The Exploration Development Technology Program leads the Agency in the development of advanced software and information technology capabilities and research for Exploration Systems. They perform mission-driven research and development to enable new system functionality, reduce risk, and enhance the capability for NASA’s explorations missions. NASA’s focus has clarified around Exploration, and the agencies expertise and capabilities are being called upon to support these missions. The Crew Exploration Vehicle (CEV) and teams of humans and robots working in space will all require advances in integrated systems health management, autonomous systems for the crew and mission operations, radiation hardened processing, and reliable, dependable software. Exploration requires the best of the nation’s technical community to step up to providing the technologies, engineering, and systems to regain the frontiers of the Moon, to extend our reach to Mars, and to explore the beyond. These advanced Avionics and Software technologies will be implemented in the CEV, Crew Launch Vehicle (CLV), and robotic missions; embedded in operations; flown on spacecraft; and used by astronauts.

**Subtopics**

_X1.01 Automation for Vehicle and Habitat Operations_

**Lead Center: ARC**

**Participating Center(s): JPL, JSC**

Automation and autonomy are key elements in realizing the vision for space exploration. Constellation systems that would benefit from automation and autonomy include crewed vehicle systems, surface robots, habitats, and infrastructure (in situ resource utilization, power systems, etc.). Needed capabilities range from decision support systems in Mission Control to autonomous robotic operations for the Moon and Mars. These capabilities will be instrumental for decreasing workload, reducing dependence on Earth-based support staff, enhancing response time, and releasing crew and operators from routine tasks to focus on those requiring human judgment. In addition, significant reductions in Mission Risk can be achieved through the use of automated checking and enforcing of flight rules and constraints.

The NASA Exploration Technology Development Program (ETDP) has been developing a set of core autonomy capabilities that can adjust the level of human interaction from fully supervised to fully autonomous. To further the application of adjustable automation and autonomy, development is needed in three broad areas:
Execution Tools

Executives are a key autonomy capability. However, support tools are needed to facilitate the authoring and validation of execution scripts. Tools that are not tied specifically to one executive would provide NASA the most flexibility in applying such tools across projects. Examples of needed capabilities include:

- Graphical tool for monitoring and debugging plan execution;
- Graphical tool for creating and editing execution scripts;
- Tools for authoring and validating execution plans;
- User friendly abstraction of low-level execution languages by adding syntactic enhancements.

Decision Support Systems

Decision support systems amplify the efficiency of operators by providing the information they need when and where they need it. As the complexity of the constellation system increases, so must the capabilities of decision support systems. Decision support tools are needed that:

- Command and supervise complex tasks while projecting the outcome of actions and identify potential problems;
- Understand system state, including visualization and summarization;
- Allow the system to interact with a user when generating the plan and allow evaluation of alternate courses of action;
- Integration of a planning and scheduling system as part of an on-board, closed loop controller;
- Scale up existing techniques to larger problem applications.

Trustable Systems

Systems that support or interact with crew require a very high level of reliability. Tools are needed that improve the reliability and trustworthiness of autonomous systems. These include:

- Ability to predict what the system will do;
- Guarantees of behavioral properties;
• Other properties that increase the operator’s trust;

• Verifiability (e.g., restricted executive languages that facilitate model-based verification).

To enable the application of intelligent automation and autonomy techniques, the technologies need to address two significant challenges: configuration management and software validation.

Reusable automation software must be adaptable to new applications without undue difficulty, and easily adjusted as the application operations change. The overhead of applying automation techniques to new applications is one of the two key obstacles to acceptance of such techniques in operations. A variation of the same issue is that of adjustment as requirements and application contexts change, which is inevitable in spacecraft operations.

The software and the adaptation to a given application must also be trusted before it can be accepted. Testing and other techniques are keys to establishing such trust and ensuring the correct function of automation systems. However, in both testing and validation, the complexity of intelligent software has proven to be a major obstacle. This has led to trust and correctness issues being another key obstacle to adoption of intelligent automation systems in both unmanned, and most importantly, in crewed vehicles.

Proposals in this area should address the definition of autonomy and automation software architectures that facilitate adaptation and ensure correctness.

X1.02 Reliable Software for Exploration Systems

Lead Center: ARC

Participating Center(s): JPL, JSC, LaRC

The objective of this subtopic is to bring to fruition software engineering technologies that enable engineers to cost-effectively develop and maintain NASA mission-critical software systems. Particular emphasis will be on software engineering technologies applicable to the high levels of reliability needed for human-rated space vehicles. A key requirement is that proposals address the usability of software engineering technologies by NASA (including NASA contractors) engineers, and not only specialists.

Many of the capabilities needed for successful human exploration of space will rely on software. In addition to traditional capabilities, such as GNC (guidance, navigation, and control) or C&DH (command and data handling), new capabilities are under development: integrated vehicle health management, autonomous vehicle-centered operations, automated mission operations, and further out - mixed human-robotic teams to accomplish mission objectives. It will be challenging, but critical to NASA's exploration objectives to ensure that these capabilities are reliable and can be developed and maintained affordably. Proposals should clearly indicate how the technology is expected to address the challenge of reliability and affordability. Mission phases that can be addressed include not only the software life-cycle (requirement engineering through verification and validation) but also upstream activities (e.g., mission planning that incorporates trade-space for software-based capabilities) and post-deployment (e.g., new approaches for computing fault tolerance; rapid reconfiguration, and certification of mission-critical software.
Software engineering tools and methods that address reliability for exploration missions are sought. Projects can address technology development and maturation that provide for the following and related capabilities:

- Automated software generation methods from engineering models that are highly reliable;
- Scalable verification technology for complex mission software, e.g., model-checking technology that addresses the 'state explosion' problem and static-analysis technology that addresses mission-critical properties at the system level;
- Automated testing that ensures coverage targeted both at the system level and software level, such as model-based testing where test-case generation and test monitoring are done automatically from system-level models;
- Technology for calibrating software-based simulators and test-beds against high-fidelity hardware-in-the-loop test-beds in order to achieve dependable test coverage;
- Technology for verifying and validating autonomy capabilities including intelligent execution systems, model-based diagnosis, and Integrated Systems Health Management (ISHM);
- Software-based radiation fault tolerance for computation;
- Methods and tools for development and validation of autonomic software systems (systems that are self protecting and self healing).

X1.03 Radiation Hardened/Tolerant and Low temperature Electronics and Processors

Lead Center: LaRC
Participating Center(s): GSFC, MSFC

Electronic technologies that are to be used in near-term exploration activities must be capable of operating on the lunar and/or Martian surfaces. Systems will need to operate across a wide temperature range and must survive frequent (and often rapid) thermal-cycling. For example, the Moon's equatorial regions experience temperature swings from -180°C to +130°C during the lunar day/night cycle, and the sustained temperature at the shadowed regions of lunar poles can be as low as -230°C. Likewise, the diurnal temperature on Mars spans from about -120°C to +20°C. While many types of devices can operate down to very low temperatures (e.g., SiGe HBT's), there are significant circuit design challenges that need to be addressed.

Thermal cycling present in lunar and Martian environments introduces reliability concerns associated with mechanical stress and fatigue of components and integrated circuits. For example, thermal cycling may result in mechanical or packaging related fractures. The selection of appropriate materials is therefore critical to developing suitable electronic products.
In addition, electronic systems and/or components must be radiation tolerant, operating reliably after receiving a total ionizing dose (TID) greater than but not equal to 50 krad (Si) and providing single-event latchup immunity (SEL) greater than but not equal to 100 MeV cm$^2$/mg.

Proposals are sought in the following specific areas:

- **Wide temperature (-180°C to +130°C) and low-temperature (-230°C), radiation-tolerant, low-power circuits including analog-to-digital converters, digital-to-analog converters, low-noise pre-amplifiers, voltage and current references, multiplexers, power switches, microcontrollers, and integrated command, control, and drive electronics for sensors, actuators, and communications transponders.**

- **Packaging capable of surviving numerous thermal cycles and tolerant of the extreme temperatures on the Moon and Mars. This includes the use of appropriate materials including substrates, die-attach, encapsulants, thermal compounds, etc.**

- **Tightly-integrated electronic sensor and actuator modules that include power, command and control, and processing. Such modules should be capable of operating at the lunar and/or Martian temperature extremes.**

- **Radiation-tolerant, SEL immune, wide temperature (-180°C to +130°C), and low-temperature (-230°C) RF electronics for short-range and long-range communication systems.**

- **Computer Aided Design (CAD) tools for predicting the electrical performance, reliability, and life cycle for low-temperature and wide-temperature electronic systems and components.**

- **Physics-based device models valid at temperature ranging from -230°C to +130°C to enable design, verification and fabrication of custom mixed-signal and analog circuits.**

- **Circuit design and layout methodologies/techniques that facilitate improved low-temperature (-230°C) analog and mixed-signal circuit performance.**

- **Radiation-tolerant processors with significantly improved throughput and processing efficiencies. Chip-level (not board-level) technologies optimized for numerically intensive algorithms and applications with the following minimum performance metrics are sought:**
  - Sustained throughput - 2 GMACS (16-bit operations);
  - Power efficiency - 1 GMACS/W (16-bit operations);
  - Total ionizing dose - 100 krad;
  - Single event upset rate - 10-10 errors / bit-day;
  - Single event latchup - greater than 75 MeV/cm$^2$/mg;
  - Operational temperature range - -55°C to +125°C.

Proposals should demonstrate a working knowledge of temperature concerns, whether they be mechanical (material transition points, thermal stress, fatigue, fracture, etc.) or electrical (carrier freezeout, base-emitter
Research should be conducted in two phases. During Phase 1, research should demonstrate the technical feasibility and show a path towards a hardware/software demonstration. During Phase 2, emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into space-worthy systems. When applicable, researchers should deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

X1.04 Integrated System Health Management

Lead Center: ARC
Participating Center(s): JPL, KSC, MSFC

Innovative health management technologies are needed throughout NASA’s Constellation architecture in order to increase the safety and mission-effectiveness of future spacecraft and launch vehicles. In human space flight, a significant concern for NASA is the safety of ground and flight crews under off-nominal or failure conditions. The new Ares Crew Launch Vehicle will provide the means to abort the crew using a launch abort system. In case of a catastrophic failure during launch or ascent, the decision to abort the crew needs to be made within a very brief timeframe and with high certainty: either false positive or false negative crew abort indications carry a large safety and cost burden. Furthermore, the Constellation architecture allows for fully-automated crew abort under certain circumstances, increasing the accuracy and sensitivity requirements on the system health management function for the Ares launch vehicle and the Orion crew capsule.

There are other health and status requirements beyond launch and ascent. Traditional means of verifying space system health and status, such as caution and warning systems that are triggered by off-nominal sensor values are rather limited in their utility. In addition to issues such as sensor failures and false alarms, redline-triggered caution and warning events are difficult to interpret, often requiring involvement of large numbers of mission support staff to isolate a failure and initiate a recovery procedure. Health and status methods that depend on support from the ground are likely to become a safety liability as communication delays or bottlenecks increase (e.g., lunar trips). Under these circumstances, autonomous and automated solutions to systems health management provide the best means of increasing crew safety and mission success probability for future space exploration missions. For deployment on human missions, health management systems must be treated as Class A human-rated systems as defined by NASA procedural requirements (NPR 7150.2) and must undergo formal verification and validation.

Future ground operations will require quick and efficient turnaround and processing of spacecraft for launch. In addition, new operations concepts must be developed to provide a high level of safety and mission assurance while reducing ground processing and mission support staff. New methods driven by health management innovation may be used to curtail system lifecycle costs through more cost-effective inspection and certification of flight systems, as well as more cost-effective management of ground and mission operations.

Proposals should be responsive to the overall goals and objectives of NASA’s Constellation and Lunar Precursors and Robotics Programs. Proposals may address specific vehicle health management capabilities required for
exploration system elements (crewed spacecraft, launch systems, habitats, rovers, etc.). In addition, projects may focus on one or more relevant subsystems such as solid rocket motors, liquid propulsion systems, structures and mechanisms, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing testbeds or facilities at one of the participating NASA centers (ARC, MSFC, KSC, or JPL) for technology validation and maturation are strongly encouraged.

Specific technical areas of interest related to integrated systems health management include the following:

- **Methods and tools to enable early-stage design of health management functionality during the development of space systems.** These methods and tools should provide a means to optimize health management system design at the functional level to decide on failure detection methods, sensor types and locations, and identify additional functionality to safeguard against failures before costly design decisions have been made.

- **Innovative methods for sensor validation and robust state estimation in the presence of inherently unreliable sensors.** Proposals should focus on data analysis and interpretation using legacy sensors rather than development of new sensors or sensor systems.

- **Model-based methods for fault detection and isolation in rocket propulsion systems based on existing sensor suites during pre-launch propellant loading and during mission operations.**

- **Concepts for advanced built-in-tests for spacecraft avionics that reduce or eliminate the need for extensive functional verification and to predict remaining life of avionics systems based on usage history.**

- **Methods for robust control of critical components, subsystems, and systems and robust execution of critical sequences during launch operations or flight.** Of special interest are robust recovery methods and innovative approaches to functional redundancy for the purpose of enhancing safety, availability, and maintainability.

- **Prognostic techniques able to anticipate system degradation and enable further improvements in mission success probability, operational effectiveness, and automated recovery of function.** Proposals in this area should focus on systems and components commonly found in spacecraft.

- **Innovative human-system integration methods that can convey a wealth of health and status information to flight crews, ground and mission support staff quickly and effectively, especially under off-nominal and emergency conditions.**

- **Verification and validation techniques for advanced fault detection and prognostic capabilities leading to certification for use in human rated critical systems in a cost-effective manner.**

- **Innovative approaches to effective utilization of health information from NASA spacecraft and launch vehicles with seamless integration to ground based systems using commercial health information from programmable logic controller systems and commercial Reliability, Availability and Serviceability (RAS) systems.**