific Technology: Internal Combustion Engine
Contributing Editor: Tim Smith
Phone: 216-977-7546 Fax: 216-433-5100 Email: Timothy.D.Smith@nasa.gov

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Specific Technology Description:
Internal combustion engines (ICE) can be used to provide primary propulsion for a number of UAV systems. Currently some versions of UAV systems (Predator, Altus, etc) use internal combustion engines for propulsive power. The systems currently in operation all run on hydrocarbon based fuels. However, the range of operation may be expanded to high altitude long endurance (HALE) missions with the use of hydrogen as a propellant. For high altitude operations, internal combustion engines require the use of multiple turbo chargers to supply the required airflow and pressure.

Current State of the Technology:
Hydrocarbon ICE = TRL 9: Currently in multiple flight vehicles.
Hydrogen ICE = TRL 7: Not currently in flight vehicles, but engines have been used in prototype automobiles.

Assessment does not include operations combined with turbo-chargers.

Identify funded programs that contribute to the development of this specific technology
Past funding for ICE was from the NASA Environmental Research Aircraft and Sensor Technology (ERAST) program. Hydrogen ICE is being funded as part of the Department of Energy Freedom Car program and private investment from the automotive industry.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Multistage turbochargers and heat exchangers for high altitude operations. General durability and reliability testing.

Identify funded programs that contribute to the development of the critical supporting technology:
None known at this time.

Forecast of specific technology:
Hydrogen ICE: TRL = 9 within 5 years if funding provided for development. Technology maturation will require altitude testing combined with turbo-charging systems and endurance testing.

Specific Technology Cost Drivers: *Operating and development costs.*
Turbo-chargers, heat exchangers to remove waste heat, engine durability and reliability.

Known competing or disruptive technologies:
Electric aircraft using either regenerative Proton Exchange Membrane (PEM) fuel cells or consumable PEM fuel cells or Solid Oxide Fuel Cells (SOFC).

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
ICE with hydrocarbon fuel has been used in a number of early UAVs: TEAL RAIN, Condor, Strato 2C, Raptor D2, Perseus B, Altus, and Predator – Source Bents etal. NASA/TM-1998-206636

Technology Assessment – Resource & Research Summary

Known sources of information:

- Bents, David J.; Mockler, Ted; Maldonado, Jaime; Harp, James L., Jr.; King, Joseph F.; Schmitz, Paul C.; *Propulsion System for Very High Altitude Subsonic Unmanned Aircraft*. NASA/TM-1998-206636, Apr. 1998
- Bents, David J.; Mockler, Ted; Maldonado, Jaime; Hahn, Andrew; Cyrus, John; Schmitz, Paul; Harp, Jim; King, Joseph: *Propulsion Selection for 85kft Remotely Piloted Atmospheric Science Aircraft*, NASA-TM-107302 Oct. 1996
- Ford Hydrogen IC: http://media.ford.com/newsroom/feature_display.cfm?release=18794
- Predator A: http://en.wikipedia.org/wiki/RQ-1_Predator
- Rotax Engine: http://www.kodiakbs.com/engines/914.htm

Research being done:

Regulatory/security issues? ITAR:
Yes, depending upon the mission application.

- USRA Analysis

1. Technology Description	Strengths: Hydrogen has good potential for enhancing the performance of UAVs. Hydrocarbons are an established fuel source. Weaknesses: Hydrogen is not a good choice for UAV missions of interest due to its poor volumetric energy efficiency, difficult storage and handling characteristics, tanks and cryogenic infrastructure and leakage.
2. State of the Technology	Strengths: High TRL for hydrogen-fueled IC engines (7) but they have not been demonstrated with turbochargers, which should be a relatively small extension to the current technology Weaknesses: Basis of using hydrogen as the fuel It is instructive here to add some observations on the use of hydrogen for UAV propulsion. These comments apply to the series of "Technologies" in this category. Gaseous hydrogen takes up an enormous volume, and even liquid hydrogen occupies four times the volume of an equivalent of jet fuel. In order to use hydrogen one must have cylindrical or spherical tanks that are well insulated. In jet and piston engine aircraft, you get the fuel volume "for free" in the wing box. This CANNOT be done with hydrogen. A hydrogen powered UAV will consequently have an increase in fuel consumption, an increase in the wetted area, and an increase in weight. A final thought is that hydrogen is very expensive in comparison to hydrocarbon fuels.
3. Enabling Technology Development	There are some DOE efforts in this area. Hydrogen and fuel mixtures in engines has been done more successfully than engines with hydrogen alone. The optimization of hydrogen fuelled engines is just beginning to be studied.
4. Technology Dependencies	Limited discussion/explanation. Standard development of turbocharger is noted.
5. Technology Forecast	TRL 9 noted within five years, resulting in a fully operational system.
6. Technology Gaps	Strengths: Minimal development of fairly straightforward subcomponent. Weaknesses: The proposed multistage hydrogen turbochargers will entail a huge research and development – very many problems: The turbines will have to operate in a wet steam environment.
7. Technology Cost Drivers	Development & integration costs can escalate due do nature of hydrogen systems.
8. Competing Technologies	Strengths: This is a better approach compared to a fuel-cell powered UAV. Weaknesses: Existing engines seem to do fine and they are off-the-shelf with no R & D investment required.

9. UAV Application Demonstrations	Strengths: Hydrocarbon ICE's already in use - straightforward to replace powerplant. Weaknesses: Nothing has been demonstrated for hydrogen – it is just a proposal.
10. Sources of Information	Few references given, but cross-checking references did not indicate a preference for hydrogen-fueled primary propulsion.
11. Technology Capabilities	Not addressed; Because of the problems stated above a better system might be one where a supercharger [or two superchargers and an intercooler] is used instead of a multistage turbocharger.
12. Current Research	Not addressed; This is an active area of research, and this proposed work can use those results to advantage.
13. Regulatory Issues	Mission-dependent. Potentially ITAR.

3.9.11 Propulsion System: High Power Density Propulsion Using High Temperature Superconducting Motors

- TWG Output

Enabling Technology: Propulsion - High Power Density Motors Date: 3/22/06

Specific Technology: High Temperature Superconducting Motors
Contributing Editor: Dr. Dexter Johnson
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Specific Technology Description:
NASA has a goal to develop specialized unmanned aerial vehicles (UAV) to meet NASA science mission objectives. Current propulsion technology limits the endurance and range of UAVs. The NASA Glenn Research Center's High Power Density Motor (HPDM) development research team has investigated applying its technology to high-altitude, long-endurance remotely operated aircraft (HALE ROA) to enhance vehicle performance. Consequently, a mission analysis of a HALE ROA was conducted to determine if HPDMs are a viable solution for these propulsion challenges. This study shows that HPDM technology could be viable for future aircraft and UAV performing civil missions like hurricane tracking. Based on the assumptions and analysis of this study, these motors will allow aircraft to fly longer while reducing harmful emissions.

Current State of the Technology:
Designs, analysis and actual cryogenic motor tests show that such cryogenic motors could produce three or more times as much power per unit weight as turbine engines can, whereas conventional motors produce only 1/5 as much power per weight as turbine engines. The highest TRL rating for this technology is estimated to be about TRL-5 based upon the success of technology development efforts over the 6 year history of this research development Successes have led to world record (and patent pending) motor power density levels.

Identify funded programs that contribute to the development of this specific technology

The NASA GRC in-house program in this area is constructing and testing sub-scale models of several candidate motor types: switched reluctance (in testing), axial-gap permanent magnet (under construction) and superconducting synchronous (under construction). Contracts support the development and construction of a motor large enough to power a general-aviation-sized aircraft, optimization studies to explore the limits of synchronous motor power density, the development of a novel composite conductor and the development of an MgB2 conductor suitable for synchronous motor rotors. This work was previously funded primarily through the Revolutionary Aeropropulsion Concepts project and more recently from the Fundamental Aeronautics Program Subsonic Fixed Wing project.

ELEMENTS OF NASA GLENN PROGRAM IN HIGH-POWER-DENSITY MOTORS

	Performing Org.	Type	Status
Cryogenic (non-superconducting) motor in liquid nitrogen	NASA GRC	--	Testing
Tip-Drive Permanent-Magnet Motor	NASA GRC	--	Testing
Superconducting Synchronous Motor	NASA GRC	--	In Fabrication
Systems Analysis of Heavy, Efficient Drives	NASA GRC	--	In-Progress
2 MW Superconducting Motor/Generator in Liquid Hydrogen	NASA/AF	Space Act	In-Progress
Optimized Motors with Novel Conductor	Penn. State	NRA	In-Progress
MgB2 Superconducting Coils for Synchronous Motors	HTRI	SBIR	In-Progress

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
Additionally advances in the following areas would be beneficial

1. Develop ways to utilize cryogenic cooling to reduce the weight of power conditioning electronics.
   a. The power electronics weight fraction may be another limitation to a proposed electric propulsion system.
2. Higher temperature superconducting materials with enhanced mechanical, electrical, and magnetic properties.
   a. Higher temperature superconductors will require less cooling than lower temperature superconductors
   b. Enhanced mechanical properties will allow longer wire and more robust wire to be produced and used enabling more compact coil windings and increased power density
   c. Enhanced electrical properties will permit higher current density enabling higher power density.
   d. Enhanced magnetic properties will allow higher flux densities yielding higher power density.
3. Increased fuel cell power density.
   a. Fuel cell power density may be a greater inhibitor to electric propulsion than motor power density.
4. Development of turbogenerators.
   a. May provide an alternative to fuel cell power
5. Hydrogen fuel infrastructure (safe and cheap production, transport, storage, etc.)

Identify funded programs that contribute to the development of the critical supporting technology:
Advanced Fuel Cell/Power Task in Subsonic Fixed Wing Program

Forecast of specific technology:
It is anticipated that this technology can reach TRL-6 in the next 5 years. Optimization of the motor technology may progress well if sufficient programmatic support is provided but uncertainty in the development of critical supporting technology is unclear at this time.

Specific Technology Cost Drivers:
Development costs associated with demonstrating performance of motor concepts and components.

Known competing or disruptive technologies:
No comment.

Major Events/Milestones:

Event:	2006	2007	2008	2009	2010
Subsonic Fixed Wing	**x**	**?**	**?**	**?**	**?**

Demonstrated for UAV application?:
No, however a mission analysis (yet to be published) of a HALE ROA was conducted to determine if HPDMs are a viable solution for its propulsion challenges.

Technology Assessment – Resource & Research Summary

Known sources of information:
- NASA Glenn Research Center Program in High Power Density Motors for Aeropropulsion, NASA/TM—2005-213800
- http://www.grc.nasa.gov/WWW/AERO/base/URETI/

Research being done:
NASA Glenn In-house, and in cooperation with Contract and Other Government Agency efforts.
Aeropropulsion URETI

Regulatory/security issues? ITAR:
None

- USRA Analysis

1. Technology Description

Strengths: It is a good idea only if room temperature superconductors are discovered. The likelihood of this is very small in the next decade.

Weaknesses: Many...Designing a lightweight aircraft with a superconducting motor and the associated cryogenics will be difficult. A weakness is also the lack of a description of the power source for the motor.

2. State of the Technology

Strengths: Great potential for cryogenic motors.

Weaknesses: Putting this technology into a useful aircraft seems to stretch engineering principles of design.

3. Enabling Technology Development

Strengths: This is an active research area with applications in many areas

Weaknesses: UAV applications have small chances of success.

4. Technology Dependencies

Good assessment.

5. Technology Forecast

Assumptions ? Rationale ?

6. Technology Gaps

Many…

7. Technology Cost Drivers	Weaknesses: This would be very expensive to develop, deploy, and operate/maintain.
8. Competing Technologies	Weaknesses: Existing engines are doing the job at very low cost, with a robust supporting infrastructure. The infrastructure required to support SC motors would be complex and very expensive.
9. UAV Application Demonstrations	Limited to one…
10. Sources of Information	NASA-centric
11. Technology Capabilities	Strengths: Realistic assessments of the technology. Weaknesses: No assessment for UAV applications.
12. Current Research	NASA GRC-centric
13. Regulatory Issues	None identified…

3.10 Collision Avoidance

3.10.1 Overview

- TWG Output

Enabling Technology: Collision Avoidance Systems Date: March 17, 2006

Contributing Editor: Mark Skoog
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Enabling Technology Description:
Collision avoidance (CA) is a basic functional requirement for aircraft to safely operate. The process of collision avoidance involves sensing the surrounding environment, assessing the potential of colliding with those hazards that were detected and taking corrective action to avoid the hazard when a collision is imminent. The potential hazards that are of concern in collision avoidance are ground (the surface of the earth), airborne (other vehicles in the airspace), weather, ground obstacles (towers, power lines, ground equipment/vehicles) and surface features (buildings, foliage).

Most all of the CA process is performed by the pilot in a piloted aircraft to include the use of the pilot's eyes to visually detect and track the hazards. With the operator of the UAV remotely located, a CA system is foreseen as a critical feature to allow a UAV to operate with an equivalent level of safety to that of a piloted aircraft.

Air collision avoidance is unique in that it not only provides safety for the vehicle and its occupants but it also provides safety for other vehicles and their occupants flying in the air space. As a result, a number of regulatory requirements regarding the ability to perform both aspects of the air collision avoidance safety role are placed on vehicles that are to be operated in the national air space (NAS).
Finally, collision avoidance is influenced by a combination of mission requirements, procedures and systems. A collision avoidance system is needed only when mission requirements will expose the vehicle to potential hazards. Procedures alone can be used in conjunction with the air traffic management system to allow a UAV to operate in the NAS, however, these procedures carry a burden that impact routine operations and may severely restrict the UAV's ability to carry out some missions.

Current State of the Technology:
The technical readiness of CA systems to support UAV operations can not be completely assessed. As a minimum, air collision avoidance is a regulatory requirement for UAVs to operate in our NAS. The levels of performance for a UAV to meet this requirement have not yet been defined and no regulatory process exists. With the current lack of regulatory requirements, organizations desiring to operate a UAV in the NAS today must seek a certificate of authorization (COA) from the FAA prior to filing a flight plan. The COA process takes between 15 and 60 days. Once a COA is issued it authorizes the UAV to execute a specific mission only at specified times and dates for only a limited period of time. Once this period of time has passed or if some deviation from the predefined mission is desired, a new COA is needed and the COA process must be initiated again. In the past year Experimental Certificates have been issued to a very limited number of UAVs.[1] These certificates have not allowed any expansion of UAV operations; instead they are being used as an alternative to civil organizations applying for a COA and have involved much of the same process and limitations of the normal COA process.

Many CA systems exist for piloted aircraft, however most require a pilot to react and execute the evasion maneuver. With UAV operators remotely receiving and commanding the vehicle through a command and control link, technical and safety issues arise with the additional latencies induced into the CA process via the link. A few systems exist that do not require the pilot to react. These systems make the collision assessment and automatically execute the evasion maneuver. Most all of these systems are focused on providing ground collision avoidance and do not address air collision avoidance. Initial research has been conducted in a flight evaluation of an automatic air collision avoidance system on a piloted aircraft, however additional research is required. This research is unfunded at this time. Additionally, with the lack of regulatory requirements it is uncertain what detection sensors will be required to support an air collision avoidance system. A number of small independent efforts have taken place and are underway by organizations looking at various sensors. None of these are funded to couple the sensors to an automatic system on a UAV. The current system used on piloted aircraft, TCAS II, is unsuitable as is for use on a UAVs. Modification would be required to support UAV collision avoidance and all equipped aircraft (UAV and piloted platforms) would need to be retrofitted with the modifications.

In summary, automatic ground collision avoidance should be relatively adaptable to UAVs. The TRL is 7 for fighter attack aircraft with a relatively straight forward (low technical risk) development effort to achieve TRL 8. Air, weather and obstacle avoidance is of a lower TRL and final regulatory requirements have yet to be defined.

[1] *"ACCESS 5 Concept of Operations",* NASA Dryden Flight Research Center, Edwards, CA, February 2006.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?
The FAA is leading an effort to define the regulatory requirements for UAVs. Special Committee 203 (SC-203) is undertaking this task. One of the goals of SC-203 is to provide the needed definition of requirements to enable collision avoidance development for UAVs.

The Sensing for UAV Awareness (SEFAR) program funded by AFRL is beginning to address the see and avoid issue for the Global Hawk and Predator platforms. The funded portion of this program only brings this technology to piloted/UAV-surrogate platforms. Options are being investigated to fly this on a Predator platform.

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
An Automatic Air Collision Avoidance System fully integrated onto a UAV is required to first allow the complete maturation of regulatory requirements. Without an example of a working system it is not possible to completely define the regulatory requirements. A regulatory requirement definition must then be finalized prior to development of a certifiable system for a UAV. This regulatory definition will likely precipitate the need for sensor and architecture refinements.

Forecast of enabling technology:
If a program were initiated to integrate an eventual certifiable air collision avoidance system onto a UAV and that program were conducted hand-in-glove with the SC-203 effort, it may be possible to mature this technology in a three year period.

Identify and articulate any technology gaps discovered:
No fundamental technology gaps have been identified. The issues surrounding this problem are a lack of specific collision avoidance standards and requirements as well as, the lack of a funded program to integrate and flight test the system onto a UAV.

Enabling Technology Cost Drivers:
An integrated program for maturing air collision avoidance on UAVs would cost roughly $10M.

Known competing or disruptive technologies:
No specific disruptive technologies identified. However, the initial approach of the UAV industry and DoD concerning air collision avoidance has been somewhat disruptive towards obtaining their desired goal of certification. Many individual efforts have been initiated by various entities with a limited focus on how to make operations easy for the UAV and keep the UAV safe. Solutions suggested did not take into consideration interoperability (i.e. the impact on other traffic and systems already operating in the NAS). These early suggested solutions were eventually not acceptable to the FAA. This rejection created an adversarial atmosphere in the eyes of industry and DoD between them and the FAA. Some of this adversarial atmosphere still exists within industry and the DoD.

- USRA Analysis

1. Technology Description

Strengths: Provides an accurate general description of Collision Avoidance. Provides a description of collision avoidance for manned flights. It correctly incorporates the several dimensions of the problem in terms of its variety (aircraft-to-aircraft collisions, CFIT etc).

Weaknesses:
Does not discuss any specific CA technology. No discussion of 'uniqueness of the technology" or how the technology contributes to UAV capabilities, instead is merely a statement that "Air collision avoidance is unique…" without describing how the technology challenge is different from manned aircraft operations. Should encompass the various levels of importance CA problem takes, as a function of the UAV type. For large UAVs, the problem is pretty much the same as for manned aircraft. However, what about small UAVs, whose operation may be limited to class-G airspace? The collision avoidance problem definition may then change fundamentally.
Need clear understanding of the challenges and possibilities posed by collision avoidance in the context of UAV's. For example, future systems are expected to effect collision avoidance in large measure through cooperation between multiple craft. Even with manned aircraft such a future has already been envisioned for the coming generation of air traffic control (ATC) systems. Much of the disruptions noted in the concluding paragraph will be obviated within this framework. (The remark about pilots relying on eyesight to avoid collisions is valid for VFR operations only. VFR operations are extremely sketchy and cannot serve as a standard for automated CA.)

2. State of the Technology

Strengths:
Good review of regulatory status and COA process. Good understanding of research in collision avoidance of ground vehicles. The absence of well-formulated requirements is a strong impediment to CAS development for UAVs. VFR "see and avoid" rules are flawed for UAVs.

Weaknesses:
The process described is dated in light of FAA AFS-400 Policy Memo 05-01. COA process is now only available to the DoD or public entities. Could have gone into more detail about the weaknesses of current DSA systems. "Lack of regulatory requirements" is not entirely accurate. There are many regulations pertaining to manned aircraft that would also apply to UAS operations [14 CFR Parts 91, 21, 23, 25, 27 and 29]. The challenge for UAS operators is complying with existing regulations until the FAA promulgates new or modified regulations that are specific to the UAS community, civil and military. Unclear description of TRL. Level 7-8 may be appropriate for highly sophisticated manned fighter aircraft, but how is that relevant to UAS ? Should mention current efforts at 'see (or sense) and avoid' development efforts in academia. Need to provide more of an assessment of the technological challenges confronting UAV collision avoidance. Much of future systems will use cooperative methods with less reliance on a remote operator. Questionable to claim that technology of ground vehicle collision avoidance will directly translate to UAV's. There are a number of additional issues in UAV collision avoidance not faced by ground vehicles. For example, UAV's must avoid each other's wake. There are technical challenges posed by manner in which UAV's have to operate, that are not present with ground vehicles.

3. Enabling Technology Development

Strengths:
Mentions regulatory development by FAA, and ongoing work in AFRL. Reference to RTCA SC-203.

Weaknesses: Did not answer second part of question - "Will these programs support TRLs needed for maturation?" Limited useful information was included, would like to have read more about SEFAR and AFRL. Very little information given save the scant information relating to Sensing for UAV Awareness (SEFAR) program funded by AFRL.. Misses significant DARPA funded research.

4. Technology Dependencies

Strengths:
Focus on regulatory development. Identification of the need for an "Automatic Air Collision Avoidance System"

Weaknesses:
Doubt the FAA is going to propose regulations and rules to accommodate technology developments; on the contrary, existing regulations and modifications thereof will continue to stress "equivalent level of safety" standards and anyone intending to operate in the NAS will have to comply with whatever standards are set forth in the regulations. So, the technology will follow the regulations, not the other way around.

Should mention how many vehicles types should be incorporated in the bottom-up study: How many aircraft classes/types should be considered ? The range of UAV sizes and masses is much larger than that of civilian aircraft. There is much more to this than just regulatory development. The technological challenges are very substantial.

5. Technology Forecast

Strengths:
Provides an estimate of three year period.

Weaknesses:
Very little to support the conclusion that a 3-year maturity is possible. Appears to be a WAG without any supporting data. SC-203 is currently only identifying gaps in the regulations, while acknowledging that current regulations clearly pertain to UASs. The assumption that a system could be developed in 2-3 years might hold for one UAV category (e.g. manned-aircraft-sized UAVs), but would take much longer if it were broadened to other UAV classes. Sense and Avoid for small UAVs evolving in urban environment pose a brand new set of challenges that basic research has not answered. Overall, the challenges apparently factored into this calculation are rather naïve.

6. Technology Gaps

Strengths: Focus on development of standards and integration and flight testing.

Weaknesses:The entire report describes the technology gap that currently prevents UASs from operating in the NAS without a COA or Special Airworthiness Certificate.
While there are no technology gaps for large size UAV collision avoidance (it would probably look a whole lot like an automated TCAS anyway), the same cannot be said of other UAVs (smaller UAVs evolving in class G airspace). Should mention achieving collision avoidance through cooperation. How to

cope with unforeseen circumstances. Integration with communication constraints, etc.

7. Technology Cost Drivers

Strengths: Provides a $10M figure.

Weaknesses: No justification provided for this figure. This seems very optimistic, given the challenges that remain, and research that must be conducted. One system [one aircraft?] or an integrated system that could be accessed by multiple platforms? Another WAG.

8. Competing Technologies

Strengths: Focuses on interoperability issues and has a good understanding of regulatory issues. An accurate description of the observed attitudes of DoD and many “players” in the UAS industry.

Weaknesses: How is an 'attitude' equivalent to a technology? One potential competing technology are existing communication protocols. These are not naturally designed for integration of controls and communications in cooperative collision avoidance task. Protocols dedicated toward this are needed, but the temptation to take off the shelf protocols may win out.

9. UAV Application Demonstrations

Not addressed; Suggest consult DARPA and DoD funding agencies. Technology demonstrated limited to that of piloted/UAV-surrogate platforms.

10. Sources of Information

Not addressed; huge amount of untapped AVAILABLE information and resources

11. Technology Capabilities

Not addressed; For single UAV’s confronted with unexpected circumstances, adaptive control techniques must be developed. For cooperative UAV’s the science and technology of cooperation must be developed. A tight integration of communications/computing/signal processing and control issues is needed.

The “Holy Grail” in this industry is a Detect, Sense, and Avoid system that exceeds the Equivalent Level of Safety for manned aircraft. Until that is achieved, UAVs will not operate in the NAS without COAs or SACs. The basic technology exists, but no one has come up with the software and sensing architecture that meets even the current FAA standards, and those standards are under review for revision.

12. Current Research

Not addressed; There are hundreds of technical reports and papers, doctoral dissertations, reports to various government agencies, and material developed at conferences being held all over the world that are focused on the UAS industry. Aviation Week & Space Technology magazine has weekly articles on some aspect of UAS. Academic research, dedicated to acquiring a fundamental understanding of the issues, is noted in 11, and developing technologies toward them, is ongoing.

13. Regulatory Issues

Not addressed; Interspersed through the report but not specifically provided here. All existing Federal Aviation Regulations apply to UAVs, and there are no exemptions or exclusions contemplated. That is the problem, because UAVs cannot fully comply with those regulations with the existing and available technology.

3.11 Over-the-Horizon

3.11.1 Overview

- TWG Output

Enabling Technology: Over the Horizon Communications *Date:*

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Specific Technology Description:
Over the Horizon Communications (OTH) or more commonly referred to as Beyond Line of Sight (BLOS) communications is a basic function required for UAVs to be operated in the Global airspace. OTH is required for Command and Control (C2), situational awareness, health and status of the vehicle, and real time or near real time vehicle position (latitude, longitude, and elevation above a given point above the surface of the earth at a given moment) through the Global Positioning Satellite (GPS) or the AV's on-board navigation system both for safety and scientific purposes. The additional needs for researchers to have C2 with their instruments, instrument health and status, receive real time data, snap shots, or determine status of on-board data recorders are also required.

Currently for OTH C2 the industry is using UHF Milsat, (2.4K baud to 56K baud) for Line of Sight (LOS) and BLOS, INMARSAT (2.4K baud to 64K Baud) for over the ocean, and predominantly KU Band (data rates limited by Band Width of satellite transponder, modulation scheme, antenna size etc. but KU baud rate can be as high as twice the transponder bandwidth) Geo synchronous satellites for coverage over the earths major land masses.

Current State of the Technology:
The technical readiness of the satellite communications industry and commercially available communications hardware.

At the time this document is being written, the U.S. Government (DOD, CIA, NSA etc) are the major users and drivers of this technology. The classes of vehicle and operational environment / requirements dictate the level of communications required. For many of their applications LOS communications is sufficient but there are applications that require BLOS capabilities.

UHF Milsat is a DOD asset only and currently is not available for commercial use. TRL# 9

INMARSAT-International Maritime Satellite (primarily a phone and fax system to ships at sea) has been used by the Global Hawk program to provide C2 for transit over the worlds oceans. TRL #9
(Note) Global Hawk is currently the only US Gov. operated UAV (per Northrop Grumman and L3-COM West) that has used INMARSAT and is advertised as an operational C2 capability for Global Hawk.
Also, there is interest from General Atomics to add this capability to the Predator class vehicle.
INMARSAT Transceivers are commercially available and the system used by L3-COM was an adaptation of a Commercially of the Shelf (COTS) system.

KU Band Sat com- Currently the KU constellation of satellites located in geosynchronous orbit (Clark Belt) are primarily commercially operated (Non Government). KU was selected by DOD as the primary high bandwidth data transmition medium due to the availability of bandwidth and the location of the satellites. These satellites are placed in orbits that primarily cover land masses (largest concentration of customers) and provide little to no coverage over the earths oceans. TRL # 9

(Note) There is no mention of L, S, X, K, or KA band satellites. The requirements were purely DOD driven as to the band selected.

TDRSS—NASA Tracking Data Relay Satellite System was not mentioned. No data was available to the author at the time I penned this to support TDRSS ever having supported a UAV, and with the exception of the Space based Telemetry and Range Safety (STARS) airborne phased array antenna, that a airborne system capable of being installed in a UAV had ever been certified for operations through TDRSS.

Identify funded programs that contribute to the development of this specific technology
The DOD, Homeland Security, Coast Guard and other Government agencies are leading the efforts.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity?

Miniaturization: Reductions in weight and power consumption are a critical issue for all UAVs. The majority of UAV science missions call for endurances greater than twenty four hours and up to seven to ten days. IRIDIUM, INMARSAT, and KU band transceiver footprints would exclude them from being players for platforms other than Predator or Global Hawk class airframes. The need to miniaturize is paramount.

Bandwidth Efficiency: Currently Global Hawk and Predator use the Offset Quadrature Phase Shift Key (OQPSP) modulation scheme with thirty two to thirty eight inch parabolic tracking antennas that require 15MHz to + 40MHz transponder bandwidth –respectively-- to push 3.5Mbs- 4Mbs of data from the vehicle to the ground. Currently G2 Government Satellite Services, Pan Am sat, and Defense Information Services Agency (DISA) (commercial and Gov. Satellite service brokers / providers) price for KU bandwidth is $4.5K per MHz per Month. For one month of Predator operations the average price is $67-$72K.
Advances in modulation techniques and more efficient antenna design are required to bring the $$ per MHz to something within the realm of reason.

KU Band: Currently per G2 and Pan Am Sat. the KU band transponder utilization over the continental U.S. is at approx 75% of its available capacity. Due to the fact that Predator needs a full 15MHz bandwidth it is often not available and forces the Predator operator to purchase it in advance of their operations increasing the overall cost of operations. Per G2 and Pan Am Sat, “there is insufficient bandwidth available to support several Predator or Global Hawk class UAV KU band SatCom requirements “simultaneously” in the US.”

There need to be a fundamental shift on the part of the UAV operators to transition to KA or some other frequency band to allow for the increase UAV operations.

Insufficient time was provided to this author to adequately pulse industry and other Gov. Agency’s as to any ongoing efforts in the aforementioned fields. Further investigation and possible collaboration or directly funded efforts on the part of NASA and the science community are warranted.

Identify funded programs that contribute to the development of the critical supporting technology:
The Research Environment Vehicle Embedded Analysis on Linux (REVEAL) project at NASA Dryden is in the process of miniaturizing the IRIDIUM single channel modem assembly for mini and possibly micro UAV applications. Additional efforts are unknown at this time; DOD efforts are not always publicized.

Insufficient time was provided to this author to adequately pulse industry and other Gov. Agency’s as to any ongoing efforts in the aforementioned fields. Further investigation and possible collaboration or directly funded efforts on the part of NASA and the science community are warranted.

Forecast of specific technology:
If the current OQPSK modems were to be replaced with more efficient ‘Turbo Product Code” and minor adjustments were made to the KU Band antennas already installed on the Predator and Global Hawk—possibly reducing their bandwidth requirements / while maintaining there current data rate capabilities / link margins etc— with adequate funding--possibly three years.

The development and fielding of airborne SatCom systems utilizing other frequency bands (L, S, C, X, K, and KA) and more efficient modulation schemes—possibly three years.

The launching of additional satellites to provide over ocean coverage and reduce the current KU constraints is five to seven years. Per G2—it takes three to five years or possibly longer to get a satellite designed, licensed, launched, and operational.

Specific Technology Cost Drivers:
No comment

Known competing or disruptive technologies:
None

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
Yes- the list is substantial, All major aircraft manufacturers, Boeing, Northrop Grumman, General Atomics, to name a few and a large number of smaller manufacturers are fielding a host of UAVs ranging in size and capability from the Global Hawk class to micro UAVs that fit in the palm of your hand. All of these manufacturers are currently using available mature technologies to support their C2 and data needs and in some instances—leading the development efforts of emerging technologies.

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:
DISA, Northrop Grumman Corporation, General Atomics, L3-COM West Salt Lake, Utah, G2 US. Government Satellite Services, Pan Am Sat Satellite Services

Research being done:
Unknown

Regulatory / security issues? ITAR:
Unknown

Non-US efforts:
Unknown

List Any Assumptions:
KU band has been the frequency of choice. The UAV industry needs to work more closely with the commercial satellite service providers in developing the long term strategies necessary to provide global, cost effective coverage if this capability is ever going to go “public.”

The insertions of satellites in the Clark Belt that provide over the ocean coverage are required for high bandwidth real time and near real time C2 and data transmission solutions.

Transition from the OQPSK modulation scheme and other less efficient schemes are paramount to the better utilization of existing KU band spectrum to support the cost effective growth of this industry.

Some acceptable level of autonomy is needed to reduce the band width requirements for the transmission of data necessary to support the operations of UAVs in the National Airspace.

- USRA Analysis

1. Technology Description

Strengths:
Hits all of the major relevant technology needs – both link types and operator interfaces. The Technology Working Group Assessment (TWGA) description addresses many critical issues associated with over-the-horizon (OTH) communications. The description includes current technology capabilities as well as technologies which will require research and development.

Weaknesses:
Most of the technologies described are appropriate for larger UAV platforms due to size/weight/power restrictions. These technologies include high bandwidth data communications and all-weather operation as well as others. Did not really answer all question areas in much detail; e.g., limitations to applicability

Depending on the mission, terrain and range/altitude dictate the need for OTH communication. The requirement for higher data rates inherently limits the range of communication in low transmit power applications due to the increased noise power (vs intelligent receivers) in the wide receiver bandwidth. Mostly copied from NASA Interim Status Report, Appendix B.

2. State of the Technology

Strengths:
Good assessment of system possibilities and satellite capabilities.

Weaknesses: While TDRS has not been used with UAV's, it has been used to support ground systems, ELV's, and balloon payloads. This should make TDRS an easy transition to UAV work.

3. Enabling Technology Development

Strengths:
TRL level is probably at the correct estimated level. Some programs are identified for technology development from known funding sources.

Weaknesses:
Could mention TDRS LPT effort for transponders that could be adapted to UAV work. Also commercial vendor platforms for TDRS.
The OASIS program capabilities need to be expanded. Does not really survey NASA-wide developments that may be relevant; e.g.., items from GSFC Code 500, Project OMNI. GRC may also have relevant projects from aeronautical side. Other relevant payload (IP-centric, plug-and-play) and MMI efforts for spacecraft would be relevant here.

There are many NASA and contractor efforts for payload development that can be applied here. Also, look at AF responsive space concepts also for DoD leverage.

4. Technology Dependencies

Strengths:
Key technology areas for development are identified.

Weaknesses:
Did not identify an apparent weakness – NASA is not leveraging existing space communications and payload development efforts from the space side for much of the UAV work.

5. Technology Forecast	Not addressed; There is a lot of current work available on UAV research. Given that body of work, the assessment should attempt to predict when future needs could be met. This should include the impact of current lack of organized access to the NAS. May need additional assessment to determine if advanced modulation techniques work with existing sitcom systems and unanticipated results do not happen (e.g., spectral re-growth, etc.).
6. Technology Gaps	Not addressed; High bandwidth systems are going to be difficult on all but large platforms due to power/weight/size constraints on smaller UAV platforms. Security and electronic interference problems are also considerable challenges.
7. Technology Cost Drivers	Not addressed; Technology development is probably most hampered by the lack of adequate airspace access. An open architecture system is probably the most cost effective to allow for technology reuse over multiple programs. No real costing numbers given – just broad-brush assessment.
8. Competing Technologies	Not addressed; Satellite observation is one feasible competing technology but it doesn't generally allow for the close interaction possibilities of a UAV.
9. UAV Application Demonstrations	The assessment mentioned DoD UAV systems. Discussion could be included here. There have also been airborne observation applications in the agricultural world.
10. Sources of Information	Would expect that there are reports available in various government agencies, including DOD and NASA.
11. Technology Capabilities	Not addressed; A ground-based repeater system could also be used to relay information.
12. Current Research	Not addressed
13. Regulatory Issues	Not addressed; the obvious problem here is for civil UAV access of NAS.

3.11.2 Enabling Technology: IRIDIUM L-Band Satellite Constellation

- TWG Output

Enabling Technology OTH Date: 03/22/06

Specific Technology: IRIDIUM: L Band Low Earth Orbiting (LEO) Satellite constellation.
Contributing Editor: Charles J. McKee
Phone: 661 276 3037 Fax: 661-276-5332 Email: charles.j.mckee@dfrc.nasa.gov

Specific Technology Description:
IRIDUM consists of Sixty Six (66) Low Earth Orbiting (LEO) cross linked satellites operating as a fully integrated communications network providing Global satellite voice and data service over the oceans, airways and Polar Regions with data rates of 2.4kbs per IRIDIUM channel.

Current State of the Technology:
For voice and data communications this technology is TRL 9. It is well supported by the national and international communications industry.

Identify funded programs that contribute to the development of this specific technology
Research Environment Vehicle Embedded Analysis on Linux (REVEAL) a 12 channel prototype modem and voice phone system with variable data rates of 2400 baud – 28.8K baud. This technology developed by NASA Dryden has been used to support the following science mission data and communications requirements through IRIDIUM on the following platforms:
DC-8 aircraft—AirSAR-CRCO4 (2004), INTEX-NA (2004), AIRSAR-04_AK (2004), PAVE (2005), INTEB-B (2005) and the upcoming NAMMA (2005) Mission, ER-2—TCSP (2004), and ALTAIR (2005)—NOAA demonstration and support of a NOAA package being flown on the up-coming AMES Fire Mission. REVEAL through the IRIDIUM constellation has the ability to provide a half-duplex communications link to and from the science instrument allowing for Command and Control interactivity.

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
The ability to command and control a UAV through IRIDIUM is yet to be demonstrated. NASA Dryden has been in discussions with Northrop Grumman (Global Hawk), General Atomics (IKAHANA and ALTAIR), and L3-COM West Salt Lake, Utah on developing the ability to provide command and control of the aforementioned UAV platforms through IRIDIUM. This has been discussion only. The need to have a continuous link to UAVs for command and control, Situational awareness, and above all, safety- is paramount.

Identify funded programs that contribute to the development of the critical supporting technology:
None

Forecast of specific technology:
Current discussions with Northrop Grumman, General Atomics, and L3-COM indicate there is a desire by DOD to incorporate the IRIDIUM system into the suite of OTH communication links used to operate DOD UAV assets.

Per discussions with L3-COM West Salt Lake, Utah would put this at a TR L# 2. (Technology Concept and application Formulated).

Specific Technology Cost Drivers:
IRIDIUM is an automated system using a dial-up modem-essentially—makes a phone call to the device on the aircraft to establish the communications link with your instrument or communications interface device or data and instrument control interface.

Known competing or disruptive technologies:
None

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:

Yes, for voice, data transmission from onboard sensors, and control of a on-board instrument through IRIDUM by the principal investigator through the NASA Dryden REVEAL system.

<u>Technology Assessment – Resource & Research Summary</u>

Known sources of information:

For REVEAL--Lawrence.C.Freudinger@dfrc.nasa.gov
For L3-COM West, Director of Government Programs—Robert.E.Anderson@L-3com.com / Robert is the single point of contact for the Global Hawk and Predator DOD, OTH communications efforts for UAV Command and Control .

Research being done:
Per the IRIDIUM Consortium—there is a plan to launch new satellites to upgrade from 2.4kbs to 64kbs per channel (within the next few years).

Regulatory / security issues? ITAR:
Unknown / Further research required. (DOD is a heavy player in the IRIDIUM game)

Non-US efforts:

List Any Assumptions:
If this technological capability were to be developed it would go a long way to solving some of the real time / near-real time command and control, data, sensor control, and management issues for single UAVs , swarming UAVs, and Mother ships with link requirements to siblings. This is a low band-width system with limited capabilities.

- USRA Analysis

No USRA review and analysis of this topic was provided.

3.11.3 Enabling Technology: INMARSAT L-Band Broadband Global Area Network

- TWG Output

Enabling Technology OTH Date: 03/22/06

Specific Technology: INMARSAT L band-Broadband Global Area Network (BGAN)
Contributing Editor: Charles J. McKee
Phone: 661 276 3037 Fax: 661-276-5332 Email: charles.j.mckee@dfrc.nasa.gov

Specific Technology Description:
The Broad Band Global Area Network (BGAN) operates in the L Band frequency range and provides a 512Kbs by 126Kbs broad band data connection-- Supporting data, phone, streaming IP, and text. This service would provide a wide band data link to UAVs operating over all major land masses and the world's oceans with the exception of the Arctic and Antarctic. This satellite data service would provide the UAV and science community with a broad band data connection for over the ocean (outside of the current commercial L, S, C, KU , K, and KA band satellite footprints) real time / near real time UAV command and control , sensor data download, and real-time / near-real time interaction with the sensor by the principal investigator.

Current State of the Technology:
The current INMARSAT BGAN Satellite constellation has not been completed, the last satellite in the constellation providing coverage to the continental US is due to be launched in the next few months, but when completed should be able to provide broad band wide area coverage. At the current time there are no airborne BGAN terminals in operation with a TRL of 1. The ground based segment is, however, full functional at a TRL 9.

Identify funded programs that contribute to the development of this specific technology
None

Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:
The airborne terminal and antenna tracking system have not been developed.

Identify funded programs that contribute to the development of the critical supporting technology:
None

Forecast of specific technology:*.*
Per the consortium: there is an ongoing effort by a European company to develop a "Airborne" BGAN satellite communications terminal; contact information is forthcoming. The current TRL level of that effort is unknown.

Specific Technology Cost Drivers: *Operating and development costs.*
The airborne terminal would require no operators. This would be a stand alone communications system with a phone modem (dial-up) like connection .Antenna pointing information would be provide through the aircraft on-board navigation system or a GPS receive built into the airborne terminal to maintain link with the satellite.

If NASA were to identify this as an emerging technology that would provide a cost effective solution to many current and proposed UAV, OTH issues then, efforts to work with the INMARST consortium and local communication system houses would be in order.

If no ITAR issues- then a possible collaboration between NASA and the European entity currently involved in the development of the "airborne terminal" may be in order.

The development of / use of more efficient data modulation technologies could, theoretically, improve the data through put and link margins required to support some of the proposed missions.

Known competing or disruptive technologies:
None

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?:
No

Technology Assessment – Resource & Research Summary

Known sources of information:
Vendor:
Stratos
USA
Toll free: +1 888 766 1313
Tel: +1 709 748 4233
E-mail: info@stratosglobal.com
Web www.thepowerofbgan.com

Research being done:
No NASA / DOD effort has been identified at this time.

Regulatory / security issues? ITAR:
Unknown / International Consortium

Non-US efforts:
This is a European system. Per the vendor “no” known US efforts for utilizing airborne BGAN wide band data services (apart from my personal inquire) are currently underway at this time.

List Any Assumptions:
If the airborne data terminal capability were to be developed it would go a long way to solving some of the real time / near-real time command and control, data, sensor control, and management issues for single UAV , swarming UAVs, and Mother ship with link requirements with siblings; providing a single Line of Sight (LOS) and Beyond Line of Sight (BLOS) communication solution for all missions that do not require over the pole and 10Mbs or higher data rates.

- USRA Analysis

No USRA review and analysis of this topic was provided.

3.12 Reliable Flight Systems

3.12.1 Overview

- TWG Output

Enabling Technology: Reliable Flight Systems Date: 3/23/06

Contributing Editor: Dr. Ivan Somers
Phone: **Fax:** **Email:**

Enabling Technology Description:
The ability of a UAV flight system to adapt to system or hardware failures is a key technology for flying UAVs with an acceptable level of safety and perhaps the most critical system for the aircraft is the flight control system (FCS). This technology, generic to any UAV application, provides for high reliability and is one of the foundations for unrestricted access to the air space by UAVs. Initial reports from the FAA regarding UAVs indicate they are looking for "reliability comparable to a piloted aircraft". The issue of reliability can be addressed from two viewpoints. The first is basic reliability of the onboard systems. The second is the reliability of an on-board pilot in being able to recognize a failure and adapt to the situation. Both of these viewpoints must be considered in assessing the reliability of UAV flight systems. This technology is especially important for long endurance flights in remote areas, where options for recovery are limited.

One approach to system reliability is simply to increase the redundancy of flight systems. This comes with both an initial cost and an on-going weight penalty. Another approach would add on-board intelligence to recognize and remedy a failure.

Current State of the Technology: *Provide a short summary including current TRL and basis for this assessment.*
Simulations of adaptive flight control systems have shown promise for many years, and several methods of adaptive control have found their way to flight test projects. The latest of these is a neural-net based system scheduled to fly on an F-15 aircraft at NASA. It is likely that the final solution will be a compromise or combination of the two approaches.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Forecast of enabling technology:
Based on ongoing intelligent flight control efforts, a TRL of 6 is assigned.

Identify and articulate any technology gaps discovered:

Enabling Technology Cost Drivers:

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event: *no information provided*					

- USRA Analysis

1. Technology Description

Strengths:
Discussion recognizes that both failure detection and system reconfiguration will be needed. Outlines reliability issues related to the flight control system, along with the ability of the flight control system to recognize and adapt to on-board failures. The flight-control system's reliability requirements are well addressed; however, safe operation for UAVs needs to consider more than just the flight-control system. For example, the issue is to protect people on the ground and in other flying vehicles. Consequently, the UAV might be "sacrificed" to provide "safety." Rather than the flight-control system having multiple redundancy and high levels of adaptability, a UAV could respond to any problems by going into a safe mode, throttling back, and circling in response to a problem. Likewise, the vehicle could be equipped with a ballistic recovery system (rocket- launched parachute) that allows the entire vehicle to safely descend to the ground.

Thus, the safe operation in the civil environment depends on what happens when the intended means of control fails. "Self destruct" methods must be traded off against (likely) more expensive, complicated, and heavier on-board intelligence and adaptive controllers.
Weaknesses:
While the flight control system is a key component of UAV reliability, other aspects are equally important. Communication link, structure, control network and power system reliability must be considered along with flight control system reliability. The statement that one approach to providing the required reliability is to increase the redundancy of the flight system implies that there is another approach. In fact there must be redundancy. The key question is how to provide the redundancy in a cost and weight effect manner.(see comments in CRITERION #8 – Competing Technologies)

Great deal of technologies and ideas other than flight controls that need to be explored for the safe operation of UAVs. FAA position that UAV "...reliability [should be] comparable to piloted aircraft..." is misleading. Pilots can provide situational awareness, detect failures, and make good decisions on the best course of action, which UAV's cannot.
A more appropriate statement of the required UAV reliability goal would be the requirement for a flight control system that would "never fail catastrophically" and would have the ability to reconfigure the flight system to achieve the best performance possible with the remaining operating components. This would then permit a gracefully loss of system performance as individual components failed.

2. State of the Technology

Strengths:
Adaptive flight control approach noted with details on pending F-15 testing. TRL 6 is assigned for current technology (under criterion #5).

Weaknesses:
As above, needs broader perspective on system reliability. Lumping all applicable technology under the general "Adaptive Control" title does not provide much insight into the state of the technologies that could be used to achieve the reliability goals.

While flight-control technology is important, this is only a part of providing safe UAV operation. In fact, it would seem that once it is determined how UAVs should be operated in the air-traffic control system, that the technology exists to facilitate it. In this process, the trade studies of different risk management scenarios is probably more critical than research on any specific flight-control solutions.

3. Enabling Technology Development

Insufficient detail. As noted, there are a number of elements that need to come together to achieve the safe operation of UAVs. Autonomous or remotely-controlled operation are important for mission performance and coordination with other vehicles in the air space. The ability to accomplish part of this has been demonstrated by military operations for some time. The civil operation must address the coordinated control of large numbers of UAVs in real time….easy in principal but perhaps not in reality.

Reliability of ARMY ground systems is a mature technology, including advanced physics modeling for prediction. UAV reliability is also being considered, including the recent development of models and flight test data analysis. Aware of ongoing effort for approximately the last two years. New requirements for vendors will include design for reliability.

4. Technology Dependencies

Not addressed;

5. Technology Forecast

TRL of 6 is overly optimistic and unrealistic. Although flight control reliability may be currently identified at TRL 6 overall UAV system reliability is at a much lower readiness rating.

6. Technology Gaps

Not addressed; UAV ability to respond to environmental conditions is not limited to missions for severe weather observation. For small UAVs, the ability to respond to wind gusts and other environmental conditions (rain, for example) may be critical to reliable performance and acceptance.

7. Technology Cost Drivers

Not addressed; Flight testing limitations (FAA and lack of well-designed/appropriate flight testing facilities).

8. Competing Technologies	Weaknesses: Little detail presented The key element of a highly reliable flight system is a sensor suite that maintains some level of acceptable performance as individual sensors or control effectors fail. Flight System Sensor system concepts that offer this type of behavior are: A. Sensor suite designed as a set of distributed/dissimilar sensors whose outputs are processed by Data Fusion algorithms to produce best estimates of the required vehicle parameters. Use the concept of analytic redundancy in which sensors are used both as primary measurements and also to infer other vehicle parameters by applying physical relationships. Examples of this concept are accelerometers positioned off the vehicles center-of-gravity that can be used to estimate a components of vehicles angular velocity or distributed GPS receivers that can be used to estimate vehicle attitudes. B. Control effector design option that provides redundancy using split control surfaces driven by independent actuators. The U S Air Force has investigated several Reconfigurable Controller concepts in which the feedback closed loop system controller design can "reconfigure" its structure and gains to optimize its performance after a sensor or control effector failure has been identified. Failure detection concepts have also been developed.
9. UAV Application Demonstrations	Not addressed; One approach to flight demonstrations may be to use optionally-piloted UAVs.
10. Sources of Information	Not addressed; review of the cruise missile state-of-the-art would identify applicable technologies. Another potential source of failure detection and reconfiguration technology would be the long term spacecraft design literature.
11. Technology Capabilities	Not addressed;
12. Current Research	Not addressed;
13. Regulatory Issues	Not addressed;

3.13 Enhanced Structures

3.13.1 Overview

- TWG Output

Enabling Technology: Enhanced Structures

Contributing Editor: David Fratello *(provided in-lieu of other SME* input) ***Date: 3/23/06***
Phone: 757-722-5565 Fax: Email: dfratello@zeltech.com

Enabling Technology Description:
The flight performance and utility of a UAV designed to fly either, or both, at high altitude or with long endurance can sometimes be significantly constrained due to the weight and design limitations placed on these unique aircraft by the aircraft's structure. Conventional structural materials provide adverse penalties on vehicle weight and design flexibility.

The use of advanced low-weight structures, and advanced low-cost composite manufacturing methods, and active flight elements, will allow significantly reduced structural weight and the use of bold, unconventional aerodynamic designs. This, in turn, can significantly enhance the useable science payload size and weight.

New lightweight material development, flexible structural controls, "morphing" aircraft airfoil and planform shapes, and active flights controls for gust alleviation and to maximize performance efficiencies may have significant impact in this area.

Current State of the Technology: *Provide a short summary including current TRL and basis for this assessment.*
These lightweight designs are necessarily more flexible than traditional structures and can suffer from vibration causing increased noise levels, a shorter fatigue life or dynamic performance degradation. Some form of passive or active suppression is required to reduce the vibration levels.
Current work is taking place in the modeling and design of systems based on piezoceramic actuators. Particular interest is concerned with the control algorithms, optimal placement of sensors and actuators, shaped sensors and structural integrity. For passive vibration control, constrained layer damping incorporating viscoelastic material shows great promise and methods to model this material are being investigated.

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Forecast of enabling technology:
For the advanced technologies discussed, their TRLs are estimated to vary within the range of 1 and 3.

Identify and articulate any technology gaps discovered:

Enabling Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event: *no data provided*					

- USRA Analysis

1. Technology Description

Strengths:
Good, brief, highlights of important aspects of structures for HALE UAVs for civil applications. Acknowledge that UAVs are unique aircraft systems requiring unconventional aerodynamic designs including in-flight airfoil and planform shaping. In addition, new materials, structural controls, and flight controls for gust alleviation are listed as enabling technologies.
Weaknesses:
The discussion is somewhat limited, even for an overview. Current expectations for enhanced UAV structures include multi-disciplinary structural systems (i.e., multi-functional designs) that are also key enabling technologies for increasing payload and performance of small UAVs. Larger UAVs and high-altitude, long-endurance aircraft have different structural concerns. Enabling structural technologies will be different for UAVs of different size.
More detail should be provided into the specific enabling technologies such as advanced composites and active flight elements as both of these cover a very broad range. No mention is made of the aerodynamic benefits that morphing structures can provide into improving vehicle performance. No discussion is given to non-rigid structures such as inflatables.
The empty weight fraction for a high-altitude, long-endurance UAV needs to be far below that of more traditional aircraft designs when using conventional materials and structural concepts. Would also argue that both conventional structural materials AND traditional structural concepts limit the amount that the empty weight fraction can be reduced.
Rather than conventional materials providing an “adverse penalty”, they limit the empty weight fraction of a HALE UAV.

2. State of the Technology

Strengths:
Some specific ideas about actuators (only piezoceramic though) and sensors are mentioned, as is one concept for passive vibration control.

Weaknesses:
Report focuses on flexibility of light weight structures rather than assessment of state of the technology. Should address types of materials and structures currently being used in the design and testing of enhanced structures. 'Enhanced structure' does not necessarily mean lightweight; in fact, an enhanced structure may be heavier than a traditional one, but it offers some additional benefit(s) such as increased strength, morphing capability, or stowage.

No TRL levels are mentioned for the technologies identified in the enabling technologies section. It should be possible to assess the current TRLs for aspects of morphing aircraft (based upon the DARPA and NASA LaRC work), unconventional materials (based upon the body of work in new aluminum alloys, nano-composites), multifunctional structures (based upon several efforts including work from AFRL, NASA LaRC, DARPA and others), control of flexible structures (based upon previous work for HALE concepts and possibly from space structure-related work), and adaptive and advanced flight controls.

This section begins with a discussion about the need for more flexible structures. Highly flexible structure is one strong concept for reducing the empty weight fraction of UAV concepts. However, this discussion seems improperly placed in the technology assessment document.

Currently, excessive vibration is more of a concern for payload systems with strict pointing requirements than for long-term structural health. However, as overall reliability of UAV systems increases, long-term structural health monitoring systems may become of interest for UAVs. There are currently mature health-monitoring technologies available.

Inflatable structures are currently TRL level 4-5. Structures with embedded antennas are TRL 2-3.
While conventional materials are cited as limiting HALE UAVs, there is no mention of other “unconventional” materials in the technology description. Composites are mature enough to be considered conventional. The concepts of “active flight elements” and “morphing” airfoil and planform shapes need to be better characterized. The concept of active flight controls and advanced control strategies for flexible structures may allow for the wings of HALE UAVs to be far more flexible than their traditional counterparts. The structural concept development for UAVs with highly-flexible wings would need to be conducted in collaboration with the development of the control strategies.

The technology description could also address multifunctional structures. Some on going research has investigated structures that incorporate a function in addition to carrying loads suggests that electrical systems (e.g. avionics or wiring harnesses) might be included in the load-bearing structure. This could possibly save weight and volume in a UAV platform.
Other concepts, like capacitating structures that store energy or energy harvesting structures that generate electricity from deflections experienced by the structure, have potential uses in enhanced structures for UAVs.
Believe that health monitoring is another technology under evaluation in the Civil UAV program; improved structural health monitoring could allow designers to use much lower safety factors or design margins than are used in traditional structural design practice. This could also be mentioned here.

3. Enabling Technology Development

Not addressed;
There are several programs and projects that would contribute to enhanced structures for UAVs include the recently-ended Aircraft Morphing project from NASA LaRC, DARPA's Morphing Aircraft Structures and Energy Harvesting programs. There was a recent DoD MURI in the area of energy harvesting. Many DoD contractors are pursuing sensorcraft programs for the USAF; these sensorcraft concepts have many features in common with civil HALE UAVs and would provide contributions to civil UAV structures. There are numerous efforts investigating the use of nano-composites to further improve strength- and stiffness-to-weight ratios. There have also been several projects investigating multifunctional structures; one fairly well documented program was supported by AFRL Space Vehicles directorate.

Research mentioned earlier in piezo-electric/piezo-ceramic actuators (provide vibration alleviation) and morphing/shape change could be described in this section as well. DARPA's recently concluded Compact Hybrid Actuator Program (CHAP) is one relevant program that moved these small actuator systems forward on the TRL scale.

NASA Mars Airplane programs are developing many of the enabling technologies.

Inflatable/rigidable wings (UV-curing epoxy/fiber composite) were demonstrated (inflation and curing) at 90,000 ft in May 2003
and at 60,000 ft in May 2004. Inflatable wings were demonstrated (inflation and maintaining flight pressure) at 95,000 ft and
afterwards descending to ground level in April 2005.

4. Technology Dependencies

Not addressed;
Supporting technologies like low-cost composites manufacturing have been mentioned. Interdependencies between enhanced structures and health monitoring exist and are important. Interdependencies between enhanced structures and power and propulsion may also exist, if multi-functional structures are considered. Any bold or non-traditional aerodynamic concepts will demand interdependencies between advanced aerodynamics and enhanced structures. Some possible dependencies: lightweight power development (particularly batteries), flow control technology (such as MEMS), materials (such as carbon nanotubes).

To enable "bold" new concepts for structures and aerodynamics, approaches that allow the designer to more fully explore a wide design space are needed; concepts like those developed for Multi-disciplinary Design Optimization (MDO) are needed and continued support of MDO research will help the design of enhanced structures for UAVs.

5. Technology Forecast	Strengths: There is very little content in this section of the document, and what appears is copied from the capabilities and technologies appendix provided. Weaknesses: The identified enabling technology features could be listed with respect to their individual TRLs. Some of the technologies may be well above TRL 3, as several programs have matured the technologies to lab demonstrations and even flight experiments (e.g.,. the DARPA MAS program conducted several wind tunnel tests; believe that the DARPA energy harvesting program is conducting – or will shortly – flight tests on an small aircraft). Many systems under development are at a much higher TRL of 5 (component and/or breadboard validation in relevant environment) and other systems have been flight tested at TRLs of 6 (system/subsystem model or prototype demonstration in a relevant environment (ground or space) and 7 (system prototype demonstration in a space environment).
6. Technology Gaps	Not addressed; There are still several gaps in the technologies relevant to UAVs. For instance, composites using carbon nano-fibers have been proposed, but the fibers of carbon nano-tubes have proven difficult to manufacture. Multi-functional structures in which the load-bearing structure also performs electrical functions (e.g. embedded wiring harnesses) have issues with electrical compatibility between the electrical conducting elements and the structural material. Approaches for morphing the aircraft shape have not been fully explored, nor have appropriate systems-level studies been conducted to assess their impact on the aircraft. For small UAVs, understanding low-Reynolds number aerodynamics is critical. The list of Technology Target Areas omits this important research area. In general, it has not received the attention required for advancing small UAV technologies.
7. Technology Cost Drivers	Not addressed; Hard pressed to comment on this section; clearly answers to previous questions about TRL levels and technology gaps will highlight issues for technology development costs. Assume that the costs for manufacturing nano-composites will be high, given the current difficulty in fabricating nano-fibers. Weight and power requirements are primary drivers as well as development of materials and testing in relevant environments (wind tunnel and flight testing at high altitude). Operating costs of the UAV may be increased in the maintenance category by using adaptive or morphing wings, active flight controls, and structural health monitoring. Inspection of traditional composites for damage is difficult, so this could be increased if nano-composites were to be used. However, if advanced structures technology is effectively employed for UAVs, the fuel-related operating costs may be significantly reduced. This assessment of costs should be supported by systems analysis studies conducted for civil UAVs.

8. Competing Technologies

The context of competing technologies is not completely clear for enhanced structures. While working under the assumption that a fixed-wing UAV is the target, however, airship concepts may also provide the HALE capability alluded to in the technology description. For high-altitude, long-endurance airships, many of the necessary structural concepts would be different. There may be little need for shape change in an airship; certainly, an airship would not rely on wings for lift.

If composite materials (or nano-composite) materials were assumed to be the most promising for civil UAVs, then advanced aluminum alloys could present a competing technology.
Potentially disruptive technologies could arise from using biologically-inspired wing structures (in contrast to the spar-rib-skin approach traditionally used in fixed-wing aircraft).
In addition to missions requiring access to the NAS, UAV development is delayed by difficulties faced by all developers and system integrators who require flight testing due to FAA regulations (and lack of regs).

9. UAV Application Demonstrations

There have been several different demonstrations of relevant structures technology on UAVs, particularly in small demonstrations. Believe that there have been small demonstrator vehicles constructed for the DARPA morphing aircraft structures program and for the DARPA energy harvesting program. Wind tunnel models on the same scale as UAV aircraft were built and tested in the NASA LaRC Transonic Dynamics Tunnel. Many companies, universities and government labs have demonstrated use of advanced materials and enhanced structures on UAVs as well as manned aircraft (e.g., the active aeroelastic wing).

HELIOS demonstrated the operation of a highly-flexible wing structure; this illustrated very large magnitude deflections and very interesting aeroelastic response. A recent AFRL VA demonstrator vehicle flew with a flexible, joined wing concept.

10. Sources of Information

Not addressed;
Many of the aforementioned programs have associated documentation that should be listed in this section of the document. There is a host of ongoing research in the area of enhanced structures for UAVs that is continually being updated through both journal and archival publications, including review articles and textbooks.

11. Technology Capabilities

Many additional required technologies are mentioned in the previous criteria. For instance, if advanced materials like nano-composites are to be used, the manufacture of nano-fibers/nano-filaments is a required technology. If morphing airfoils or wing planforms are to be used, further work in skins that can accommodate high-strain rates and also handle pressure loads.

Design tools are also needed to accommodate non-traditional structural concepts for UAVs. For instance, most structural analysis tools are not well suited to support the design of large deformation structures. Continued improvement of multidisciplinary design and analysis tools are needed so that the aerodynamic/structural/controls design can be more tightly integrated for light-weight UAV structures.

12. Current Research

This section should review the programs mentioned in previous comments. There is great interest in UAVs in Europe. Sure that there are numerous

	additional research activities that would be relevant for enhanced UAV structures.
13. Regulatory Issues	Not addressed; This is fairly significant; much UAV research work is subject to ITAR restrictions. Some effort should be made here to address this. Primary regulatory issues may involve airframe/structure safety related to fatigue and control, although these can be addressed during the testing phases of any technology development.

Appendix A

USRA – NASA Civil UAV Technology Review Project Report

NASA Civil UAV Technology Review

Project Report

12 July 2006

Universities Space Research Association

Jeffery Cardenas
Project Manager

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

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In addition, we also wish to acknowledge the leadership and guidance of Dr. Ivan Somers, Civil UAV Capabilities Assessment Team in undertaking this independent assessment and his support of this project.

EXECUTIVE SUMMARY

The National Aeronautics and Space Administration (NASA) has embarked on a bold Civil Uninhabited Aerial Vehicle (UAV) Capabilities Assessment initiative to develop and maintain a recognized national leadership role for the Agency in all aspects of UAV technology and operational environments. Through the strategic funding of critical programs and technologies to increase performance criteria, reduce system(s) costs, and enhance UAV system capability, NASA seeks to accelerate the applications of UAVs to support Earth science research and to stimulate economic development in support of UAV systems.

The methodology used to achieve these objectives is based on an assessment process and product that will serve as a national roadmap for the development of civil UAV applications. Through a broad assessment vetted with participating agencies, and as a complement the Office of Secretary of Defense UAS (Unmanned Aircraft System) Roadmap, the NASA-led Roadmap effort will address the following:

- **Determine/document potential civil missions for all UAVs based on user-defined needs;**
- **Determine/document the technologies necessary to support those future missions;**
- **Discuss the present state of the** *platform capabilities* **and** *required, enabling technologies* **– those in-progress, planned, and non-existent.**
- **Provide foundations for development of a comprehensive** *Civil UAV Roadmap.*

The assessment process and resulting Civil UAV Roadmap will provide feedback and guidance to technology investments in the public and private sectors. It will match user needs and missions with enabling UAV technologies as they progress over the next ten years. The assessment and Roadmap will be a dynamic process and document, so that the program adapts to state changes in user needs and to advances in the states-of-the-art in the enabling technologies.

The Universities Space Research Association (USRA) Civil UAV Technology Review Project was implemented over the period from April – June 2006, supporting the NASA Civil UAV Capabilities Assessment Team by providing experts from academia proficient in the UAV enabling technologies. The participating Subject Matter Experts (SMEs) have provided not only a review and evaluation of the various technology areas identified, but have been engaged in assessing the Civil UAV programmatic concepts. The results of this project and the related findings support the current approach and results of NASA Civil UAV Capabilities Assessment initiative thus far, and are discussed in detail in the following Project Report.

This Report is a detailed narrative of the information presented at the Project Concurrence Briefing held 26 June 2006, Washington, D.C.

INTRODUCTION

BACKGROUND

As a complement to the U.S. Office of the Secretary of Defense Unmanned Aircraft Systems (UAS) Roadmap, 2005-2030, NASA is leading a significant effort to assess and evaluate the capabilities of UAVs and Uninhabited Aerial Systems (UASs) for application in the civil and commercial sectors. Through the implementation of the Civil UAV Development Organization, the following program features are highlighted;

1. Provide a single point source of information for enabling technologies in the civil sector;
2. Enlist objective support for budget and investment decisions;
3. Enable multi-Agency collaboration on project investment funding among organizations with common interests.

(It should be noted that the term "Unmanned Aircraft System/UAS" is the emerging Department of Defense (DOD) descriptive phrase, rather than "UAV". UAS refers to the entire system, including the aircraft platform, surface/ground components, and architecture elements. The terms are used interchangeably in this report.)

CIVIL UAV DEVELOPMENT ORGANIZATION

As established, the major components of the Development Organization are as follows:

- *Civil UAV Assessment Team* - to collect potential UAV user mission needs, coordinate analysis of technology for the civil missions, to develop an assessment of the states-of-the-art for enabling civil UAV technologies, and to provide technology investment priorities/strategies via the Civil UAV Roadmap.
- *Technology Working Groups* – composed of technology Subject Matter Experts (SMEs), including members from other civil agencies and academia, to assist the Assessment Team in identifying the states-of-the-art for technologies that support/enable the used-defined missions.
- *Steering Committee* – to help facilitate communications and provide guidance to the partner Agencies and the Assessment Team.

More specifically, the Civil UAV Assessment Team is charged with the following:

- Assessment of the *technologies* necessary to support required civil UAV mission *capabilities;*
- Evaluation of civil UAV mission readiness based on technology maturation forecasts;

- Identification of UAV technology gaps and potential areas where R&D investments may be warranted;
- Providing a methodological approach to identifying and tracking potential technologies that could *revolutionize* the capabilities of UAV systems and their applications;
- Establishment of Technology Working Group (TWG) composed of Subject Matter Experts from NASA, academia, and industry, to…
  - Identify, track, and assess as a function of time the maturation curves of each,
  - Identify, track, and assess revolutionary technologies, policy issues, public perception issues, privacy, and other factors impacting UAV system development.

TECHNOLOGY WORKING GROUPS

The Technology Working Groups (TWGs) are the main method by which existing and potential technologies that could revolutionize the capabilities of UAV systems and their potential uses are identified and tracked. The TWGs are the dynamic environment in which technological progress is monitored as a function of time. In support to the Assessment Team, the Civil UAV Technology Working Groups (TWGs) are responsible for…

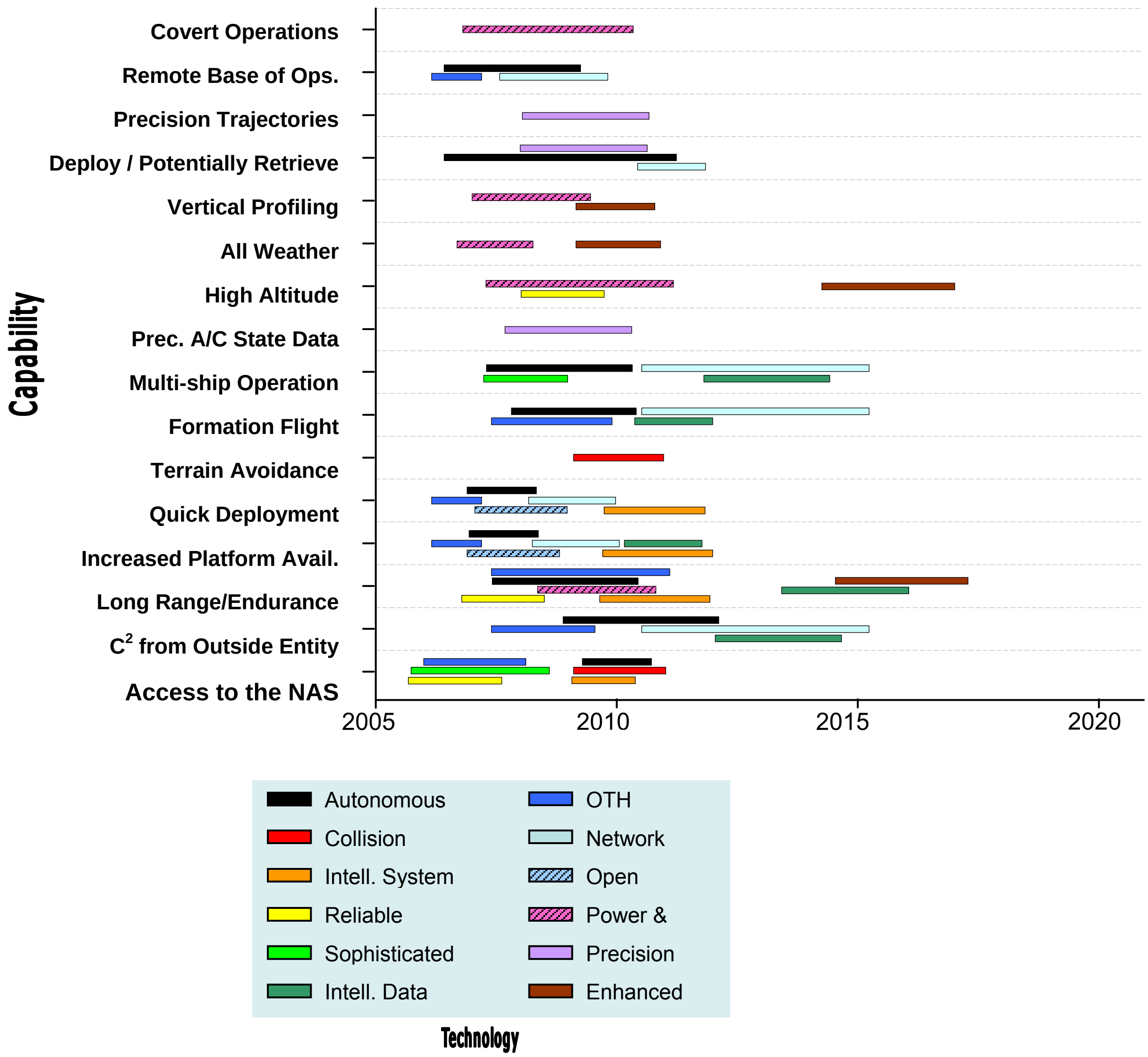
- Providing technology assessment and forecasting support to the Civil UAV Assessment Team;
- Developing, maintaining, and tracking the current state-of-the-art for identified technology areas;
- Developing/utilizing predictive models to forecast technology robustness as a function of time; including supporting technologies on the "critical path" for Civil UAV missions;
- Developing and maintaining updated technology development roadmaps that display government (federal, state, local) investments and major technology development products/deliverables;
- Developing and maintaining updated technology development roadmaps that display private sector major technology development products/deliverables;
- Documenting/maintaining academic technology research investments and trends;
- Identifying opportunities for collaboration between government, industry, and academia.

As an integral part of the Civil UAV Assessments Team, and working in partnership with the Technology Working Groups and Technical Report authors, the USRA Civil UAV Technology Review Project represents an independent peer review component to the assessment and Roadmap development process.

CAPABILITIES

The current findings of the *Earth Observation and the Role of UAVs: A Capabilities Assessment,* Version 1, March 2006 are based on an analysis of fifty-three civil missions, as identified from various government agencies and private sector organizations for both science and public benefit, under the broad categories of Earth Sciences, Land Management, and Homeland Security. (While this report did not address missions from the military sector, it is recognized that a great deal of military UAV technology will be applicable to Civil UAVs/UASs.)

The report has identified fifteen Capabilities and twelve related Enabling Technologies as needed and required to support the resulting civil UAV reference mission set. These Capabilities and their related Enabling Technologies are identified in the notional chart below:



ENABLING TECHNOLOGIES

Thirteen Civil UAV Enabling Technologies, as identified during the Capabilities Assessment process, were assigned to the nine Civil UAV Assessment Technology Working Groups (TWGs), and forty-three Enabling Technology Reports were prepared to review and document the state-of-the-technology. Note that a thirteenth Enabling Technology "Payloads Sensors" was added to identify and track mission/payload sensor instrumentation and elements. Breakout and assignment of the Enabling Technologies is as follows…

- Intelligent Data Handling, Network Communications, and Navigation Accurate Systems WG - LaRC
  - 3 Broad Enabling Technologies, 5 Sub-level Technologies, 4 Sub-sub-level Technologies
- Intelligent Mission Management, Intelligent Vehicle Systems Management, and Contingency Management WG - ARC
  - 3 Broad Enabling, 8 Sub-level, 8 Sub-sub-level
- Open Architecture WG – ARC
  - 1 Broad Enabling, 1 Sub-level, 1 Sub-sub-level
- Power & Propulsion WG – GRC
  - 1 Broad Enabling, 6 Sub-level, 11 Sub-sub-level
- Collision Avoidance WG– DFRC
  - 1 Broad Enabling, 1 Sub-level, 1 Sub-sub-level
- Over-the-Horizon Communication WG – DFRC
  - 1 Broad Enabling, 3 Sub-level Technologies, 3 Sub-sub-level
- Reliable Flight Systems WG
  - 1 Broad Enabling, 1 Sub-level, 1 Sub-sub-level
- Enhanced Structures WG
  - 1 Broad Enabling, 1 Sub-level, 1 Sub-sub-level
- Payload Sensors WG - ARC
  - 1 Broad Enabling, 6 Sub-level, 13 Sub-sub-level

The documented Enabling Technology Reports relate to the current forty-three 'Sub-sub-levels' identified above. Note that more than forty-three sub-sub-levels have been identified (see Appendix A). The Enabling technology reports were prepared according to a format established by the Civil UAV Assessment Team which served as the basis for implementing the process used by the USRA Technology Review Project.

TECHNOLOGY REVIEW PROCESS

In March 2006, USRA instituted the Civil UAV Technology Review Project with the objective of establishing an independent peer review and assessment of the forty-three NASA Civil UAV Enabling Technology Reports. Subject Matter Expert's (SMEs) from a broad spectrum of technical and systems disciplines from academia were engaged in this process. A two-step review process was utilized, consisting of an initial UAV Enabling Technology Report Review and a subsequent integrated UAV Technology Panel. Initially, it was planned that each Technology Report would be optimally reviewed by three Subject Matter Experts (SMEs); however, due to the sheer volume of reports this was not feasible due to project budgetary constraints

In implementing this project, sixty-four (64) academic SMEs were contacted – forty-two (42) were initially available and engaged, with thirty-six 36 final participants (thirty (30) SME Technology Reviewers and six (6) Panel Members).

From 1 April through 31 May 2006, the thirty SME Tech Reviewers were engaged in reviewing and evaluating an assigned number of the forty-three Enabling Technology Reports, as delivered by the NASA Civil UAV Assessment Team on 24 March 2006. The criteria used in this process was established and coordinated by USRA with NASA/DFRC. The SMEs were asked to review the assigned reports and using a Project Feedback Form provided, evaluate and comment on the following thirteen (13) criteria, providing strengths/weaknesses/comments and numerical scores for each:

- Technology Description
- State of the Technology
- Development of Enabling Technology
- Technology Dependencies
- Technology Forecast
- Technology Gaps
- Technology Cost Drivers
- Competing/Disruptive Technologies
- UAV Application Demonstrations
- Sources of Information
- Technology Capabilities
- Current Research (US/International)
- Regulatory/Security Issues

In addition to specific comments to the above areas, the SMEs also provided reference, source information with respect to the state-of-the technologies for each of the technology reports.

By 9 June 2006, ninety-four (94) reviews were completed, compiled, integrated into 41 areas for presentation to and discussion by the Civil UAV Technology Review Panel.

TECHNOLOGY REVIEW PANEL

The Technology Review Panel process provided an additional independent peer review of the Technology Report reviews and findings, as well as an independent systems review across the technical disciplines involved in UAV/UAS missions.

The Civil UAV Technology Review Panel was held 14-15 June 2006, at USRA Headquarters, Columbia, Maryland. The six Review Panel Members attending were as follows:

- Mary (Missy) Cummings, Ph.D.
  Director, Humans & Automation Laboratory
  Assistant Professor, Department of Aeronautics & Astronautics
  Massachusetts Institute of Technology

- Dara Entekhabi, Ph.D.
  Professor, Department of Civil and Environmental Engineering
  Department of Earth, Atmospheric and Planetary Sciences
  Massachusetts Institute of Technology

- James Russell, III, Ph.D.
  Co-Director, Center for Atmospheric Sciences
  Professor, Department of Physics
  Hampton University

- Rolf Rysdyk, Ph.D.
  Assistant Professor, Department of Aeronautics and Astronautics
  Control Systems Laboratory, Autonomous Flight Systems Laboratory
  University of Washington

- Thomas Schnell, Ph.D.
  Director, Operator Performance Laboratory, Center for Computer Aided Design
  Associate Professor, Department of Mechanical and Industrial Engineering
  University of Iowa

- William Sprigg, Ph.D.
  Director, Sino-U.S.Centers for Soil and Water Conservation and Environmental Protection
  Research Professor, Department of Atmospheric Sciences, Department of Soil, Water, and Environmental Sciences
  University of Arizona

Also, in attendance were Dr. Ivan Somers, Dep. Director Civil UAV Capabilities Assessment Team, Mr. Lewis Peach, USRA/Chief Engineer and Principal Agent, Mr. Jeffery Cardenas, USRA/Project Manager, Civil UAV Technology Review, and Ms. Nancy Campbell, USRA/Project Administrator.

The Review Panel was instructed to use the same thirteen evaluation criteria as used by the SME Technology Reviewers, as follows:

- Technology Description
- State of the Technology
- Development of Enabling Technology
- Technology Dependencies
- Technology Forecast
- Technology Gaps
- Technology Cost Drivers
- Competing/Disruptive Technologies
- UAV Application Demonstrations
- Sources of Information
- Technology Capabilities
- Current Research (US/International)
- Regulatory/Security Issues

The Review Panel was constructed as a *working group*, assembled to evaluate the NASA Enabling Technology Reports and the related SME reviews with the objectives of…

- Commenting on the technology reports & reviews, with respect to evaluation criteria;
- Identifying cross-cutting findings and recommendations across enabling technologies (related to Broad Area Technologies);
- Identify and track potential technologies that could *revolutionize* the capabilities of UAV systems and their applications;
- Recommending Civil UAV Enabling Technology area *programmatic* priorities;
- Establishing the engagement of the academic community as partner with NASA in the Civil UAV Capabilities Assessment.

Review Panel results were captured in the Civil UAV Capabilities Assessment Program Recommendations (subsequent section of this report) and the Civil UAV Enabling Technology Review Recommendations, Appendix C. These findings were presented to NASA Civil UAV Capabilities Assessment Team members at the Project Concurrence Briefing on 26 June 2006 in Washington, DC. Representatives from NASA HQs, ARC, DFRC, GRC, and LaRC attended and participated in the briefing. Comments, suggestions, and issues raised during the Concurrence Briefing have been incorporated into this report.

PANEL REVIEW FINDINGS & RECOMMENDATIONS

Programmatic Recommendations

As mentioned, one the requirements imposed on the Review Panel was to recommend Civil UAV Capabilities Assessment *programmatic* perspectives and priorities. Given this, the following program recommendations are presented:

1. Establish a balance of 'Requirements Driven' technologies (needed to meet the anticipated reference mission set) with the identification of an 'Technology Opportunities' set, reflecting a complete approach to technology development and maturation, enabling new capabilities and/or missions that will provide a forecast of future mission opportunities.

2. Recommend an overall systems (UAS) perspective (rather than UAV platform) to assure significant and cost effective enhancement to the overall capability of C-UAVs in order to execute the anticipated reference mission set.

3. Consider program investments in a systems context to fully assess the net impact of incorporating these enabling technologies into C-UAVs, insuring the overall viability of their application as an integrated system, to assess their net cost/benefit, and to help steer the priorities of these investments.

4. Establish UAV mission requirements baseline(s) and capabilities traceability, and forecast future requirements through broad joint involvement of the academic, industry, and inter-government user communities.

5. Create a greater, general awareness (government, industry, academia) of the state-of-the-art across capabilities and enabling technologies.

6. UAS safety should be a considered a cross-cutting 'capability', and it includes the elements of Contingency Management/Collision Avoidance, UAS Reliability (Reliable Mission Systems), and the proactive influence on policy and regulatory issues.

7. Human Interfaces and factors are critical in the supervisory control of UAS (IMM), and should be viewed as a cross-cutting element of the enabling technologies.

8. Establishment of standard interfaces (platform-to-payload) is critical to mission integration, operability, and ultimate success.

ENABLING TECHNOLOGY RECOMMENDATIONS

The Subject Matter Expert (SME) reviews and comments to the Enabling Technology Reports were integrated and compiled by the Review Panel, and are presented based on the Technology Working Group categorization.

- Intelligent Data Handling, Network Communications, and Navigation Accurate Systems
  - Application of data handling technologies should be implemented across the integrated mission system (such as the UAS), where potential centralization, cost-effectiveness, and efficiencies are to be optimized
  - Network-enabled control schemes should be applied to payload systems and ATC-like applications
  - Flight safety, reliability, and robustness requirements are critical elements involved in this Broad technology Area, and the unique UAS environment should be taken into account
  - Flight performance data analysis and trending are critical
  - Application and impact of adaptive elements in these areas should be included
  - Leverage initiatives and efforts by…
    - Department of Defense (DoD)
    - Defense Advanced Research Projects Agency (DARPA)
    - Academia

- Intelligent Mission Management, Intelligent Vehicle Systems Management, and Contingency Management
  - The Civil UAV Capabilities Assessment Initiative is presented with a unique opportunity to lead a systems engineering approach in this area, especially with respect to mission and payload command and control architectures and processes
  - IMM assessment should include the issues of Human Interfaces and Factors, especially with respect to autonomy, standardized control stations, and ground control issues/challenges
  - Technology Sub-Level approaches and methodologies would benefit from an 'autonomy hierarchy' structure
  - Application of technologies (including adaptive elements) will vary at the strategic, tactical, and element/component levels
  - Identification of mission-requirements driven platform and systems capabilities and functionalities (operational models) will be key to effective implementation of IMM and IVSM
  - Awareness of challenges and uncertainties in UAS environment (adaptability) through efforts by…
    - DoD
    - DARPA
    - Academia (Condition-Based Management)

❖ Open Architecture

- Open Architecture is a critical element in the DoD/USAF Roadmap efforts, with special significance to UAS in maintenance and avionics upgrades
- OA has great impacts in multiple-UAV configurations and mission (payload) operations
- Application of plug & play concepts of OA should be investigated and their evaluated
- Integration of Open Architecture schemes (and sub-architectures) is critical a facet of assessment and implementation
- Greater awareness of research and lessons learned from…
  - DoD
  - DARPA
  - Industry (Boeing)
  - International

❖ Payload Sensors

- The scalability/maturity of existing and near-term technology capabilities to small UAVs is critical
- Knowledge and technology transfer between the theoretical and experimental approaches should be maximized
- Establish a balance between 'technology application' and 'missions of opportunity'-driven approaches
- There is potential application of distributed sensor and transmit/receive multi-UAV (UAS) configurations
- Technology dependencies and trade-offs (including power & mass) need to balanced against mission requirements
- Leverage research and development from…
  - International
  - Academia
  - DOD
  - National Oceanic and Atmospheric Administration (NOAA)
  - National Science Foundation (NSF)

❖ Power & Propulsion

- There exists uncertain application in implementing and optimizing hydrogen propulsion systems due to extensive system trades yet to be performed…
  - The infrastructure to implement and design hydrogen-based fuel systems, combustion chambers, heat exchangers, etc., is work yet to be done
  - Cost, long term storage, auxiliary equipment, etc. will have to be worked out
  - 27 degrees (R) is a real challenge.
- Awareness and leveraging of advances in other industries (e.g., lithium polymer batteries)
- Silicate Clay composite technology appears promising
- Application of carbon-fiber systems needs further research and development, especially in carbon nanotube technology

  - Need to establish the justifying rationale for superconducting internal combustion engines
  - Investigate aeronautic power & propulsion efforts by:
    - DoD (Portable Power Initiatives)
    - DARPA
    - Department of Energy (DoE)
    - Industry
    - International (Europe)

❖ Collision Avoidance

  - The challenge for UAS operators is in compliance with existing Federal Aviation Authority (FAA) regulations until new or modified regulations that are specific to the UAS community - civil and military - are implemented
  - Need to discuss enabling technology in context of 'Sense & Avoid Systems'
  - VFR guidelines cannot serve as standard for UAV collision avoidance, and there is limited application for automation as 'situational awareness' is the challenging critical element
  - Critical phases in collision avoidance are push-back, runway, and 0' to 1500' feet (above ground level)
  - Application of ground-based Collision Avoidance concepts and systems is limited.
  - Look to the following:
    - US Air Force Research Laboratory (Sensing for UAV Awareness - SEFAR)
    - DARPA
    - DOD
    - Academia (Sense & Avoid)

❖ Over-the-Horizon Communication

  - Multiple UAV (UAS) configurations and all classes of UAVs should be included in the assessment
  - High-bandwidth systems are going to be difficult on all but large platforms due to potential power/weight/size constraints on smaller UAV platforms
  - Investigate potential for applications of Telemetry and Data Relay Tracking Satellite System (TDRSS), as it is currently utilized by other platform programs
  - Be sure and include findings from:
    - NASA/GSFC/Project OMNI ('missions as nodes')
    - DoD (Responsive Space)

❖ Reliable Flight Systems

  - The NASA Roadmap initiative has a unique opportunity to lead civil efforts to establish reliability requirements for UAV-based research missions, across government, industry, and academia
  - Reliability of individual subsystems is not the correct approach; instead reliability should be addressed across entire UAS mission spectrum (end-to-end), rather than

just a 'flight control' challenge; human factor(s) should also be included; both failure detection and system reconfiguration will be needed.

- Need to assess operational models and modes in which aircraft failures occur - push-back, 0' to 1500' levels, and populated areas are critical phases of UAS missions.
- Significant improvements in this area can be achieved with *existing* technology - through sensor integration and software development.
- Manned vehicles are not quite relevant and FAA probabilistic requirements do not apply.
- Suggest some of the following technology development activities:
  - US Army (advanced physics modeling for ground systems prediction)
  - US Air Force (Reconfigurable Controller concepts - closed loop system controller design can "reconfigure" its structure and gains to optimize its performance after a sensor or control effector failure has been identified.)

❖ Enhanced Structures

- UAV are unique aircraft systems requiring unconventional aerodynamic designs, including in-flight airfoil and planform shaping. Note that Enabling Structural technologies will be different for UAVs of different size.
- Current expectations for Enhanced Structures include multi-disciplinary structural systems (i.e., multi-functional designs) that are also key enabling technologies for increasing payload and performance of small UAVs. This includes critical technologies such as advanced composites and active flight elements.
- Interdependencies between enhanced structures, advanced aerodynamics, and systems health monitoring (IVSM) exist and must be addressed.
- Application of advances in enhanced structures should be part of a holistic approach to UAV design/development., especially with respect to mission requirements and specificities.
- To enable "bold" new concepts for structures and aerodynamics, approaches that allow the designer to more fully explore a wide design space are needed - concepts such as those developed for Multi-disciplinary Design Optimization (MDO) are needed and continued support of MDO research will help the design of enhanced structures for UAVs.

- Look to the following technology development activities:
  - Morphing Aircraft (DARPA and NASA LaRC)
  - Energy Harvesting (DARPA)
  - Unconventional materials (work in new aluminum alloys, nano-composites)
  - Multifunctional Structures (USAFRL, NASA LaRC, DARPA, and others)
  - Control of flexible structures (work from high altitude, long exposure (HALE) concepts and possibly from space structure-related work)
  - Adaptive and Advanced Flight Control systems

SUMMARY

In conclusion, the Civil UAV Technology Review Project has affirmed the approach and methodology of the NASA Civil UAV Capabilities Assessment Initiative, and has offered constructive programmatic recommendations and provided specific insights and references related to the Enabling Technologies presented.

The academic Subject Matter Experts (SMEs) have provided an *initial* assessment of the state of the technology, and have articulated the critical R&T challenges. The role of Human Interface and related Factors cannot be overstressed in its importance with respect to Unmanned Aerial Systems.

- The results/findings of the Civil UAV Technology Review have been assessed with respect to the NASA UAV Capabilities Assessment initiative.
- The Civil UAV Mission Capabilities and Enabling Technology focus areas are sufficiently well-defined and interrelated to support the technology development objectives and requirements – providing guidance to the government, industry, and academic Research and Technology sectors.
- The academic Subject Matter Experts (SMEs) have provided an *initial* assessment of the state of the technology, and have articulated the critical R&T challenges.
- The role of Human Interface and related Factors cannot be overstressed in its importance with respect to Unmanned Aerial Systems.
- A systems assessment process should be established to ensure the overall viability and return-on-investment for the various R&T in a systems context, and to help establish the overall priorities of these investments.
- Based on a preliminary 'capabilities' and systems concept, and an assessment of the technology state of maturity, a national Roadmap which integrates the Civil UAV development efforts can be designed and implemented.