NASA SBIR 2021 Phase I Solicitation

Human Exploration and Operations

H3.02 Microbial Monitoring for Spacecraft Cabins
Lead Center: ARC
Participating Center(s): GRC, JSC, KSC, MSFC

Scope Title:

Spacecraft Microbial Monitoring for Long Duration Human Missions

Scope Description:

With the advent of molecular methods, emphasis is now being placed on nucleic acids to rapidly detect microorganisms. However, the sensitivity of current gene-based microbial detection systems is low (~100 gene copies per reaction), requires elaborate sample process steps, involves destructive analyses, and requires fluids to be transferred and detection systems are relatively large size. Recent advancements in the metabolomics field have potential to substitute (or augment) current gene-based microbial detection technologies that are multisteped, destructive, and labor intensive (e.g., significant crew time). NASA is soliciting nongene-based microbial detection technologies and systems that target microbial metabolites and that quantify the microbial burden of surfaces, air, and water inside for long-duration deep-space habitats.

Potable water:

A simple integrated, microbial sensor system that enables sample collection, processing, and detection of microbes or microbial activity of the crew potable water supply is sought. A system that is fully-automated and can be in-line in an Environmental Control and Life Support System- (ECLSS-) like water system is preferred.

Habitat surfaces:

Future crewed habitats in cislunar space will be crew-tended and thus unoccupied for many months at a time. When crew recovers the habitat they will want to quickly, efficiently, and accurately assess the microbial status of the habitat surfaces. A microbial assessment/monitoring system or hand-held device that requires little to no consumables is sought.

Airborne contamination:

Future human spacecraft, such as Gateway and Mars vehicles, may be required to be dormant while crew is absent from the vehicle, for periods that could last from 1 to 3 years. Before crews can return, these environments
must be verified prior to crew return. These novel methods have the potential to enable remote autonomous microbial monitoring that does not require manual sample collection, preparation, or processing.

**Expected TRL or TRL Range at completion of the Project:** 2 to 4

**Primary Technology Taxonomy:**
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.4 Environmental Monitoring, Safety, and Emergency Response

**Desired Deliverables of Phase I and Phase II:**
- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**
Phase I deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data, and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

**State of the Art and Critical Gaps:**
The state of the art on the International Space Station (ISS) for microbial monitoring is culturing and counting, as well as grab samples that are returned to Earth. NASA has invested in DNA-based polymerase chain reaction (PCR) systems, partially robotic in some cases, to eliminate the need for on-orbit culturing. However, a fully automated system is still not ready and there is still a gap for a low- or no-crew time detection system.

**Relevance / Science Traceability:**
The technologies requested could be proven on the ISS and would be useful to long-duration human exploration missions away from Earth, where sample return was not possible. The technologies are applicable to Gateway, Lunar surface, and Mars, including surface and transit. This subtopic is directed at needs identified by the Life Support Systems (LSS) Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of ECLSS. The LSS Project is under the Advanced Exploration Systems (AES) Program, Human Exploration and Operations Mission Directorate (HEOMD).

**References:**
1. A list of targeted contaminants for environmental monitoring can be found at "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants" located at: [https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs](https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs) [1]
2. Advanced Exploration Systems Program, Life Support Systems Project: [https://www.nasa.gov/content/life-support-systems](https://www.nasa.gov/content/life-support-systems) [2]
4. National Aeronautics and Space Administration, 2020 NASA Technology
H3.05 Additive Manufacturing for Adsorbent Bed Fabrication

Lead Center: ARC

Participating Center(s): JSC, MSFC

Scope Title:

Additive Manufacturing for Adsorbent Bed Fabrication

Scope Description:

Current state-of-the-art (SOA) Air Revitalization System (ARS) contaminant-removal systems utilize packed beds. Packed beds have high pressure drop, large void volumes, poor heat management, and poor mechanical stability. Some alternate sorbent technologies (e.g., structural sorbent and monolith) have been proposed previously, but they are at a low TRL and require additional research and development to prove the concepts and resolve scale-up issues. Using robocasting techniques, a type of 3D paste printing, sorbent pastes are used to print sorbent beds with custom flow paths and rod size. With this approach, sorbent beds can be designed and fabricated with controlled pressure drop, tailored flow path, minimized void spaces, good heat management, high mechanical and chemical stability, and optimized structures with high mass transfer. In addition, having the ability to formulate one’s own sorbent paste materials allows variability in binders and co-binder selections for optimal contaminant removal and thermal performance. Previous studies have been completed for a variety of sorbent pastes (activated carbon [Ref. 1], zeolite 13X [Ref. 2], 5A, 4A, polymer, amine functionalized zeolite [Ref. 3], etc.). However, these works did not focus on optimizing the printed structure for cyclic operation and addressing scale-up issues.

NASA aims to use the 3D-printed sorbent beds as drop-in replacements for packed sorbent beds such as those found in the Carbon Dioxide Removal Assembly (CDRA) on the International Space Station (ISS). Using robocasting techniques to print scale-up sorbent beds is also at a low TRL and requires additional development. However, it is the preferred technique over other options (e.g., structured sorbents) because, if successful, the resulting technology will yield equivalent system mass reduction due to better thermal and fluid management and mass transfer properties. Technology solutions could include, but not be limited to, SOA solid sorbent materials such as zeolite 13X, zeolite 5A, silica gel, metal-organic-frameworks (MOFs), and activated carbon. All proposed technologies should address issues related to scale-up, paste formulation, printability, mechanical and hydrothermal stability, system design, and heaters integration. The components used in the paste formulation must abide by spacecraft chemical safety standards. This subtopic is open for novel ideas that address any of the numerous technical challenges listed below for the design and fabrication of printed sorbent beds for humidity and/or CO₂ removal. This subtopic does not seek new sorbent chemistries, instead, zeolite paste formulation and paste printing are desired.

- Innovative concepts on how to make silica gel paste for use in removing water from air, either in a cabin humidity control system or as part of a CO₂ removal process requiring desiccation.
- Choosing the correct paste formulation for optimal and mechanical stability.
- Designing the lattice structures to minimize pressure drop, provide large surface area for mass transfer, and prevent channeling.
- Designing a heater system for thermal regeneration of the sorbent that would minimize contact resistance between heater and sorbent and minimize mass while providing a uniform temperature throughout the bed. Heaters could be commercial-off-the-shelf (COTS) types (e.g. cartridge or Kapton® heaters) or they could...
NASA is especially interested in technologies that can be incorporated into closed-loop life-support systems. Three life-support functions of particular interest are CO$_2$ removal, cabin humidity control, and trace contaminant control, as solid sorbents are particularly suited to these applications. Technologies targeting other NASA life-support functions are also of interest.

Proposals targeting CO$_2$ removal applications should consider the following:

- Improvements in sorbent CO$_2$ capacity and selectivity leading to smaller, more efficient components, lower energy consumption, and operation at lower CO$_2$ partial pressures are highly desirable.
- Increases in the robustness of sorbent materials to mechanical stresses and temperature and humidity changes/cycling.
- Full-scale systems must achieve the following performance targets:
  - CO$_2$ removal rate of 4.16 kg/day (a 4-crew load).
  - System must maintain an environment with 3.0 mmHg ppCO$_2$ for cabin applications (based on the daily average ppCO$_2$).
  - System size $\leq 0.3 \text{ m}^3$ for a 4-crew system.
  - Average system power $\leq 500$ W of power for a 4-crew system.
  - System mass of $\leq 450$ kg for the 4-person load.
  - System must effectively separate out water vapor from cabin air (less than 100 ppm water vapor in the CO$_2$ product is desired).

System must effectively separate out oxygen and nitrogen from cabin air (less than 1% O$_2$ and 2% N$_2$ by volume in the CO$_2$ product is desired).

**Expected TRL or TRL Range at completion of the Project:** 1 to 3

**Primary Technology Taxonomy:**
- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

**Desired Deliverables of Phase I and Phase II:**

- Analysis
- Prototype
- Hardware
- Research

**Desired Deliverables Description:**

Phase I deliverables: Detailed sorbent paste formulation and analysis, proof-of-concept test data, and predicted performance (mass, volume, and thermal performance) for contaminant removal (e.g., carbon dioxide, water, or trace contaminants). Deliverables should clearly describe and predict performance over the SOA with an estimated scaled-up design for a 4-person crew.

Phase II deliverables: Delivery of technologically mature components/subsystems that demonstrate functional performance with appropriate interfaces. Prototypes should be at least at a 4-crew-member scale.

**State of the Art and Critical Gaps:**

Current and future human exploration missions require an optimized ARS that can reduce the system mass, volume, and power, and increase reliability. The SOA systems (CDRA, the Carbon Dioxide Reduction Assembly (CRA), and the Trace Contaminant Control System (TCCS) are adsorbent-based or catalyst-based and their
performances are limited because they use COTS sorbent materials. COTS sorbent pellets/beads have fixed performance parameters (e.g., mass transfer capability), which limit the ability to tailor the sorbents to meet specific needs. Spacecraft system design requirements differ from those used in industry. For example, one industrial application focuses on removing carbon dioxide at a relatively high concentration (12% from flue gas), whereas CDRA focuses on removing carbon dioxide at low partial pressure (3 mmHg). Therefore, having the ability to tailor a sorbent to NASA objectives would lead to more efficient adsorbent systems not just for the ARS but also other life support systems that utilize sorbents (e.g., the multifiltration beds). In addition, often times COTS sorbents are sold in bulk (impractical for NASA-scale systems) and become obsolete when manufacturers cease production. Instead of having to reevaluate and redesign systems for new COTS materials to address obsolescence, NASA can use a well-characterized 3D-printed sorbent formulation to remake or even to improve SOA systems. Here, having control over the formulation of these materials could mean continuity in the use of the materials as well as an ability to optimize and tailor the materials for space craft use. In addition, as new materials are available for use, (e.g., MOFs), these materials can be adapted using the same 3D-printed design. That is, once the lattice and heater designs are completed, the backbone may be used for other sorbent materials. Moreover, the 3D printing can be done commercially once an acceptable paste formulation has been established. Sorbent paste printing techniques need additional technology investment to reach a level of maturity necessary for consideration for use in a flight Environmental Control and Life Support System (ECLSS). This approach offers high returns and is a paradigm shift from the SOA, as it offers the ability to control flow paths, thermal management, and mass transfer properties.

Relevance / Science Traceability:

This technology could be a drop-in replacement for the current CO₂ adsorption beds and can be proven on the ISS with potential for application in long-duration human exploration missions, including Gateway, Lunar surface, and Mars, including surface and transit. It is imperative that CO₂ be removed to support human life during space missions. This subtopic is supported by the Advanced Exploration Systems (AES) Program in an effort to improve the SOA ARS in the ECLSS.

References:


H3.07 Flame-Retardant Textiles for Intravehicular Activities (IVA)

Lead Center: ARC
Participating Center(s): GRC

Scope Title:

Flame-Retardant Textiles for Crew Clothing and for Use in Spacecraft Cabins

Scope Description:

There is a textile technology gap for apparel fabrics for lunar and planetary human exploration. While there are industrial fabrics that are flame retardant in oxygen-enriched atmospheres up to 100% at ambient pressure, there is
no apparel or furnishing fabric that is flame retardant in enriched atmosphere of 36% oxygen at a pressure of 8.2 psi (56.5 kPa). The challenge for developing next-to-the-skin flame-retardant fabrics comes from the many other requirements these fabrics must satisfy. They must be comfortable. This means they must have high drape, be soft to the touch, and have no inherent unpleasant smell. In addition, they cannot be toxic through the skin or outgas toxic chemicals. These fabrics must be washable and durable over a period of up to three years of repeated use. In other words, these fabrics must have physical and mechanical properties (no static cling, color fastness, tensile strength and elongation dry and wet, tear resistance, bending stiffness, torsional stiffness, abrasion resistance, etc.) that make them suitable for use in T-shirts and pants to be worn in an atmosphere containing 36% oxygen. NASA needs such new fabrics to send astronauts to the Moon in order to later establish a sustainable human presence beyond low Earth orbit (LEO) or on the Moon, and in preparation for a future trip to Mars.

The gap in textile technology that affects IVA results from the need to protect astronauts inside space vehicles and space habitats with atmosphere of 34 ± 2% oxygen at a pressure of 8.2 psi (56.5 kPa). During the period the astronauts reside in the Lunar Lander, they will need fire protection provided by their clothing as they will not continuously wear their space suits during the entire period the lander is on the Moon.

**Expected TRL or TRL Range at completion of the Project:** 1 to 3

**Primary Technology Taxonomy:**
- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype

**Desired Deliverables Description:**

In Phase I, the deliverable should be a report demonstrating the feasibility to produce new flame-retardant, nontoxic apparel fibers and/or finishing treatments on existing fibers that do not support combustion in an atmosphere of 36% oxygen at a pressure of 8.2 psi. The chemical process for developing a synthetic fiber or a finishing treatment, including any test results, should be fully described to understand any toxicity issue related to processing. Furthermore, the researchers should describe the rheological, physical, and mechanical properties of the new fiber or finishing treatment and explain how these properties will make these fibers suitable for apparel applications.

In Phase II, the deliverable should be a fiber that can withstand the production processes used in the textile industry. The researchers should therefore process the new fiber and experiment with different processing conditions to determine which conditions will lead to consistent results that will enable scaling-up production. In other words, the researchers must demonstrate that they can make fine yarns that will not break or produce excessive lint when woven into fabrics. It is highly desirable that samples of fabrics be developed and evaluated.

**State of the Art and Critical Gaps:**

The state of the art in flame-retardant apparel fibers and fabrics for use next to the skin is mostly represented by meta-aramids, modacrylic, and flame-retardant (FR) fibers (FR rayon, FR wool, etc.). These fibers will not support combustion in air, but they burn in an atmosphere of 36% oxygen.

The critical gap is the absence of an inherently strong, flame-retardant (in 36% oxygen), nontoxic, and comfortable fiber to use for next-to-the-skin clothing.

**Relevance / Science Traceability:**

This work will benefit several space programs, namely the lunar Human Landing System (HLS), Orion, Gateway, and Artemis, enabling the astronauts to function in habitats, pressurized rovers, and other space vehicles with
enriched oxygen atmospheres and to shorten prebreathe times prior to extravehicular activities (EVAs).

References:


H4.05 Advancements in Water and Air Bladder Assemblies and Technology

Lead Center: ARC

Scope Title:

Advancements in Feedwater Supply Assembly Technology

Scope Description:

The current technology for the Feedwater Supply Assembly (FSA) has many challenges to overcome including material durability and water capacity. Therefore, new innovative ideas and solutions are sought. The FSA will be integrated into the Exploration Extravehicular Mobility Unit (xEMU) Portable Life Support System (PLSS) and contained in the suit hatch compartment. The hatch volume is not a uniform shape and the current design uses cylindrical bladders which are not capable of optimizing water volume quantities. Additionally, many challenges exist in the material currently used for the FSA bladders. This material is known for its ability to maintain cleanliness and sterility; however, when made into these particular bladders, material failure and leakages are common at low cycle counts when tested as a pressurized system. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, durability and extensibility will become some of the most important requirements as well.

The FSA shall be a sterile compliant bladder, capable of storing ultrapure feedwater with a relatively high-cycle life when pressurized. In order for the thermal control loop to operate properly, a water source is needed. A volumetrically adaptable, sterile, and durable feedwater bladder is essential. The suit pressure acts on this bladder and as water evaporates, the bladder resupplies the loop. The bladder must be clean and not leak particulates or polymer chains into the water over long periods of quiescence. The maximum design pressure (MDP) for the system will be 35 psid with a nominal operating pressure of 15 psid. These bladders will be reused in a fill-drain-refill = 1 cycle environment. The current cycle life requirement is 696 cycles per bladder. Additional requirements are captured in the reference located at the following link: https://ntrs.nasa.gov/search.jsp?R=20190033446 [8]. Having a bladder with these qualities not only buys down the safety risk of rupture, it promotes reliability at higher pressures and provides an avenue to extend Extravehicular Activity (EVA) length.

This subtopic is relevant to the xEMU, International Space Station (ISS), as well as commercial space companies. The goal is to have proposed solutions to be designed, built, integrated, and tested at the Johnson Space Center and integrated into the xEMU. These solutions have the potential for a direct infusion path as the PLSS is matured to meet the design and performance goals.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
Desired Deliverables Description:

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the Exploration Portable Life Support System (xPLSS). Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xPLSS or in a representative loop of the PLSS is desired.

State of the Art and Critical Gaps:

As the design for the new xEMU is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. The FSA is at a stall in technology development and requires new innovative ideas. This solicitation is an attempt to seek new technologies for the FSA. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, durability and extensibility will become some of the most important requirements.

Relevance / Science Traceability:

This technology may be relevant to the xEMU, ISS, as well as commercial space companies. As a new Space Suit xPLSS is being designed, built, integrated, and tested at the Johnson Space Center and integrated into the xEMU, solutions will have a direct infusion path as the xPLSS is matured to meet the design and performance goals.

References:

Feedwater Supply Assembly Requirements are located at the following links:

1. Feedwater Supply Assembly (FSA 431) requirements are located at the following link: [https://ntrs.nasa.gov/search.jsp?R=20190033446](https://ntrs.nasa.gov/search.jsp?R=20190033446) [8]
2. Auxiliary Feedwater Supply Assembly (FSA 531) requirements are located at the following link: [https://ntrs.nasa.gov/search.jsp?R=20190033446](https://ntrs.nasa.gov/search.jsp?R=20190033446) [8]

Note to offeror: The following two drawings referenced in the requirements shall be provided if offeror is selected for award.

1. Feedwater Supply Assembly (FSA 431) Drawing SLN 13102397
2. Auxiliary Feedwater Supply Assembly (FSA 531) Drawing SLN 13102398

Scope Title:

Advanced Pressure Garment Bladder Materials

Scope Description:

The current pressure garment bladder in the legacy space suit is a urethane-coated Oxford-weave nylon. This bladder material serves as the gas bladder of the space suit and, along with the restraint material, comprises the pressure garment bladder/restraint assembly which is sized and patterned to accommodate both anatomical movement and a range of sizing. The bladder is patterned using heat sealing or radio-frequency (RF) welding techniques. While this material has been acceptable for many years, there are known deficits. The urethane coating has high tack and can result in excessive friction against the skin. Embossing or flocking of the bladder, while not significantly increasing weight, may be viable solutions to this issue, although there may be others.
In addition, the current bladder needs to be manually wiped with biocide after each Extravehicular Activity (EVA) to prevent microbial growth. This contributes to crew overhead time and may be challenging with advanced suit architectures on the Moon which inhibit routine access to all bladder locations. An antimicrobial treatment or coating on the air-tight side of the pressure bladder will improve long-term performance of the Pressure Garment System (PGS) and reduce crew time and consumables.

Lastly, while the bladder material is sufficiently strong to contain the pressurization loads of the suit in the event that the restraint layer experiences catastrophic failure, it is not impervious to damage itself through puncture from a sharp edge/corner or from an incoming micrometeorite, impacting mission success and/or crew safety. As such, a self-healing bladder could mitigate this risk and provide a more robust bladder/restraint system in the next-generation suit assembly.

In addition to one or more of the aforementioned design goals, a successful solution should also meet all of the following requirements:

1. The bladder material is capable of being bonded together into gore or convolute patterns without the use of an adhesive;
2. The bladder material bonded seams shall have a bond strength of at least 85 lb/in;
3. The bladder material shall not leak more than \(3.9 \times 10^{-8}\) lbm/hr-in\(^2\) of oxygen at 4.3 psid.

This subtopic is relevant to the Exploration Extravehicular Mobility Unit (xEMU), International Space Station (ISS), as well as commercial space companies. The goal is to have proposed solutions to be designed, built, integrated, and tested at the Johnson Space Center (JSC) and integrated into the xEMU. These solutions have the potential for a direct infusion path as the xEMU is matured to meet the design and performance goals.

**Expected TRL or TRL Range at completion of the Project:** 3 to 5

**Primary Technology Taxonomy:**
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

**Desired Deliverables of Phase I and Phase II:**

- **Prototype**

**Desired Deliverables Description:**

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the xEMU. Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xEMU or specific to Pressure Garment Bladder is desired.

**State of the Art and Critical Gaps:**

As the design for the new xEMU is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. This solicitation is an attempt to seek new technologies for the Pressure Garment Bladder. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, durability and extensibility will become some of the most important requirements.

**Relevance / Science Traceability:**

This may be relevant to the xEMU, ISS, as well as commercial space companies. As a new xEMU PGS is being designed, built, and tested at JSC, solutions will have a direct infusion path as the xEMU is matured to meet the
design and performance goals.

References:

Note to offeror:

Sample drawings of patterned gore and/or convolute bladder assemblies shall be provided if offeror is selected for award.

H5.01 Lunar Surface Solar Array Structures

Lead Center: LaRC

Participating Center(s): GRC

Scope Title:

Lunar Surface Solar Array Structures

Scope Description:

NASA intends to land near the lunar South Pole (between 85 and 90 S latitude) by 2024 in Phase I of the Artemis Program and then establish a sustainable long-term presence by 2028 in Phase II. At exactly the lunar South Pole (90 S), the Sun elevation angle varies between -1.5° and 1.5° during the year. At 85 S latitude, the elevation angle variation increases to between -6.5° and 6.5°. These persistently shallow Sun grazing angles result in the interior of many polar craters never receiving sunlight (and accumulating volatiles including water ice) while some nearby elevated ridges and plateaus receive sunlight up to 100% of the time in the summer and up to about 70% of the time in the winter. For this reason, these elevated sites are promising locations for human exploration and settlement because they avoid the excessively cold 354-hr nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

This subtopic seeks structural and mechanical innovations for 10 kW relocatable solar arrays near the South Pole for powering in situ resource utilization (ISRU) equipment, lunar bases, dedicated power landers and rovers, and that can deploy and retract at least 5 times. Retraction will allow valuable solar array hardware to be relocated, repurposed, or refurbished and possibly also to minimize nearby rocket plume loads and dust accumulation. Also, innovations to raise the bottom of the solar array by up to 10 m above the surface to reduce shadowing from local terrain are required [Ref. 3]. The ability to be relocated is assumed to be through use of a separate surface-mobility system (i.e., not part of the solar array system), but design of array structures and mechanisms should accommodate loads likely to be encountered during transport along the lunar surface. Suitable variations of existing array concepts [e.g., Ref. 4-5] are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: 35 m² (10 kW at beginning of life) per unit.
- Single-axis sun tracking about the vertical axis.
- Up to 10-m height extension boom to reduce shadowing from local terrain.
- Deployable, stable base for supporting tall vertical array on unprepared lunar surface.
- Base must accommodate a local 15° terrain slope.
- Adjustable leveling to within 1° of vertical.
Retractable for relocating, repurposing, or refurbishing.
Number of deploy/retract cycles in service: >5; stretch goal >10.
Lunar dust, radiation, and temperature resistant components.
Specific mass: >75 W/kg including all mechanical and electrical components.
Specific packing volume: >20 kW/m³ including all mechanical and electrical components.
Factor of safety of 1.5 on all components.
Lifetime: 10 years.

Suggested areas of innovation include:

- Novel array and support base packaging, deployment, retraction, and modularity concepts.
- Lightweight, compact components including booms, trusses, ribs, substrates, and mechanisms.
- Novel actuators for telescoping solar arrays such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Mechanisms with exceptionally high resistance to lunar dust.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Optimized use of advanced lightweight materials (but not materials development).
- Integration of existing structural health monitoring technologies.
- Validated modeling, analysis, and simulation techniques.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Completely new concepts; e.g., thinned rigid panel or 3D-printed solar arrays, nonrotating telescoping “chimney” arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters.

Proposals should emphasize structural and mechanical innovations, not photovoltaics, electrical, or energy storage innovations, although a complete solar array systems analysis is encouraged. If solar concentrators are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over unconcentrated planar solar arrays. Solar array concepts should be compatible with state-of-the-art solar cell technologies with documented environmental degradation properties. Design, build, and test of scaled flight hardware or functioning lab models to validate proposed innovations is of high interest.

**Expected TRL or TRL Range at completion of the Project:** 4 to 5
**Primary Technology Taxonomy:**
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures
**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**
In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests. In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their Technology Readiness Level (TRL). TRLs at the end of Phase II of 4 or higher are desired.

**State of the Art and Critical Gaps:**
Deployable solar arrays power almost all spacecraft, but they primarily consist of hinged, rigid panels. This traditional design is too heavy and packages too inefficiently for lunar surface power. Furthermore, there is usually
no reason to retract the arrays in space, so self-retractable solar array concepts are unavailable except for rare exceptions such as the special-purpose International Space Station (ISS) solar array wings. In recent years, several lightweight solar array concepts have been developed but none of them have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 10-kW solar array for surface electrical power near the lunar South Pole for diverse needs including ISRU, lunar bases, dedicated power landers, and rovers.

Relevance / Science Traceability:

Robust, lightweight, redeploable solar arrays for lunar surface applications are a topic of great current interest to NASA on its path back to the Moon. New this year, the subtopic extends the focus area from landers to other powered elements of the lunar surface architecture along with refined design guidelines. There are likely several infusion paths into ongoing and future lunar surface programs, both within NASA and also with commercial entities currently exploring options for a variety of lunar surface missions. Given the focus on the lunar South Pole, NASA will need vertically deployed and retractable solar arrays that generate 10 to 40 kW of power. The 10-kW-class solar array structures are also applicable for Science Mission Directorate (SMD) ConOps (concept of operations) on the Moon to recharge batteries on a Mars Science Laboratory- (MSL-) class rover.

References:


H5.02 Hot Structure Technology for Aerospace Vehicles

Lead Center: MSFC

Participating Center(s): AFRC, JSC, LaRC

Scope Title:

Hot Structures Technology for Aerospace Vehicles

Scope Description:

This subtopic deals with the development of reusable nonmetallic hot structure technology for structural components exposed to extreme heating environments on aerospace vehicles. Desired hot structure systems encompass multifunctional structures that can reduce or eliminate the need for active cooling or separate thermal protection system (TPS) materials. The potential advantages of using hot structure systems in place of actively cooled structures or a TPS with underlying cool structure include reduced mass, increased mission performance (such as reusability), improved aerodynamics for aeroshell components, improved structural efficiency, and increased ability for nondestructive inspections. Hot structure is an enabling technology for reusability between missions or mission phases, such as advanced propulsion systems requiring multiple engine firings and vehicles requiring aerocapture/aerobraking followed by entry, descent, and landing. The development of hot structure technology for (a) combustion-device liquid rocket engine propulsion systems and (b) aerodynamic structures for aeroshells, control surfaces, wing leading edges, and heatshields is of great interest. Examples of prior flight-
proven hot structures include: (a) the nozzle extension for the Centaur RL10B-2 upper-stage rocket engine, and (b) wing leading edges and control surfaces for the Space Shuttle Orbiter, Hyper-X (X-43A), and/or X-37B.

This subtopic seeks to develop innovative, low-cost, damage-tolerant, reusable, and lightweight fiber-reinforced hot structure technology applicable to aerospace vehicles and components exposed to extreme temperatures. At a minimum, materials developed under this subtopic should be capable of operating at a temperature of at least 1,371 °C (2,500 °F)—higher temperatures are of even greater interest, such as up to 2,204+ °C (4,000+ °F). These aerospace vehicle applications are unique in requiring the hot structure to carry primary structure vehicle loads and to be reusable after exposure to extreme temperatures during liquid rocket engine firings and/or atmospheric entry. The material systems of interest for use in developing hot structure technology include advanced carbon-carbon (C-C) and ceramic matrix composite (CMC) materials. Potential applications of interest for hot structure technology include: (a) propulsion system components (hot-gas valves, combustion chambers, and nozzle extensions), and (b) primary load-carrying aeroshell structures, control surfaces, leading edges, and heatshields.

Proposals should present approaches to address the current need for improvements in operating temperature capability, toughness/durability, reusability, and material system properties, as well as the need to reduce cost and manufacturing time requirements. Focus areas should address one or more of the following:

- Improvements in manufacturing processes and/or material designs to achieve repeatable uniform material properties, while minimizing data scatter, that are representative of actual vehicle components: specifically, material property data obtained from flat-panel test coupons should correlate directly to the properties of prototype and flight test articles.

- Material/structural architectures and multifunctional systems providing significant toughness and/or durability improvements over typical 2D interlaminar mechanical properties while maintaining in-plane and thermal properties when compared to state-of-the-art C-C or CMC materials. Examples include incorporating through-the-thickness stitching, braiding, or 3D woven preforms. Advancements in oxidation protection that enhance durability are also of interest: matrix inhibition, oxidation resistant matrices, exterior environmental coatings, etc.

- Manufacturing process methods that enable a significant reduction in the cost and time required to fabricate materials and components. There is a great need to reduce cost and processing time for hot structure materials and components – current state-of-the-art materials are typically expensive and have fabrication times often in the range of 6 to 12 months, which can limit or exclude the use of such materials. Approaches enabling reduced costs and manufacturing times should not lead, however, to significant reductions in material properties. Advanced manufacturing methods may include but are not limited to the following: (a) rapid densification cycles, (b) high char-yield resins, (c) additive manufacturing (AM), and (d) automated weaving, braiding, layup, etc.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials
Desired Deliverables of Phase I and Phase II:
Desired Deliverables Description:

Research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstrations. Phase I feasibility studies should also address cost and the risks associated with the hot structures technology.

In addition to the final report, delivery of a representative sample(s) of the material and/or technology addressed by the Phase I project should be provided at the conclusion of the Phase I contract—for example: (a) coupons appropriate for thermal and/or mechanical material property tests, or (b) arc-jet test specimens. Plans for potential Phase II contracts should include the delivery of manufacturing demonstration units to NASA or a Commercial Space industry partner during Phase II. Testing of such test articles should be a part of the anticipated Phase II effort. Depending upon the emphasis of the Phase II work, such test articles may include subscale nozzle-extension test articles or arc-jet test specimens/hot structure components.

State of the Art and Critical Gaps:

The current state of the art for composite hot structure components is limited primarily to applications with maximum use temperatures in the 1,093 to 1,593 °C (2,000 to 2,900 °F) range. While short excursions to higher temperatures are possible, considerable degradation may occur. Reusability is limited and may require considerable inspection before reuse. Critical gaps or technology needs include: (a) increasing operating temperatures to 1,649 to 2,204+ °C (3,000 to 4,000+ °F); (b) increasing resistance to environmental attack (primarily oxidation); (c) increasing manufacturing technology capabilities to improve reliability, repeatability, and quality control; (d) increasing durability/toughness and interlaminar mechanical properties (or introducing 3D architectures); (e) decreasing cost, and (f) decreasing overall manufacturing time required.

Relevance / Science Traceability:

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring reusability, increased damage tolerance, and the durability to withstand long-duration space exploration missions. The ability to allow for delivery and/or return of larger payloads to various space destinations, such as the lunar South Pole, is also of great interest.

The Advanced Exploration Systems (AES) Program would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial Space programs, such as Commercial Orbital Transportation Services (COTS), Commercial Lunar Payload Services (CLPS), and Next Space Technologies for Exploration Partnerships (NextSTEP), are also interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology include the Space Launch System (SLS) and the Human Landing System (HLS) for propulsion applications.

Potential NASA users of this technology exist for a variety of propulsion systems, including the following:

- Upper-stage engine systems, such as those for the Artemis SLS.
- In-space propulsion systems, including nuclear thermal propulsion systems.
Lunar/Mars lander descent/ascent propulsion systems.

Propulsion systems for the Commercial Space industry, which is partnering with and supporting NASA efforts.

Finally, the U.S. Air Force is interested in such technology for its National Security Space Launch (NSSL), ballistic missile, and hypersonic vehicle programs. Other non-NASA users include the U.S. Navy, the U.S. Army, the Missile Defense Agency (MDA) and the Defense Advanced Research Projects Agency (DARPA). The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high temperature composites technology.

References:

Liquid Rocket Propulsion Systems:


Hypersonic Hot Structures:


Note: The above references are open literature references. Other references exist regarding this technology, but they are International Traffic in Arms Regulations (ITAR) restricted. Numerous online references exist for the subject technology and projects/applications noted, both foreign and domestic.

H6.04 Model-Based Systems Engineering for Distributed Development
Lead Center: ARC

Scope Title:

Model-Based Systems Engineering for Distributed Development

Scope Description:

Systems Engineering technology is both a critical capability and a bottleneck for NASA human exploration development. NASA looks to a sustainable return to the Moon to enable future exploration of Mars, components such as Lunar Gateway and Artemis will require partnerships with a wide variety of communities. Building from the success of the international partnerships for International Space Station (ISS), space agencies from multiple governments are looking for roles on the Gateway. A particular focus has been made to include the rapidly growing commercial space industry to provide an important role in supporting a sustained presence on the Moon. All of these potential partners will have their own design capabilities and their own development processes and internal constituencies to support. Integrating and enabling disparate systems built in different locations by different owners to all work cohesively together will require a significant upgrade to the core-systems engineering capabilities.

In the last decade, Model-Based Systems Engineering (MBSE) technology has matured as evidenced by the development of Systems Modeling Language (SysML) tools and frameworks that support engineers in development efforts from requirements through hardware and software implementation. MBSE holds considerable promise for accelerating, reducing overhead labor, and improving the quality of systems development. However, a remaining bottleneck is the coordination and integration of system development across distributed organizations, such as the multiple partners developing Lunar Gateway and eventual Mars exploration. This subtopic seeks technology to fill this gap.

Areas of particular need include:

- Methodologies that support integration among tools and exchange of information between multidisciplinary artifacts using automated intelligent reasoning.
- The definition of open interface standards and tools to enable inspection of distributed models across engineering domains.
- Tools or systems that allow models to be shared across development environments and trace the resulting system model back to contributions from multiple partners while maintaining information security (International Traffic in Arms Regulations (ITAR), Export Administration Regulations (EAR), sensitive but unclassified (SBU)) and protecting intellectual property.
- Modeling visualization environments that facilitate user interaction from multiple stakeholders perspectives with varying expertise in MBSE.
- Executable requirements specification with precise semantic links disparate development sources.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.2 Modeling

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:
Phase I: Prototype software to demonstrate proof of concept.

Phase II: Functional software that is ready to be tested in an operational environment by end users.

**State of the Art and Critical Gaps:**

For distributed development, the state of the art tends to be laboriously negotiated interface control documents and manual integration processes that are inherently slow and labor intensive. In an effort to overcome these challenges, MBSE and SysML in particular has seen significant adoption at NASA (Gateway, Resource Prospector, Europa Clipper, Space Communications and Navigation [SCaN], Space Launch System [SLS]) especially after the MBSE Pathfinder (2016/2017) and MBSE Infusion And Modernization Initiative (MIAMI, 2018/2019) studies. However, these pilot programs and a survey of NASA's use of MBSE conducted by NASA Independent Verification & Validation (IV&V) and Ames Research Center identified critical challenges and factors of concern, including:

- Sharing and version control of models and information contained in the models.
- Integration of MBSE tools with domain specific tools.
- Steep learning curve for users with limited MBSE experience.
- Testing, verification, and validation with SysML have limited use.
- No tools exist for formally specifying requirements and linking to model properties.

With programs such as Gateway and Artemis that require coordination among multiple NASA centers, international space agencies, and commercial partnerships these challenges will be amplified and should be considered when addressing the scope of this subtopic. Tool infrastructures that enable integrated support of requirements tracing, design reference points, intelligent reasoning of data, and interface constructs are generally not available except within proprietary boundaries. We need tools that support integrated development and model sharing across development environments and that support use across multiple vendors.

**Relevance / Science Traceability:**

This subtopic would be of relevance to all Human Exploration and Operations Mission Directorate (HEOMD) missions, but of particular interest will be Gateway and Artemis development. Those systems have already adopted the use of MBSE tools and tools sought to help reduce potential system integration bottlenecks. Over the next 3 to 5 years, there will be considerable opportunity for small business contributions to be matured and integrated into the support infrastructure as Gateway evolves from concept to development program. Longer term plans for human exploration, including a sustained lunar presence and manned Mars missions, would benefit from disruptive innovations that improve the entire project life-cycle including mission design, acquisition, development, and deployment.

**References:**

General references:

- NASA's assessment of the state of the art for MBSE: [https://www.nasa.gov/nesc/articles/se-mbse-state-of-the-discipline](https://www.nasa.gov/nesc/articles/se-mbse-state-of-the-discipline) [17]
- SysML: [http://www.omgsysml.org](http://www.omgsysml.org) [18]

Areas of specific interest with references:

- Ensuring information exchange of digital artifacts are transferable and up to date among multiple stakeholders.
  - [Digital Engineering Information Exchange Working Group (DEIX WG)](http://www.deixwg.org) [19]
  - [CCSDS Electronic Data Sheets](http://ccsdseds.org) [20]
- Computational tools to augment human decision making and reasoning on complex systems with large
amounts of data from disparate sources

- Augmented Intelligence for Systems Engineering challenge team (AI-SECT) [21]

- Web-based interfaces including CRUD (create, read, update, delete) operations and digital review sign-offs for models particularly for reviews required in NPR 7123.1 System Engineering Requirements.
  - Open-MBEE: https://openmbee.org [22]
  - OSLC: https://open-services.net/ [23]
- Formal requirements specification and test case generation with traceability to a single source of truth.
  - OpenCAESAR: https://opencaesar.github.io [26]
  - Digital Thread for Smart Manufacturing [27]

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**H6.22 Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition**

Lead Center: ARC

Participating Center(s): ARC

**Scope Title:**

**Neuromorphic Capabilities**

**Scope Description:**

This subtopic specifically focuses on advances in signal and data processing. Neuromorphic processing will enable NASA to meet growing demands for applying artificial intelligence and machine learning algorithms onboard a spacecraft to optimize and automate operations. This includes enabling cognitive systems to improve mission communication and data-processing capabilities, enhance computing performance, and reduce memory requirements. Neuromorphic processors can enable a spacecraft to sense, adapt, act, and learn from its experiences and from the unknown environment without necessitating involvement from a mission operations team. Additionally, this processing architecture shows promise for addressing the power requirements that traditional computing architectures now struggle to meet in space applications.

The goal of this program is to develop neuromorphic processing software, hardware, algorithms, architectures, simulators, and techniques as enabling capability for autonomous space operations. Emerging memristor and other radiation-tolerant devices, which show potential for addressing the need for energy-efficient neuromorphic processors and improved signal processing capability, are of particular interest due to their resistance to the effects of radiation.
Additional areas of interest for research and/or technology development include: (a) spiking algorithms that learn from the environment and improve operations, (b) neuromorphic processing approaches to enhance data processing, computing performance, and memory conservation, and (c) new brain-inspired chips and breakthroughs in machine understanding/intelligence. Novel memristor approaches that show promise for space applications are also sought.

This subtopic seeks innovations focusing on low-size, -weight, and -power (-SWaP) applications suitable to lunar orbital or surface operations, thus enabling efficient onboard processing at lunar distances. Focusing on SWaP-constrained platforms opens up the potential for applying neuromorphic processors in spacecraft or robotic control situations traditionally reserved for power-hungry general-purpose processors. This technology will allow for increased speed, energy efficiency, and higher performance for computing in unknown and uncharacterized space environments including the Moon and Mars. Proposed innovations should justify their SWaP advantages and target metrics over the comparable relevant state of the art.

Expected TRL or TRL Range at completion of the Project: 4 to 6
Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I will emphasize research aspects for technical feasibility and show a path toward a Phase II proposal. Phase I deliverables include concept of operations of the research topic, simulations, and preliminary results. Early development and delivery of prototype hardware/software is encouraged.

Phase II will emphasize hardware and/or software development with delivery of specific hardware and/or software products for NASA, targeting demonstration operations on a low-SWaP platform. Phase II deliverables include a working prototype of the proposed product and/or software, along with documentation and tools necessary for NASA to use the product and/or modify and use the software. In order to enable mission deployment, proposed prototypes should include a path, preferably demonstrated, for fault and mission tolerances. Phase II deliverables should include hardware/software necessary to show how the advances made in the development can be applied to a CubeSat, SmallSat, and rover flight demonstration.

State of the Art and Critical Gaps:

The current state of the art (SOA) for in-space processing is the High Performance Spaceflight Computing (HPSC) processor being developed by Boeing for NASA Goddard Space Flight Center (GSFC). The HPSC, called the
Chiplet, contains 8 general purpose processing cores in a dual quad-core configuration. Delivery is expected by December 2022. In a submission to the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program, the highest computational capability required by a typical space mission is 35 to 70 GFLOPS (billion fast logical operations per second).

The current SOA does not address the capabilities required for artificial intelligence and machine learning applications in the space environment. These applications require significant amounts of multiply and accumulate operations, in addition to a substantial amount of memory to store data and retain intermediate states in a neural network computation. Terrestrially, these operations require general-purpose graphics processing units (GP-GPUs), which are capable of teraflops (TFLOPS) each—approximately 3 orders of magnitude above the anticipated capabilities of the HPSC.

Neuromorphic processing offers the potential to bridge this gap through a novel hardware approach. Existing research in the area shows neuromorphic processors to be up to 1,000 times more energy efficient than GP-GPUs in artificial intelligence applications. Obviously, the true performance depends on the application, but nevertheless the architecture has demonstrated characteristics that make it well-adapted to the space environment.

Relevance / Science Traceability:

The Cognitive Communications Project, through the Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program, is one potential customer of work from this subtopic area. Neuromorphic processors are a key enabler to the cognitive radio and system architecture envisioned by this project. As communications become more complex, cognition and automation will play a larger role to mitigate complexity and reduce operations costs. Machine learning will choose radio configurations and adjust for impairments and failures. Neuromorphic processors will address the power requirements that traditional computing architectures now struggle to meet and are of relevance to Lunar return and Mars for autonomous operations, as well as of interest to HEOMD and Science Mission Directorate (SMD) for in situ avionics capabilities.

References:

Several reference papers that have been published at the Cognitive Communications for Aerospace Applications (CCAA) workshop are available at: http://ieee-ccaa.com. [28]

H6.23 Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration

Lead Center: ARC

Participating Center(s): JSC

Scope Title:

Learning and Adaptation for Space Cognitive Agents

Scope Description:

This subtopic solicits intelligent autonomous agent cognitive architectures that are open, modular, make decisions under uncertainty, and learn in a manner that the performance of the system is assured and improves over time. Cognitive agents for space applications need to adapt and learn from observation, instruction, and interaction as
missions proceed. The value of preprogrammed agents that do not adapt over time will diminish in extended missions. Building upon the success of the previous solicitations, this extended scope will enable small businesses to develop both the learning technology and the necessary assurance technology within the scope of cognitive agents that forward base mission control to spacecraft and habitats, and multiply the cognitive assets available to the crew.

It should be feasible for cognitive agents based on these architectures to be certified or licensed for use on deep space missions to act as liaisons that interact both with the mission control operators, the crew, and most, if not all, of the spacecraft subsystems. With such a cognitive agent that has access to all onboard data and communications, the agent could continually integrate this dynamic information and advise the crew and mission control accordingly by multiple modes of interaction including text, speech, and animated images. This agent could respond to queries and recommend to the crew courses of action and direct activities that consider all known constraints, the state of the subsystems, available resources, risk analyses, and goal priorities.

Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable to provide crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true requiring this NASA investment.

Proposals should emphasize analysis and demonstration of the feasibility of various configurations, capabilities, and limitations of a cognitive architecture suitable for crew support on deep space missions. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

Proposals should emphasize analysis and demonstration of the feasibility of various configurations, capabilities, and limitations, and address learning and adaptation during mission scenarios of a cognitive architecture suitable for crew support on deep space missions. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.3 Collaboration and Interaction

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software
Desired Deliverables Description:

For Phase I, a preliminary cognitive architecture, preliminary feasibility study, and a detailed plan to develop a comprehensive cognitive architecture feasibility study are expected. A preliminary demonstration prototype of the proposed cognitive architecture is highly encouraged.

For Phase II, the Phase I proposed detailed feasibility study plan is executed generating a comprehensive cognitive architecture, comprehensive feasibility study report including design artifacts such as System Modeling Language/Unified Modeling Language (SysML/UML) diagrams, a demonstration of an extended prototype of an agent that instantiates the architecture interacting with a spacecraft simulator and humans executing a plausible Human Exploration and Operations Mission Directorate (HEOMD) design reference mission beyond cislunar orbit (e.g., Human Exploration of Mars Design Reference Mission: [29]), and a detailed plan to develop a comprehensive cognitive architecture feasibility study suitable for proposing to organizations interested in funding this flight capability is expected. A Phase II prototype suitable for a compelling flight experiment on the ISS is encouraged.

State of the Art and Critical Gaps:

Long-term crewed spacecraft, such as the International Space Station, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in low-Earth orbit and still require significant real-time support from Earth. Autonomous agents performing cognitive computing can provide crew support for future missions beyond cislunar by providing them robust, accurate, and timely information, and perform tasks enabling the crew more time to perform the mission science. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to onboard agents that team with flight crews to autonomously manage a space-flight mission.

The majority of Apollo missions required the timely guidance of mission control for success, typically within seconds of an off-nominal situation. Outside of cislunar space, the time delays will become untenable for Earth to manage time-critical decisions as was done for Apollo. The emerging field of cognitive computing is a vast improvement on previous information retrieval and integration technology, and is likely capable to provide this essential capability.

Investments continue to be made in a wide variety of cognitive agents. However, a critical gap that this subtopic addresses is assured learning for cognitive agents enabling it to appropriately adapt to the crew it interacts with in a manner that assures performance improves and not degrades over time mitigating risks related to learning systems.

Relevance / Science Traceability:

This subtopic is directly relevant to the HEOMD Advanced Exploration Systems (AES) domain: Foundational Systems - Autonomous Systems and Operations.
There is growing interest in NASA to support long-term human exploration missions to the Moon and eventually to Mars. Human exploration up to this point has relied on continuous communication with short delays. To enable missions with intermittent communication with long delays, new artificially intelligent technologies must be developed in order to keep the crew sizes small. Technologies developed under this subtopic are expected to be suitable for testing on Earth analogues of deep space spacecraft as well as the Deep Space Gateway envisioned by NASA.

References:

3. ACC'20 - The 4th International Conference on Applied Cognitive Computing: [Link](https://americancse.org/events/csce2020/conferences/acc20) [31]

H8.01 Low Earth Orbit (LEO) Platform Utilization to Foster Commercial Development of Space

Lead Center: JSC

Participating Center(s): ARC, GRC, JPL, KSC, LaRC, MSFC

Scope Title:

Use of the International Space Station (ISS) to Foster Commercialization of LEO Space

Scope Description:

This subtopic seeks proposals that advance NASA’s objective of leveraging the unique ISS capabilities (microgravity and exposure to space) to catalyze markets leading to a broad commercial demand for LEO. Of specific interest are proposals that could lead to valuable terrestrial applications and foster a scalable and sustainable demand for commercial markets in LEO. Use of the ISS will facilitate validation of these applications and enable development of the minimal viable product required to significant capital and lead to growth of new and emerging LEO commercial markets in the following areas: in-space manufacturing, regenerative medicine, bioengineering, and advanced materials production.

Expected TRL or TRL Range at completion of the Project: 3 to 7
Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For Phase I, as a minimum, a written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware and software demonstration in orbit. Bench or lab-level demonstrations are desirable.

Desired deliverables at the end of Phase II would be engineering development units and/or software packages for NASA-sponsored testing that could be turned into proof-of-concept systems suitable for flight demonstrations.

State of the Art and Critical Gaps:

The ISS is being used to stimulate both the supply and demand of commercial marketplace as NASA supports the development of the LEO space economy.

Relevance / Science Traceability:

This subtopic is in direct support of NASA’s recent policy to enable commercial and marketing activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development.

References:

- Space Station Research & Technology
  at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer [33]
- Center for the Advancement of Science In Space, Inc.
  at: https://www.issnationallab.org/(link is external) [34]

H9.01 Long-Range Optical Telecommunications

Lead Center: GRC

Participating Center(s): GRC, GSFC

Scope Title:
Free-Space Optical Communications Technologies

Scope Description:

This subtopic seeks innovative technologies for advancing free-space optical communications by pushing future data volume returns to and from space missions in multiple domains with return data rates >100 Gbps (cis lunar, i.e., Earth or lunar orbit to ground), >10 Gbps (Earth-Sun L1 and L2), >1 Gbps/AU² (deep space), and >1 Gbps (planetary lander to orbiter and/or inter-spacecraft). Ground-to-space forward data rates >25 Mbps at ranges extending to farthest Mars ranges are targeted. Optical metrology (optometrics) services, including high-precision ranging, Doppler, and astrometric measurements derived from the optical communications signal, are sought as well.

Innovative technologies offering low size, weight, and power (SWaP) with improved efficiency, reliability, robustness, are sought for novel state-of-the-art spaceflight laser communication systems, with supporting ground technologies.

Photon-counting sensitivity, near infrared (NIR), spaceflight worthy detectors/detector arrays for supporting laser ranging for potential navigation and science are of particular interest. Ground-based technologies that support operations of large-aperture daytime light collectors are needed to transition deep space optical communications to operational status. High-power, NIR, intensity-modulated lasers with fast rise times and low-timing jitter (subnanosecond) are needed to support high forward data rates and laser ranging.

Proposals are sought in the following specific areas:

Flight Laser Transceivers:

Low-mass, high-effective isotropic radiated power (EIRP) laser transceivers for links over planetary distances with:

- 30- to 50-cm clear aperture diameter telescopes for laser communications.
- Targeted mass of optomechanical assembly per aperture area, less than 200 kg/m².
- Cumulative wave-front error and transmission loss not to exceed 2 dB.
- Advanced thermal-mechanical designs to withstand planetary launch loads and flight temperatures by the optics and structure, at least -20 to 70 °C operational range.
- Design to mitigate stray light while pointing transceivers 3° from edge of Sun.
- Survive direct Sun pointing for extended duration (few hours to days).
- Transceivers fitting the above characteristics should support robust link acquisition tracking and pointing characteristics, including point-ahead implementation from space for beacon assisted and/or "beaconless" architectures. Innovative solutions for mechanically stiff, light-weighted thermally stable structural properties are sought.
- Acquisition, tracking, and pointing architectures that can operate with dim laser beacons (irradiance of few pW/m² as entrance of flight aperture) from Mars farthest ranges.
- Pointing loss allocations not to exceed 1 dB (pointing errors associated loss of irradiance at target less than 20%).
- Receiver field-of-view (FOV) of at least 1 mrad angular radius for beacon assisted acquisition, tracking, and pointing.
- As a goal, additional focal plane with wider FOV (>10 mrad) to support onboard astrometry is desired.
- Beaconless pointing subsystems for space-to-ground operations beyond 3 AU.
- Assume integrated spacecraft microvibration angular disturbance of 150 μrad (<0.1 Hz to ~500 Hz).
- Low-complexity small-footprint agile laser transceivers for bidirectional optical links (>1 to 10 Gbps at a
nominal link range of 1,000 to 20,000 km) for planetary lander/rover-to-orbiter and/or space-to-space cross links.

- Disruptive low-SWaP technologies that can operate reliably in space over extended mission duration.
- Vibration isolation/suppression systems that will integrate to the optical transceiver in order to reject high frequency base disturbance by at least 50 dB.
- Desire integrated launch locks and latching mechanism.
- Robust for spaceflight.
- Should afford limited +/-5 to +/-12 mrad actuated field-of-regard for the optical line of sight of the transceiver.

Flight Laser Transmitters:

- High-Gbps laser transmitters.
- 1,550-nm wavelength.
- Lasers, electronics, and optical components ruggedized for extended space operations.
- High rate 10 to 100 Gbps for cislunar.
- 1 Gbps for deep space.
- Integrated hardware with embedded software/firmware for innovative coding/modulation/interleaving schemes that are being developed as a part of the Consultative Committee for Space Data Systems (CCSDS).
- High peak-to-average power laser transmitters for regular or augmented M-ary pulse-position modulation (M-PPM) with M = 4, 8, 16, 32, 64, 128, and 256 operating at NIR wavelengths, preferably 1,550 nm, with average powers from 5 to 50 W.
- Subnanosecond pulse.
- Low-pulse jitter.
- Long lifetime and reliability operating in space environment ( >5 and as long as 20 yr).
- High-modulation and polarization extinction ratio with 1 to 10 GHz line width.
- Space-qualifiable wavelength division multiplexing transmitters and amplifiers with 4 to 20 channels and average output power >20 W per channel; peak-to-average power ratios >200; >10 Gbps channel modulation capability.
- >20% wall-plug efficiency (direct current- (DC-) to-optical, including support electronics) with description of approach for stated efficiency of space-qualifiable lasers.
- Multiwatt Erbium-doped fiber amplifier (EDFA), or alternatives, with high-gain bandwidth (>30 nm, 0.5 dB flatness) concepts will be considered.
- Radiation tolerance better than 50 krad is required (including resilience to photodarkening).

Receivers/Sensors:

- Space-qualifiable high-speed receivers and low-light-level sensitive acquisition, tracking, pointing, detectors, and detector arrays.
- NIR wavelengths: 1,064 and/or 1,550 nm.
- Sensitive to low-irradiance incident at flight transceiver aperture (~ fW/m² to pW/m²) detection.
- Low subnanosecond timing jitter and fast rise time.
- Novel hybridization of optics and electronic readout schemes with in-built preprocessing capability.
- Characteristics compatible with supporting time-of-flight or other means of processing laser communication signals for high-precision range and range rate measurements.
- Tolerant to space radiation effects, total dose >50 krad, displacement damage and single event effects.

Novel technologies and accessories:

- Narrow bandpass optical filters.
- Space-qualifiable, subnanometer to nanometer, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~40 dB).
- NIR wavelengths from 1,064- to 1,550-nm region, with high transmission through Earth’s atmosphere.
- Reliable tuning over limited range.
- Novel photonics integrated circuit (PIC) devices targeting space applications with objective of reducing...
SWaP of modulators, without sacrificing performance.
- Proposed PIC solutions should allow improved integration and efficient coupling to discrete optics, when needed.
- Concepts for offering redundancy to laser transmitters in space.
- Optical fiber routing of high-average powers (10s of watts) and high-peak powers (1 to 10 kW).
- Redundancy in actuators and optical components.
- Reliable optical switching.

Ground assets for optical communication:

Low-cost, large aperture receivers for faint optical communication signals from deep-space subsystem technologies:

- Demonstrate innovative subsystem technologies for >10-m-diameter deep-space ground collector.
- Capable of operating to within 3° of solar limb.
- Better than 10-µrad spot size (excluding atmospheric seeing contribution).
- Desire demonstration of low-cost, primary-mirror segment fabrication to meet a cost goal of less than $35K per square meter.
- Low-cost techniques for segment alignment and control, including daytime operations.
- Partial adaptive correction techniques for reducing the FOV required to collect signal photons under daytime atmospheric “seeing” conditions.
- Innovative adaptive techniques not requiring a wave-front sensor and deformable mirror of particular interest.
- Mirror cleanliness monitor and control systems.
- Active metrology systems for maintaining segment primary figure and its alignment with secondary optics.
- Large-core-diameter multimode fibers with low temporal dispersion for coupling large optics to detectors remote (30 to 50 m) from the large optics.
- 1,550-nm sensitive photon counting detector arrays compatible with large-aperture ground collectors with a means of coupling light from large-aperture diameters to reasonably sized detectors/detector arrays, including optical fibers with acceptable temporal dispersion.
- Integrated time tagging readout electronics for >5 gigaphotons/sec incident rate.
- Time resolution <50 ps at 1-sigma.
- Highest possible single photon detection efficiency, at least 50% at highest incident photon-flux rates.
- Total detector active area >0.3 to 1 mm²
- Integrated dark rate <3 megacount/sec.
- Optical filters.
- Subnanometer noise equivalent bandwidths.
- Tunable in a limited range in the 1,550-nm spectral region.
- Transmission losses <0.5 dB.
- Clear aperture >25 mm, and acceptance angle >40 mrad or similar etendue.
- Out-of-band rejection of >50 dB from 0.7 to 1.8 µm.
- Multikilowatt laser transmitters for use as ground beacon and uplink laser transmitters.
- NIR wavelengths in 1.0- or 1.55-µm spectral region.
- Capable of modulating with narrow nanosecond and subnanosecond rise times.
- Low-timing jitter and stable operation.
- High-speed real-time signal processing of serially concatenated PPM operating at a few bits per photon with user interface outputs.
- 15- to 60-MHz repetition rates.

Examples of potential outcomes are, prototype hardware with embedded software and/or firmware of components or assemblies for free-space optical communications (FSOC) optical transceivers, flight and ground laser transmitters, high-sensitivity space-worthy detectors, and novel FSOC photonics targeting near-earth and deep-space applications.

**Expected TRL or TRL Range at completion of the Project:** 2 to 5

**Primary Technology Taxonomy:**
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.1 Optical Communications

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

For all technologies lowest cost for small volume production (5 to 20 units) is a driver. Research must convincingly prove technical feasibility (proof of concept) during Phase I, ideally with hardware deliverables that can be tested to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

State of the Art and Critical Gaps:

The state of the art (SOA) for FSOC can be subdivided into near-Earth (extending to cis lunar and translunar distances) and planetary ranges with the Lagrange points falling in between.

Near-Earth FSOC technology has matured through a number of completed and upcoming technology demonstrations from space. Transition from technology demonstration to an operational service demands low-SWaP, novel high-speed (10 to 100 Gbps) space-qualified laser transmitters and receivers. Transmitters and receivers servicing near-Earth applications can possibly be repurposed for deep-space proximity links, such as landed assets on planetary surfaces to orbiting assets with distances of 5,000 to 100,000 km or inter-satellite links. Innovative light-weight space-qualified modems for handling multiple optical-modulation schemes. Emerging photonics technologies that can benefit space FSOC applications are sought.

Deep space FSOC is motivated by NASA's initiative to send humans to Mars. Critical gaps following a successful technology demonstration will be light-weighted 30- to 50-cm optical transceivers with a wide operational temperature range -20 to 50 °C over which wave-front error and focus is stable; high peak-to-average power space qualified lasers with average powers of 20 to 50 W; and single photon-sensitive radiation-hardened flight detectors with high-detection efficiency, fast rise times, and low-timing jitter. The detector size should be able to cover 1 mrad FOV with an instantaneous FOV comparable to the transmitted laser beam width. Laser pointing control systems that operate with dim laser beacons transmitted from Earth or use celestial beacon sources. For Deep Space Optical Communications (DSOC) ground laser transmitters with high-average power (kW class) but narrow line-widths (<0.25 nm) and high-variable repetition rates are required. Innovative optical coatings for large aperture mirrors that are compatible with near-Sun pointing applications for efficiently collecting the signal and lowering background and stray light. Reliability through space-qualified materials and component selection and implementation of redundancy are highly sought after to enable sending humans to planetary destinations, as well as enable higher resolution science instruments. Deriving auxiliary optometrics from the FSOC signals to support laser ranging and time transfer will also be critical for providing services to future human missions to Mars. High-rate uplink from the ground to Mars with high-modulation rate high-power lasers are also currently lacking.

Relevance / Science Traceability:

A number of FSOC-related NASA projects are ongoing with launch expected in the 2019-2022 time frame. The Laser Communication Relay Demonstration (LCRD) is an Earth-to-geostationary satellite relay demonstration to launch in 2021. The Illuma-T Project will follow to extend the relay demonstration to include a low Earth orbit (LEO) node on the International Space Station (ISS). In 2023, the Optical to Orion (O2O), Artemis II, demonstration will transmit data from the Orion crewed capsule as it performs a translunar trajectory and return to Earth.

In 2022, the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending
FSOC links to AU distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstrations Mission (TDM) program and Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program.

Of the 6 technologies recently identified by NASA for sending humans to Mars, laser communications was identified

(https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars) [36]

References:

https://www.nasa.gov/mission_pages/tdm/lcrd/index.html [37]

https://www.nasa.gov/directorates/heo/scan/opticalcommunications/illuma-t [38]


https://www.nasa.gov/mission_pages/tdm/dsoc/index.html [40]

H9.03 Flight Dynamics and Navigation Technologies

Lead Center: GRC

Participating Center(s): JSC, MSFC

Scope Title:

Advanced Techniques for Trajectory Design and Optimization

Scope Description:

NASA seeks innovative advancements in trajectory design and optimization for Earth orbit, cislunar, and interplanetary missions, including:

- Low-thrust trajectories in a multibody dynamical environment.
- Small-body (moons, asteroids, and comets) exploration.
- Distributed space systems (swarms, constellations, or formations).

In particular, NASA is seeking innovative techniques for optimization of trajectories that account for:

- System uncertainties (i.e., navigation errors, maneuver execution errors, etc.).
- Spacecraft and operational constraints (power, communications, thermal, etc.).
- Trajectory impacts on ability to make required navigational and/or science observations.
Furthermore, innovative techniques that allow rapid exploration of mission design trade spaces, address high-dimensionality optimization problems (i.e., multimoon/multibody tours; low thrust, multispiral Earth orbits), apply novel artificial intelligence/machine learning (AI/ML) algorithms or provide unique methods for visualizing and manipulating trajectory designs are sought.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (GMAT), Collocation Stand Alone Library and Toolkit (CSALT), Copernicus, Evolutionary Mission Trajectory Generator (EMTG), Mission Analysis Low-Thrust Optimization (MALTO), Mission Analysis, Operations, and Navigation (MONTE), and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

**Expected TRL or TRL Range at completion of the Project:** 3 to 6

**Primary Technology Taxonomy:**
- Level 1: TX 15 Flight Vehicle Systems
- Level 2: TX 15.2 Flight Mechanics

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Software

**Desired Deliverables Description:**

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

**State of the Art and Critical Gaps:**

Algorithms and software for optimizing trajectories while considering system uncertainties, spacecraft and operational constraints, and trajectory impacts on making navigational or science observations, do not currently exist. In addition, designing trajectories for complex missions, such as low-thrust cis-lunar or multibody tour missions rely heavily on hands-on work by very experienced people. That works reasonably well for designing a single-reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

**Relevance / Science Traceability:**

Relevant missions include:

- Artemis - Lunar Gateway.
- Europa Clipper.
- Lucy.
- Psyche.
- Dragonfly.
- Lunar IceCube.
• Roman Space Telescope.

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. Providing algorithms and software to speed up this process will enable missions to more fully explore trade spaces and more quickly respond to changes in the mission.

References:

1. General Mission Analysis Tool
   (GMAT): [https://software.nasa.gov/software/GSC-18094-1](https://software.nasa.gov/software/GSC-18094-1) [41], [https://gmat.atlassian.net/wiki/spaces/GW/overview?mode=global](https://gmat.atlassian.net/wiki/spaces/GW/overview?mode=global) [42].
2. Collocation Stand Alone Library and Toolkit
   (CSALT): [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003690.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003690.pdf) [43]
3. Evolutionary Mission Trajectory Generator
   (EMTG): [https://software.nasa.gov/software/GSC-16824-1](https://software.nasa.gov/software/GSC-16824-1), [https://github.com/nasa/EMTG](https://github.com/nasa/EMTG) [44].
4. Copernicus: [https://software.nasa.gov/software/MSC-26673-1](https://software.nasa.gov/software/MSC-26673-1) [45], [https://www.nasa.gov/centers/johnson/copernicus/index.html](https://www.nasa.gov/centers/johnson/copernicus/index.html) [46].
5. Mission Analysis Low-Thrust Optimization
   (MALTO): [https://software.nasa.gov/software/NPO-43625-1](https://software.nasa.gov/software/NPO-43625-1) [47]

Scope Title:

Autonomous Onboard Spacecraft Navigation, Guidance, and Control

Scope Description:

Future NASA missions require precision landing, rendezvous, formation flying, proximity operations (e.g., servicing and assembly), noncooperative object capture, and coordinated platform operations in Earth orbit, cislunar space, libration orbits, and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous, onboard spacecraft navigation and maneuver planning and execution technologies for applications in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, orbit determination, and maneuver planning, including:

- Onboard relative and proximity navigation, multiplatform relative navigation (relative position, velocity and attitude, or pose), which support cooperative and collaborative space operations such as On-orbit Servicing, Assembly, and Manufacturing (OSAM).
- Advanced filtering techniques that address rendezvous and proximity operations as a multisensor, multitarget tracking problem; handle nonGaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe, precision landing on small bodies, planets, and moons, including real-time 3D terrain mapping, autonomous hazard detection and avoidance, terrain relative navigation, and small body proximity operations.
- Machine vision techniques to support optical/terrain relative navigation and/or
spacecraft rendezvous/proximity operations in low and variable lighting conditions, including artificial intelligence/machine learning (AI/ML) algorithms.

- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission resequencing, onboard computation of large divert maneuvers, primitive body/lunar proximity operations, and pinpoint landing, including robust onboard trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS), Navigator NavCube, core Flight System (cFS), or other available NASA hardware and software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

**Expected TRL or TRL Range at completion of the Project:** 3 to 6

**Primary Technology Taxonomy:**
- Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
- Level 2: TX 17.2 Navigation Technologies

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration. For proposals that include hardware development, delivery of a prototype under the Phase I contract is preferred, but not necessary.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components with complete and preliminary integration and testing in an operational environment.

**State of the Art and Critical Gaps:**

Currently navigation, guidance, and control functions rely heavily on the ground for tracking data, data processing, and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round trip communication time delays make it necessary to reduce reliance on Earth for navigation solutions and maneuver planning. Spacecraft that arrive at a near-Earth asteroid (NEA) or a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids, and may require rapid navigation updates to feed autonomous trajectory guidance updates and control. NASA currently does not have the navigational, trajectory, and attitude flight control technologies that permit fully autonomous approach, proximity operations, and landing without navigation support from Earth-based resources.

**Relevance / Science Traceability:**

Relevant missions include:
On-orbit Servicing, Assembly and Manufacturing (OSAM).
LunaNet.
avtonomic Navigation, Guidance and Control (autoNGC).
Roman Space Telescope.
Europa Clipper.
Lucy.
Psyche.

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications requirements on network services, increase operational agility, and enable near real-time replanning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

References:

3. NavCube: (https://goo.gl/bdobb9 [53])
4. core Flight System (cFS): https://cfs.gsfc.nasa.gov/ [54]

Scope Title:

Conjunction Assessment Risk Analysis (CARA)

Scope Description:

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 cm and the number of objects in orbit is steadily increasing, which causes an increasing threat to human spaceflight and robotic missions in the near-Earth environment. The NASA CARA team receives screening data from the 18th Space Control Squadron concerning predicted close approaches between NASA satellites and other space objects. CARA determines the risk posed by those events and recommends risk mitigation strategies, including collision avoidance maneuvers, to protect NASA non-human-spaceflight assets in Earth orbit. The ability to perform CARA more accurately and rapidly will improve space safety for all near-Earth operations. This subtopic seeks innovative technologies to improve the CARA process including:

- Improved conjunction assessment (CA) event evolution prediction methods, models, and algorithms with improved ability to predict characteristics for single
and ensemble risk assessment, especially using artificial intelligence/machine learning (AI/ML).

- AI/ML applied to CA risk assessment parameters.
- Middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions).
- Methods for combining commercial data (observations or ephemerides) with 18th Space Control Squadron (18 SPCS) derived solutions (available as Vector Covariance Messages, Conjunction Data Messages, or Astrodynamics Support Workstation output) to create a single improved orbit determination solution including more data sources.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan toward Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:

Current state of the art has been adequate in performing CA and collision mitigation for space objects that fall under the high interest events (HIE). With the incorporation of the Space Fence and the deployment of large constellations, the number of objects tracked and assessed for conjunctions is expected to greatly increase. This presents a critical gap in which current approaches may not suffice. Thus, smarter ways to perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk assessment, middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions), improved CA event evolution prediction, and AI/ML applied to CA risk assessment parameters and/or event evolution are needed. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for CA.

Collision avoidance maneuver decisions are based on predicted close approach distance and probability of collision. The accuracy of these numbers depend on underlying measurements and mathematics used in estimation. Current methods assume Gaussian distributions for errors and that all objects are shaped like cannon balls for nongravitational force computations. These assumptions and others cause inaccurate estimates that can lead decision makers to perform unnecessary collision avoidance maneuvers, thus wasting propellant. Better techniques are needed for orbit prediction and covariance characterization and propagation. Better modeling of nongravitational force effects is needed to improve orbit prediction. Modeling of nongravitational forces relies on knowledge of individual object characteristics.
Relevance / Science Traceability:

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth, cislunar, and lunar environments. The ability to perform CARA more accurately will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer term predictions, and reduce propellant usage for collision avoidance maneuvers.

References:

2. NASA Orbital Debris Program Office: https://www.orbitaldebris.jsc.nasa.gov/ [59].

H9.05 Transformational Communications Technology

Lead Center: GRC

Participating Center(s): GSFC

Scope Title:

Revolutionary Concepts

Scope Description:

NASA seeks revolutionary transformational communications technologies, for lunar exploration and beyond, that emphasize not only dramatic reduction in system size, mass, and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. The proposer is expected to identify new ideas, create novel solutions, and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (?10 yr) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program. The transformational communications technology development will focus research in the following areas:
• Systems optimized for energy efficiency (information bits per unit energy).
• Hybridization of communications and sensing systems to maximize performance and minimize size, weight, and power (SWaP), especially for harsh environments.
• Advanced materials; smart materials; electronics embedded in structures; functional materials; graphene-based electronics/detectors.
• Techniques to overcome traditional analog-to-digital converter speed and power consumption limitations.
• Technologies that address flexible, scalable digital/optical core processing topologies to support both radio-frequency (RF) and optical communications in a single terminal.
• Nanoelectronics and nanomagnetics; quantum logic gates; single electron computing; superconducting devices; technologies to leapfrog Moore’s law.
• Energy harvesting technologies to enhance space communication system efficiency.
• Human/machine and brain-machine interfacing to enable new communications paradigms; the convergence of electronic engineering and bioengineering; neural signal interfacing.
• Quantum communications, methods for probing quantum phenomenon, methods for exploiting exotic aspects of quantum theory.

The research should be conducted to demonstrate theoretical and technical feasibility during the Phase I and Phase II development cycles and be able to demonstrate an evolutionary path to insertion within approximately 10 years. Delivery of a prototype of the most critically enabling element of the technology for NASA testing at the completion of the Phase II contract is expected.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies
Desired Deliverables of Phase I and Phase II:

• Research
• Analysis
• Prototype

Desired Deliverables Description:

Phase I deliverables shall include a final report describing theoretical analysis and prototyping concepts. The technology should have eventual commercialization potential.

For Phase II consideration, the final report should include a detailed path towards Phase II prototype hardware.

State of the Art and Critical Gaps:

While according to the Business R&D and Innovation Survey of the $323 billion of research and development performed by companies in the United States in 2013, Information and Computing Technology industries accounted for 41%. But it must be understood that the majority of these investments seek short-term returns and that most of the investment is in computer technology, cloud computing and networking, semiconductor manufacturing, etc.—not new and futuristic “over-the-horizon” technologies with uncertain returns on investment. As a concrete example, deep-space mission modeling indicates a need for a 10× improvement in data rate per decade out to 2040. How will that be achieved? To some extent that goal will be achieved by moving to Ka-band and optical communications and perhaps antenna arraying on a massive scale. But given the ambitiousness of the goal, disruptive technologies like what is being sought here, will be required.

Relevance / Science Traceability:

NASA seeks revolutionary, transformational communications technologies that emphasize not only dramatic reduction in system size, mass, and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. This is a broad subtopic expected to identify new
ideas, create novel solutions, and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (?10 yr) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program.

References:

NASA Space Communication and Navigation (SCaN) Network Architecture Definition Document Executive Summary

https://www.nasa.gov/sites/default/files/files/SCaN_ADD_Vol1Rev4.pdf [64]

H9.07 Cognitive Communication

Lead Center: GRC

Participating Center(s): GSFC, JPL

Scope Title:

Lunar Cognitive Capabilities

Scope Description:

NASA's Space Communication and Navigation (SCaN) program seeks innovative approaches to increase mission science data return, improve resource efficiencies for NASA missions and communication networks, and ensure resilience in the unpredictable space environment. The Cognitive Communication subtopic specifically focuses on advances in space communication driven by onboard data processing and modern space networking capabilities. A cognitive system is envisioned to sense, detect, adapt, and learn from its experiences and environment to optimize the communications capabilities for the user mission satellite or network infrastructure. The underlying need for these technologies is to reduce both the mission and network operations burden. Examples of these cognitive capabilities include:

- Link technologies—reconfiguration and autonomy, maximizing use of bandwidth while avoiding interference.
- Network technologies—robust intersatellite links, data storage/forwarding, multinode routing in unpredictable environments.
- System technologies—optimal scheduling techniques for satellite and surface relays in distributed and real-time environments.

Through Space Policy Directive-1, NASA is committed to landing American astronauts on the Moon by 2024. In support of this goal, cognitive communication techniques are needed for lunar communication satellite and surface relays. Cognitive agents operating on lunar elements will manage communication, provide diagnostics, automate resource scheduling, and dynamically update data flow in response to the types of data flowing
over the lunar network. Goals of this capability are to improve communications efficiency, mitigate channel impairments, and reduce operations complexity and cost through intelligent and autonomous communications and data handling. Examples of research and/or technology development include:

- Onboard processing technology and techniques to enable data switching, routing, storage, and processing on a relay spacecraft.
- Data-centric, decentralized network data routing and scheduling techniques that are responsive to quality of service metrics.
- Simultaneous wideband sensing and communications for S-, X-, and Ka-bands, coupled with algorithms that learn from the environment.
- Artificial intelligence and machine learning algorithms applied to optimize space communication links, networks, or systems.
- Flexible communication platforms with novel signal processing technology to support cognitive approaches.
- Other innovative, related areas of interest to the field of cognitive communications.

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, and surface relays), lunar communication relay satellites, Gateway, and ground stations on Earth. The lunar communication relay satellites require technology with low-size, -weight, and -power (-SWaP) attributes suitable for small satellite (e.g., 50 kg) or CubeSat operations. Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of onboard resources, such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture.

**Expected TRL or TRL Range at completion of the Project:** 4 to 6

**Primary Technology Taxonomy:**
- Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- Level 2: TX 05.5 Revolutionary Communications Technologies

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

Phase I will study technical feasibility, infusion potential for lunar operations, clear/achievable benefits, and show a path towards a Phase II implementation. Phase I deliverables include a feasibility assessment and concept of operations of the research topic, simulations and/or measurements, validation of the proposed approach to develop a given product (TRL 3 to 4) and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development, integration, test, and delivery prototype hardware/software is encouraged.

Phase II will emphasize hardware/software development with delivery of specific hardware or software product for NASA targeting demonstration operations on a small satellite or CubeSat platform. Phase II deliverables include a working prototype (engineering model) of the proposed product/platform or software, along with documentation of development, capabilities, and measurements, and related documents and tools, as necessary, for NASA to modify
and use the cognitive software capability or hardware component(s). Hardware prototypes shall show a path towards flight demonstration, such as a flight qualification approach and preliminary estimates of thermal, vibration, and radiation capabilities of the flight hardware. Software prototypes shall be implemented on platforms that have a clear path to a flight qualifiable platform. Algorithms must be implemented in software. Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables for software defined radio platforms shall be compliant with the latest NASA standard for software defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009, and NASA-HNBK-4009. The deliverable shall be demonstrated in a relevant emulated environment and have a clear path to Phase III flight implementation on a SWaP-constrained platform.

State of the Art and Critical Gaps:

To summarize NASA Technology Roadmap TA5: "As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks.... Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data.... Reconfigurable radio systems...could autonomously optimize the RF [radio-frequency] links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system in order to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance."

The technology need for the lunar communication architecture includes:

- Data routing from surface assets to a lunar communication relay satellite, where data is unscheduled, a-periodic, and ad-hoc.
- Data routing between lunar relay satellites, as necessary, to conserve power, route data to Earth, and meet quality of service requirements.
- Efficient use of lunar communication spectrum while coexisting with future/current interference sources.
- On-demand communication resource scheduling.
- Multihop, delay tolerant routing.

Critical gaps between the state of the art and the technology need include:

- Implementation of artificial intelligence and machine learning techniques on SWaP-constrained platforms.
- Integrated wide-band sensing and narrow-band communication on the same radio terminal.
- Intersatellite networking and routing, especially in unpredictable and unscheduled environments.
On-demand scheduling technology for communication links.
Cross-layer optimization approaches for optimum communication efficiency at a system level.

Relevance / Science Traceability:

Cognitive technologies are critical for the lunar communications architecture. The majority of lunar operations will be run remotely from Earth, which could require substantial coordination and planning as NASA, foreign space agencies, and commercial interests all place assets on the Moon. As lunar communications and networks become more complex, cognition and automation are essential to mitigate complexity and reduce operations costs. Machine learning will configure networks, choose radio configurations, adjust for impairments and failures, and monitor short- and long-term performance for improvements.

References:

Several related reference papers and articles include:

- "NASA Explores Artificial Intelligence for Space Communications"
- "Implementation of a Space Communications Cognitive Engine"
  - [https://ntrs.nasa.gov/search.jsp?R=20180002166](https://ntrs.nasa.gov/search.jsp?R=20180002166) [66]
- "Reinforcement Learning for Satellite Communications: From LEO to Deep Space Operations"
- "Cognitive Communications and Networking Technology Infusion Study Report"
  - [https://ntrs.nasa.gov/search.jsp?R=20190011723](https://ntrs.nasa.gov/search.jsp?R=20190011723) [68]
- "Multi-Objective Reinforcement Learning-based Deep Neural Networks for Cognitive Space Communications"
  - [https://ntrs.nasa.gov/search.jsp?R=20170009153](https://ntrs.nasa.gov/search.jsp?R=20170009153) [69]
- "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits"
  - [https://ntrs.nasa.gov/search.jsp?R=20170009386](https://ntrs.nasa.gov/search.jsp?R=20170009386) [70]
- "Architecture for Cognitive Networking within NASAs Future Space Communications Infrastructure"
  - [https://ntrs.nasa.gov/search.jsp?R=20170001295](https://ntrs.nasa.gov/search.jsp?R=20170001295) [71]
- "Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks"
  - [https://ntrs.nasa.gov/search.jsp?R=20170006541](https://ntrs.nasa.gov/search.jsp?R=20170006541) [72]

A related conference, co-sponsored by NASA and the Institute of Electrical and Electronics Engineers (IEEE), the Cognitive Communications for Aerospace Applications Workshop, has additional information available at: [http://ieee-ccaa.com/](http://ieee-ccaa.com/) [28]
H10.01 Advanced Propulsion Systems Ground Test Technology

Lead Center: KSC
Participating Center(s): KSC

Scope Title:

Advanced Propulsion Test Technology Development

Scope Description:

Rocket propulsion development is enabled by rigorous ground testing to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and nonchemical propulsion, boost stage, in-space propulsion, and so forth. It involves a combination of component and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system level ground test systems that enhance chemical and advanced propulsion technology development and certification. The goal is to advance propulsion ground test technologies to enhance environment simulation; minimize test program time, cost, and risk; and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This project is especially interested in ground test and launch environment technologies with potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

In particular, technology needs include stable combustion of oxygen and hydrogen in a low-pressure duct, developing robust materials, and advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments.

This subtopic seeks innovative technologies in the following areas:

- Design of technology/techniques for oxygen injection into a duct that assures stable combustion with hot (>1,700 R) hydrogen at low pressure (<25 psia), having an oxidizer to fuel mixture ratio of 9 for an oxygen flow rate of approximately 2.7 lbm/sec. This technology solution must be extensible to a system having an oxygen flow rate of approximately 270 lbm/sec.
- Devices for measurement of pressure, temperature, strain, and radiation in a high temperature and/or harsh environment.
- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultrahigh pressure (>8,000 psi), high flow rate (>100 lbm/sec), and cryogenic environments.
- Robust and reliable component designs which are oxygen compatible and can operate efficiently in high-vibroacoustic environments.
- Advanced materials to resist high-temperature (<4,400 °F), hydrogen embrittlement, and harsh environments.
- Tools using computational methods to accurately model and predict system performance, that integrate simple interfaces with detailed design and/or analysis software, are required. Stennis Space Center (SSC) is interested in improving capabilities and methods to accurately predict and model the transient fluid.
structure interaction between cryogenic fluids and immersed components to predict the dynamic loads and frequency response of facilities.

- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand lb/sec, in cryogenic environments and must address two-phase flows. Challenges include: accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; and fluid-structure interactions in internal flows.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

**Expected TRL or TRL Range at completion of the Project:** 4 to 6

**Primary Technology Taxonomy:**
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.1 Infrastructure Optimization

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I as a final report and show a path toward Phase II hardware/software demonstration, with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

**State of the Art and Critical Gaps:**

This subtopic seeks to provide technological advances that provide the ability to test next generation rocket propulsion systems while reducing costs, increasing efficiencies, and improving safety/reliability within the static rocket engine test environment. Specifically, the goal is to reduce costs of propellants and other fluids; reduce logistics costs; reduce times required for ground processing and launch; reduce mission risk; and reduce hazards exposure to personnel.

There is a broad range of technologies needed to support rocket propulsion testing. Dynamic fluid flow simulation is used to characterize and model the facility performance in a highly dynamic environment with NASA, Department of Defense (DOD), and commercial customers. Multiple issues remain with modeling combustion instabilities and component/facility performance. These issues can have catastrophic results if not understood completely. New test programs will require the materials to withstand extreme temperatures and harsh environments. Next-generation testing requires the ability to produce very high temperature hydrogen at high near-continuous flow rates to verify component and facility performance. The extreme and harsh environment also requires advancements in mechanical components and instrumentation.

**Relevance / Science Traceability:**

This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate (HEOMD), all test programs at SSC, and other propulsion system development centers.

**References:**

[https://www.nasa.gov/centers/stennis/home/index.html](https://www.nasa.gov/centers/stennis/home/index.html) [73]
H10.02 Autonomous Operations Technologies for Ground and Launch Systems

Lead Center: KSC

Participating Center(s): ARC, LaRC, SSC

Scope Title:

Autonomous Operations Technologies for Ground and Launch Systems

Scope Description:

For the scope of this solicitation, ground systems are considered to be the planetary or lunar surface-based infrastructure and processes used to assemble, validate, support, and maintain launch vehicles and payloads (including non-spacecraft payloads) in preparation for flight. Launch systems are considered to be the planetary or lunar surface-based infrastructure and processes used to transition launch vehicles to flight operation.

Autonomous operations technologies (AOT) are required to manage ground and launch systems activities where human intervention/interaction/presence needs to be minimized or eliminated, such as in hazardous locations/operations and in support of remote operations. AOT are required to reduce operations and maintenance (O&M) costs of flight system and payload processing operations on the ground, and to increase ground systems availability to support mission operations. AOT will also be required for extended surface O&M on the Moon and Mars.

AOT performs functions such as system and component fault prediction and diagnostics, anomaly detection, fault detection and isolation, and enables various levels of autonomous control and recovery from faults, where recovery may include system repair and/or reconfiguration. AOT are enabled by Health Management (HM) technologies, methodologies, and approaches; command, monitoring and control architectures; computing architectures; software for decision making and control; and intelligent components and devices.

AOT will be integrated into activities performed by rocket engine test facilities, propellant servicing systems, and processing and launch of vehicles and payloads. AOT will enable surface O&M, which requires a high degree of autonomy and reliability for unattended operations during extended periods of time. AOT will complement in situ resource utilization (ISRU) operations by supporting ISRU ground systems infrastructure with O&M autonomy. AOT enables Autonomous Propellant Management (APM), which requires unattended or minimally attended storage, transfer, monitoring, and sampling of cryogenic propellants, or other propellants used in launch vehicles and maneuvering systems. APM includes preplanned nominal processes, such as vehicle fill and drain, as well as contingency and off-nominal processes, such as emergency safing, venting, and system reconfiguration.

AOT solutions may enable the autonomous command, monitoring, and control of entire integrated systems, such as a propellant loading system and all other associated support systems involved in the loading process. AOT will also support tasks such as systems setup, testing and checkout, troubleshooting, maintenance, upgrades, and repair. These additional tasks drive the need for autonomous element-to-element interface connection and separation, multi-element inspection, and recovery of high-value cryogenic propellants and gases to avoid system losses.

AOT software may include prerequisite control logic (PCL) and reactive control logic (RCL), and may utilize machine learning or other forms of artificial intelligence to manage nominal system behavior and adapt to off-nominal conditions.

In addition to propellants, propellant management systems may utilize additional commodities to prepare a vehicle for launch, such as high-pressure gases for purging, pressurization, or conditioning. Propellant management
systems may also include power and data interfaces with the vehicle to configure vehicle valves or other internal systems and observe vehicle states during propellant management operations.

Specifically, this subtopic seeks the following:

- Development of technologies for automated/autonomous propellant (including cryogenic propellants) management and the servicing of commodities for launch vehicles and payloads.
- Development of high-fidelity physics-based cryogenic-thermal models and ground process simulations capable of real-time and faster than real-time performance.
  - Development of automated/autonomous algorithms for ground systems applications.
  - Machine learning environments (simulation and learning agent) for ground systems processes and applications.
  - Development of high-fidelity models and simulations for complex payload system processing, servicing, maintenance, etc.
  - Development of test and evaluation (T&E), and verification and validation (V&V) methods for automated/autonomous algorithms, models, and simulations.
- Development of technologies for ground systems Health Determination and Fault Management.
  - Prediction, prognosis, and anomaly detection algorithms and applications.
  - Detection, isolation, and recovery of system and component faults and degradation.
  - Development of T&E, and V&V methods for Health Determination and Fault Management algorithms and applications.
- Development of technologies for ground systems Health Determination and Fault Management.
  - Automated/autonomous assets management tools and applications.
  - Scheduling and prioritization algorithms and applications.
  - Human-machine information interactions and intent inferencing.
- Development of technologies for automated/autonomous planning and scheduling (P&S).
  - Use of robotic caretakers for IM&R needs.
  - Self-diagnosis in systems and components to inform condition-based maintenance.
  - Software to aid robotic agents or systems to learn IM&R functionality.
- Development of technologies for enhanced logistics and reliability.
  - Optimization and/or reduction of logistics needs (design for maintainability, commonality, and reusability).
  - Commonality of maintenance equipment, tools, and consumables.
  - Automated/autonomous asset management.
  - Automated/autonomous personnel location and condition determination.
  - Intelligent devices (sensors, actuators, and electronics with self-diagnosis capabilities, calibration on demand, self-healing capabilities, etc.).
- Standardization of architectures and interfaces for ground and launch systems.
- Standardization of ground systems design (design for maintainability, commonality, and reusability).

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I, show a path toward Phase II demonstration and deliver a demonstration package for NASA testing in operational or analog test environments at the completion of the Phase II contract. Successful Phase II technologies will be candidates for integration and demonstration in the existing Advanced Ground Systems Maintenance (AGSM) Integrated Health Management (IHM) Architecture, deployed at Kennedy Space Center (KSC).

Expected TRL or TRL Range at completion of the Project: 5 to 8

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.6 Robotics Integration

Desired Deliverables of Phase I and Phase II:
Desired Deliverables Description:

Phase I deliverables: Research, identify, and evaluate candidate technologies or concepts for systems and components fault detection, isolation and recovery, fault prediction and diagnosis, and decision-making algorithms to enable autonomy of ground systems. Demonstrate technical feasibility and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. It should identify improvements over the current state of the art and the feasibility of the approach in a multicustomer environment. Bench or lab-level demonstrations are desirable. Deliverables shall include a report documenting findings.

Phase II deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions using analog ground systems hardware and processes. Deliverables shall include a report detailing performance testing results, a plan for maturing and applying the technology to mission-worthy systems, and other relevant documentation. Delivery of a functional prototype (software and hardware) is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

State of the Art and Critical Gaps:

There are presently critical gaps between state-of-the-art and needed technology maturation levels as follows:

1. High-fidelity, physics-based, cryogenic-thermal simulations with real-time and faster than real-time performance (Current TRL is 5; Required TRL is 9).
2. Simulation component libraries to support rapid prototyping of cryogenic-thermal models (Current TRL is 5; Required TRL is 9).
3. Supervisory control software for autonomous control and recovery of propellant loading systems and infrastructure (Current TRL is 5; Required TRL is 9).
4. Software development tools to support rapid prototyping of autonomous control applications (Current TRL is 5; Required TRL is 9).
5. Architecture for integrated autonomous operations (Current TRL is 5; Required TRL is 9).

Relevance / Science Traceability:

In addition to reducing O&M costs in ground operations, this subtopic provides Human Exploration and Operations Mission Directorate (HEOMD) with an on-ramp for technologies that enable the unattended setup, operation, and maintenance of ground systems and systems on the surfaces of other planets and moons. The directive from the President to accelerate the timeline for landing astronauts on the Moon, with the goal of a sustainable lunar presence after 2028, has made these technologies even more relevant to mission success. These technology development areas are identified in the 2020 NASA Technology Taxonomy, published by the Office of the Chief Technologist, under TX04 - Robotic Systems, TX10 - Autonomous Systems, and TX13 - Ground, Test, and Surface Systems.

This subtopic also produces technologies useful to the Space Technology Mission Directorate (STMD).

References:

NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html [4])

NASA Strategic Space Technology Investment Plan (https://www.nasa.gov/offices/oct/home/sstip.html [75])
Radioprotectors and Mitigators of Space Radiation-Induced Health Risks

Scope Title:

Radioprotectors and Mitigators of Space Radiation-Induced Health Risks

Scope Description:

Space radiation is a significant obstacle when sending humans on long-duration missions beyond low Earth orbit. Although various forms for radiation exist in space, astronauts during Lunar or Mars missions will be exposed constantly to galactic cosmic radiation (GCR), which consists of high-energy particles ranging from protons to extremely heavy ions. Astronaut health risks from space radiation exposure are categorized into cancer, late and early central nervous systems (CNS) effects, and degenerative risks, which include cardiovascular diseases (CVD) and premature aging. With the current gender and age-specific exposure limits for cancer risks, few female astronauts will be able to fly long-duration missions without countermeasures.

This subtopic solicits proposals to develop biological countermeasures that mitigate one or several of the radiation risks associated with space travel. Compounds that target common pathways (e.g., inflammation) across aging, cancer, cardiovascular disease, and neurodegeneration would be preferred. Most of the countermeasure developments in the medical arena have focused on mitigating the effects of X- or gamma rays. The proposed project should focus on repurposing of technology and compounds for high-energy charged-particle applications. Compounds that are under current development or have been proven effective for other applications are both suitable for this subtopic.

Expected TRL or TRL Range at completion of the Project: 5 to 8
Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.5 Radiation

Desired Deliverables of Phase I and Phase II:

- Analysis

Desired Deliverables Description:

Deliverables for Phase I of the project will be data generated in testing the proposed radioprotectors with high energy protons. The company should test the proposed radioprotectors using high energy protons or other charged particles at space relevant doses. This testing can be performed with cell models at an accelerator facility of choice. After contract award, the company should immediately coordinate with the NASA technical monitor for any special considerations for the testing.

In Phase II of the project, the company should conduct in vivo evaluation of the radioprotectors using appropriate animal models, which may include humanized mouse models. Testing in Phase II of the project should be performed with a combination of different particle types and energies that simulate the space radiation environment. NASA will make the accelerator facility at the Brookhaven National Laboratory available for both Phase I and II of the project. Demonstration of the effectiveness in reducing proton-induced biological impacts is needed for a successful Phase II proposal.

Deliverables for Phase II of the project will be data generated using animal models and a
combination of charged particle types and energies.

**State of the Art and Critical Gaps:**

Exposure of crew members to space radiation during Lunar and Mars missions can potentially impact the success of the missions and cause long-term diseases. Space radiation risks include cancer, late and early CNS effects, CVD, and accelerated aging. Abiding by the current exposure limits for cancer risks, few female astronauts will be able to fly long-duration missions. Mitigation of space radiation risks can be achieved with physical (shielding) and biomedical means. This subtopic addresses development of drugs that mitigate one or several of the identified space radiation risks. Development of countermeasures for adverse health effects from radiation exposure is also actively supported by the Department of Defense (DOD), Department of Homeland Security (DHS), and the National Institute of Health (NIH). However, some of the radioprotectors used in radiotherapy might have toxic levels that are unacceptable for astronauts. Some of the countermeasures developed for DOD/DHS are aimed at mitigating acute radiation syndromes, but not cancer risks. Furthermore, these radioprotectors are mostly for exposure to X- or gamma rays. This SBIR subtopic solicits specifically proposals to evaluate the radioprotectors that have been proven effective in mitigating biological impacts of X- or gamma rays for space radiation applications.

**Relevance / Science Traceability:**

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Biomedical countermeasures are needed for all of the space radiation risks.

**References:**

The following references discuss the different health effects NASA has identified in regard to space radiation exposure:

- Evidence report on central nervous systems effects: [https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf](https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf) [76].
- Evidence report on degenerative tissue effects: [https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf](https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf) [77].
- Evidence report on carcinogenesis: [https://humanresearchroadmap.nasa.gov/evidence/reports/Cancer.pdf](https://humanresearchroadmap.nasa.gov/evidence/reports/Cancer.pdf) [78].

**H12.03 Portable Spatial Disorientation Simulator - Trainer**

**Lead Center:** JSC

**Scope Title:**

Portable Spatial Disorientation Simulator - Trainer

**Scope Description:**

Astronauts are at risk of spatial disorientation due to vestibular alterations during and following g-level transitions, such as landing on Earth. This disorientation has previously
been simulated using a bilateral bipolar Galvanic vestibular stimulation (GVS) delivered in a suprathreshold range (2 to 5 mA) over the mastoid processes independent of head orientation. NASA needs a portable GVS-based system that can be coupled to head orientation and movements to enhance the simulation of the g-transition induced spatial disorientation effect astronauts experience.

This system will be used for astronaut crewmembers to simulate performing landing and recovery type tasks while experiencing head-tilt contingent vertigo due to vestibular alterations. This simulator will also be used by recovery operations personnel to validate nominal and contingency procedures with a simulated deconditioned crewmember. Finally, this disorientation simulator will be used experimentally to develop sensorimotor standards related to fitness to perform critical mission tasks.

The requirements include:

- Phase 1A head-worn inertial measurement unit (IMU) sensor that can measure natural head rotation (position and velocity) and linear acceleration in all three planes.
- A GVS that is head-coupled and proportional to head tilt orientation as well as pitch and roll velocity, with the ability to adjust the algorithms to alter the IMU sensor combinations that drive the GVS signal.
- The system should also allow a user-adjustable manual gain to allow for individual sensitivity, with minimal two-fault current limit at 5 mA and emergency on/off switch.
- The system should allow a two-channel multiple electrode configuration that can provide illusory motion in both head roll and pitch axes.
- The system should be self-powered for minimally 1 hr with user switchable rechargeable batteries.
- The system should include nonvolatile memory (onboard data storage) to record IMU sensor data, GVS current delivery, and external trigger and/or manual synch event push-button timing.
- This system should be able to be worn while performing nonsuited crew landing and egress type activities without interfering with other crew-worn equipment.

**Expected TRL or TRL Range at completion of the Project:** 2 to 6

**Primary Technology Taxonomy:**
- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.6 Human Systems Integration

**Desired Deliverables of Phase I and Phase II:**

- Prototype

**Desired Deliverables Description:**

Phase I deliverable is a laboratory version of the disorientation trainer that successfully demonstrates the proof of concept for the requirements listed under scope description have been met.
Phase II deliverable is a portable wearable version of the disorientation trainer that can be deployed in field settings.

State of the Art and Critical Gaps:

While there are GVS available, there are no GVS devices on the market that are portable or that can be coupled to head movement. This capability would provide the ability to train astronauts on what to expect with regards to spatial disorientation in a realistic mission simulation.

Relevance / Science Traceability:

This is relevant to Human Exploration and Operations Mission Directorate (HEOMD), because of its applicability in human research and exploration. For example, this technology would assist in the success of the sensorimotor standards project, sponsored by NASA's Human Research Program.

References: