NASA SBIR 2021 Phase I Solicitation

Space Technology

Z1.05 Lunar and Planetary Surface Power Management and Distribution

Lead Center: GSFC

Participating Center(s): GSFC, JSC

Scope Title:

Innovative Ways to Transmit Power Over Long Distances for Lunar and Mars Missions

Scope Description:

The Global Exploration Roadmap (January 2018) and the Space Policy Directive (December 2017) detail NASA’s plans for future human-rated space missions. A major component of these plans involves establishing bases on the lunar surface for sustained presence and a new transportation capability and surface assets for a human exploration mission to Mars. Surface power generation on planetary surfaces is envisioned to require 10 to 50 kW to be efficiently transmitted distances greater than 1 km to remotely located mission elements such as habitat modules, landers, ascent vehicles, etc. While current state-of-the-art space power systems are similar in power level (e.g., the International Space Station), the transmission distances are only 10s of meters, so new high-power, high-voltage and/or new power-beaming technologies are sought to enable surface power transmission over long distances. Examples of the innovative technologies sought are lower mass/higher efficiency power electronic regulators, switchgear, cabling, connectors, wireless sensors, power beaming, power scavenging, and power management control. The technologies of interest would need to operate in extreme-temperature environments, including lunar night, and could experience temperature changes from -153 to 123 °C for lunar applications, and -125 to 80 °C for Mars bases. In addition to temperature extremes, technologies would need to withstand (have minimal degradation from) lunar dust/regolith, Mars dust storms, and space radiation levels.

In addition, new human Mars transportation capabilities are expected to require multiple channels of 100 kW or more to be efficiently transmitted 100s of meters from an
alternating current (AC) power generator to multiple electric thrusters requiring high-voltage direct-current (DC) power. Technologies sought include high-performance rotary alternators, high-performance transformers, rectifiers, and cabling.

While this subtopic would directly address the lunar and Mars base initiatives, technologies developed could also benefit other NASA Mission Directorates, including SMD (Science Mission Directorate) and ARMD (Aeronautics Research Mission Directorate). Specific projects that could find value in the technologies developed herein include Gateway, In Situ Resource Utilization (ISRU), Advanced Modular Power Systems (AMPS), In-Space Electric Propulsion, Planetary Exploration, and Hybrid Gas-Electric Propulsion. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes and the need for electronics with higher power density and efficiency.

Specific technologies of interest would include:

- Application of wide band-gap electronics in DC-DC isolating converters with wide temperature (-70 to 150 °C), high power density (>2 kW/kg), high-efficiency (>96%) power electronics and associated drivers for voltage regulation.
- Low-mass, highly conductive wires and terminations that provide reliable small gauges for long-distance power transmission in the 1 to 10 kW range, low-mass insulation materials with increased dielectric breakdown strength and void reductions with 1,000 V or greater ratings, and low-loss/low-mass shielding.
- Power-beaming concepts to enable highly efficient flexible/mobile power transfer in the 100 to 1,000 W range, including the fusion of power, communication, and navigation.
- Power generation and distribution components of a 3-phase/1,200-Hz permanent magnet alternator, 480 VAC to 650 VDC power management, and distribution with direct drive to Hall thrusters. Key components of the distribution include high-performance rotary alternators and AC transmission technologies, including alternator voltage, step-up/step-down transformers, rectifiers, and power cabling.

Note: to propose power connection/termination-related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically enabled high-voltage connectors and/or near-field wireless power transfer in the 1 to 10 kW range, see subtopic titled Dust-Tolerant Mechanisms.

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

**Primary Technology Taxonomy:**
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.3 Power Management and Distribution
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Typically, deliverables under Phase I proposals are geared toward a technology concept with associated analysis and design. A final report usually suffices in summarizing the work, but if a prototype is preferred. Phase II hardware prototypes will have opportunities for infusion into NASA technology testbeds and commercial landers.

State of the Art and Critical Gaps:

While high-power terrestrial distribution systems exist, there is no equivalent to a lunar or planetary base. Unique challenges must be overcome in order to enable a realistic power architecture for these future applications, especially when dealing with the environmental extremes that will be encountered. The temperature swings will be a critical requirement on any technology developed, from power converters to cabling or power-beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms. To enable a new Mars transportation capability for human exploration, new technology development must be started soon to address the very unique needs of a mixed AC/DC space-rated power system to prove feasibility and provide realistic performance metrics for detailed vehicle design concepts and mission trade studies.

Relevance / Science Traceability:

This subtopic would directly address a remaining technology gap in the lunar and Mars surface mission concepts and Mars human transportation needs. There are potential infusion opportunities with SMD (Science Mission Directorate) Commercial Lander Payload Services (CLPS) and HEOMD (Human Exploration and Operations Mission Directorate) Flexible Lunar Exploration (FLEx) Landers. In addition, technologies developed could benefit other NASA missions, including Gateway. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes.

References:

The Global Exploration Roadmap, January 2018: [https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf][1]


Z1.06 Radiation-Tolerant High-Voltage, High-Power Electronics

Lead Center: GSFC

Participating Center(s): GRC, JPL, LaRC

Scope Title:

Radiation-Tolerant High-Voltage, High-Power Electronics

Scope Description:
NASA’s directives for space exploration and habitation require high-performance, high-voltage transistors and diodes capable of operating without damage in the natural galactic cosmic ray space radiation environment. Recently, significant progress has been made in the research community in understanding the mechanisms of heavy-ion-radiation-induced single-event-effect (SEE) degradation and catastrophic failure of wide bandgap (WBG) power transistors and diodes. This subtopic seeks to facilitate movement of this understanding into the successful development of radiation-hardened high-voltage transistors and rectifiers to meet NASA mission power needs reliably in the space environment. These needs include:

- **High-voltage, high-power solutions**: Taxonomy Area (TX) 03.3.4, Power Management and Distribution (PMAD) - Advanced Electronic Parts, calls out the need for development of radiation-hardened high-voltage components for power systems. NASA has a core need for diodes and transistors that meet the following specifications:
  - Diodes: minimum 1200 V, 40 A, with fast recovery <50 ns. Forward voltage drop should not exceed 150% of that in state-of-the-art unhardened diodes.
  - Transistors: minimum 650 V, 40 A, with <24-mohm on-state drain-source resistance.

- **High-voltage, low-power solutions**: In support of TX 8.1.2 (Sensors and Instruments - Electronics), radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.
  - Transistors: minimum 1000 V, <40-ns rise and fall times
  - Diodes: 2 kV to 5 kV, <50-ns recovery time. Forward voltage drop should not exceed 150% of that in state-of-the-art unhardened diodes.

- **High-voltage, low- to medium-power solutions**: In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
  - Transistors: minimum 600 V, <50-ns rise and fall times, current ranging from low to >20 A.

Successful proposal concepts should result in the fabrication of transistors and/or diodes that meet or exceed the above performance specifications without susceptibility to damage due to the galactic cosmic ray heavy-ion space radiation environment (SEEs resulting in permanent degradation or catastrophic failure). These diodes and/or transistors will form the basis of innovative high-efficiency, low-mass and low-volume systems and therefore must significantly improve upon the electrical performance available from existing heavy-ion SEE radiation-tolerant devices.
Other innovative heavy-ion SEE radiation-tolerant, high-power, high-voltage discrete device technologies will be considered that offer significant electrical performance improvement over state-of-the-art heavy-ion SEE radiation-tolerant power devices.

**Expected TRL or TRL Range at completion of the Project:** 4 to 5

**Primary Technology Taxonomy:**
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.3 Power Management and Distribution

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

- Hardware
- Prototype
- Analysis

**Desired Deliverables Description:**

Phase I deliverables must state the initial state of the art for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle:

- For vertical-field power devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident linear energy transfer (LET) of 40 MeV-cm²/mg and sufficient energy to maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident LET of 75 MeV-cm²/mg and sufficient energy to fully penetrate the active volume prior to the ions reaching their maximum LET value (Bragg peak).

Deliverables in Phase II shall include prototype and/or production-ready semiconductor devices (diodes and/or transistors); and device electrical and radiation performance characterization (device electrical performance specifications, heavy-ion SEE radiation test results, and total-dose radiation analyses).

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

High-voltage silicon power devices are limited in current ratings and have limited power efficiency and higher losses than do commercial WBG power devices. Efforts to space-qualify WBG power devices to take advantage of their tremendous performance advantages revealed that they are very susceptible to damage from the high-energy, heavy-ion space radiation environment (galactic cosmic rays) that cannot be shielded...
against. Higher voltage devices are more susceptible to these effects; as a result, to date, there are space-qualified GaN transistors now available, but these are limited to 300 V. Recent radiation testing of 600-V and higher GaN transistors has shown failure susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of their rated voltage.

Specific needs in STMD (Space Technology Mission Directorate) and SMD (Science Mission Directorate) areas have been identified for spacecraft power management and distribution (PMAD), and science instrument power applications and device performance requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative solution that can provide the mass and power savings sought to enable game-changing capability. Current PPUs (power processing units) and instrument power systems rely on older silicon technology with many stacked devices and efficiency penalties. In NASA's move to do more with less (smaller satellites), and its lunar/planetary habitation objectives requiring tens to 100 kW power production, the technology sought by this subtopic is truly enabling.

State-of-the-art, currently available heavy-ion SEE-tolerant silicon power devices include a Schottky diode capable of 600 V, 30 A, and 27-ns recovery time, and a power MOSFET capable of 650 V, 8 A, with on-state resistance of 450 mohm. Commercial (non-SEE tolerant) SiC and GaN offerings are available that meet the electrical performance needs indicated in this subtopic, but that cannot meet the heavy-ion SEE requirements indicated. At this time, there are no publicly available data on the heavy-ion SEE performance of Ga$_2$O$_3$ or diamond power devices.

**Relevance / Science Traceability:**

Power transistors and diodes form the building blocks of numerous power circuits for spacecraft and science instrument applications. This subtopic therefore feeds a broad array of space technology hardware development activities by providing SEE (heavy-ion) radiation-hardened state-of-the-art device technologies that achieve higher voltages with lower power consumption and greater efficiency than presently available.

Taxonomy Area (TX) 03.3.4, Power Management and Distribution (PMAD) - Advanced Electronic Parts, calls out the need for development of radiation-hardened high-voltage components for power systems. This subtopic serves as a feeder to the subtopic Lunar and Planetary Surface Power Distribution, in which WBG circuits for PMAD applications are solicited. The solicited developments in this subtopic will also feed systems development for the NASA Kilopower project due to the savings in size/mass combined with radiation hardness.

TX 08.1.2, Sensors and Instruments - Electronics: Radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and
electrostatic analyzers. These applications are aligned with science objectives including Earth science LIDAR needs, Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to planetary and asteroid research and in the search for life on other planets such as Mars require high-voltage power systems and will thus benefit from mass and power savings from this subtopic's innovations.

References:

Partial listing of relevant references:

Megawatt-Class Nuclear Power System

Scope Description:

Recent Mars transportation assessments identify megawatt-class nuclear electric propulsion (NEP) systems as a reasonable approach for use in a crewed mission to Mars. A critical subcomponent of the reference NEP concept is a dynamic thermal-to-electric power convertor. Dynamic power convertors are needed that address the following technical challenges:

- Robust, efficient, high-reliability, long-life thermal-to-electric power conversion and controller technology in the minimum range of 100 to 500 kWe. Brayton, Rankine, and Stirling convertors are of primary interest. Multiple parallel/redundant convertors may be used to achieve the megawatt-class power level.
  - Includes subcomponents such as efficient turbomachinery, bearings, alternators, recuperators, and heat exchangers.
- Convertors must be capable of interfacing with pumped liquid-metal loops: one for thermal energy input and one for heat rejection.

In addition, liquid metal pumps that address the following technical challenges are also needed:

- Can operate for long periods of time (years) at relevant in-space (in vacuum and zero g) reactor/power generation temperatures.
- Can withstand liquid metal freeze-thaw transition during initial reactor startup in zero g.
- Low mass and high efficiency at fluid throughputs that are relevant for in-space nuclear power generation.
- Wetted surfaces of the pump composed of materials that are compatible with liquid metals under consideration for in-space nuclear power generation (NaK, Li, etc.).

The desired deliverables are primarily prototype hardware, research, and analysis to demonstrate concept feasibility and a Technology Readiness Level (TRL) range of 3 to 5. There is a strong desire for hardware that can operate or has a clear path for operation in the relevant space environment. The specified higher power levels are of priority, but demonstrations at lower power levels may be considered as long as the scaling to higher power levels is straightforward and does not require significant new technology or configuration change. The prototype hardware may include one (or more) of the following:

- Power convertor (hot-end temperature = 850 °C, cold-end temperature = 100 to 200 °C).
- Controller electronics.
- Convertor subcomponent(s).
- Liquid metal pump and/or subcomponent(s).

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.1 Power Generation and Energy Conservation
Desired Deliverables of Phase I and Phase II:
 Desired Deliverables Description:

The desired deliverables for Phase I include monthly progress reports and a comprehensive final report.

For Phase II, the primary interest is component and/or breadboard hardware that demonstrates concept feasibility in a laboratory or relevant environment. The appropriate research and analysis required to develop the hardware are also desired. The Phase II deliverables should include hardware, monthly progress reports, and a comprehensive final report.

State of the Art and Critical Gaps:

Multikilowatt electric propulsion systems are well developed and have been used on commercial and military satellites for several years. Higher power electric propulsion systems are currently being considered to support crewed missions to near-Earth asteroids and as cargo transport for sustained lunar or Mars exploration, and for very high power crewed missions to Mars and the outer planets. One of the key technologies required in a NEP system is the power convertor. A recent Mars Transportation Assessment Study was completed that included Brayton, Stirling, Rankine, thermoelectric, and thermonic technologies in the trade space. The study identified HeXe Brayton as the baseline dynamic power convertor in the reference NEP concept, with supercritical CO$_2$ Brayton and K-Rankine as the primary options. Current state-of-the-art Brayton technology has been demonstrated in a relevant space environment (ground test) in the 10s of kWe range. Convertor scaleup to the 100s of kWe per unit is required.

Relevance / Science Traceability:

This technology directly aligns with the Space Technology Mission Directorate (STMD) roadmap for space power and energy storage.

References:


Z2.01 Spacecraft Thermal Management

Lead Center: JSC

Participating Center(s): GRC, GSFC, JPL, MSFC
Scope Title:
Spacecraft Thermal Management

Scope Description:

NASA seeks new technologies that will facilitate low-mass and highly reliable thermal control systems for the exploration of our solar system. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:

- Novel three-way valves that can operate to either mix or split single-phase fluid flow passively.
- Lunar lander/surface asset thermal technologies.
- Embedded cooling of power electronics.
- Concepts for closed-loop extravehicular activity (EVA) thermal systems.

These areas are considered of equal priority, and no award preference is expected for one area over another.

Passive Three-Way Valves

NASA seeks novel three-way valves that can operate as either a mixing valve (two liquid input ports and one liquid output port) or splitting valve (one liquid input port and two liquid output ports) that can be used to passively control loop temperatures by the degree fraction of radiator bypass. Such miniature passive thermal control valves could find use in a number of single-phase mechanically pumped fluid thermal control systems. Proposed technologies must address the following design goals:

- Design shall autonomously operate without power.
- <0.1% flow rate through the shutoff port, with a goal of having a provision for no leakage/adjustable leakage through the use of a pre-installed orifice.
- Control range of 5 to 10 °C, with pre-adjustable setpoint control.
- Operational temperature limits -55 to 90 °C, nonoperational limits of -55 to 125 °C.
- Designs shall be compatible with FC-72 working fluid as well as with those used on the International Space Station (ISS) thermal control loops (water and ammonia). Retrofit of soft goods is acceptable.
- Mass desired <250 g (maximum mass 500 g).
- Unit volume <50 cm³ (maximum 100 cm³).
- Leak rate 1×10⁻⁶ scc/s gHe at 200 psia.
- Minimum 4,000 full actuation cycles, desired 17,500 cycles.
- Rad hard to 300 krad.
- 200 psia maximum expected operating pressure, 200 psia proof pressure, 800 psia burst pressure.
Lunar Surface Thermal Technology Development

NASA is seeking focused efforts to develop large human-class lunar lander technologies. Technologies should address a gap associated to long-duration habitation on the lunar surface, where temperatures range from -193 °C or lower in shadow regions (including night) to 120° C at the equatorial subsolar point. System technologies should be orientation insensitive; for example, lander side-mounted radiators must provide their function regardless of lunar surface temperature condition. Technologies are needed that allow a single vehicle design to operate in all these environments. Technologies should address reduction in mass, volume, and power usage relative to current solutions. Adding heaters can lead to increased vehicle mass due to additional power generation and storage requirements and are not considered a novel architecture approach. Proposed radiator technologies should also address micrometeoroid and orbital debris (MMOD) robustness and protection potential where appropriate.

Examples of other challenges to address in this area include the deposition of dust on radiators leading to degraded optical properties, contamination-insensitive evaporators/sublimators to enable long mission life, and self-healing coolant tubes for MMOD-impact resilience. Technologies should be suitable for use in medium-sized landers that operate near 1-kW average heat dissipation capacity.

Alternatively, technologies that utilize the conditions provided by the lunar environment to provide a critical function may also be considered; for example, air-water separator technologies that leverage the gravity field of the lunar surface, or concepts that explore the viability of utilizing the lunar surface regolith to provide long-duration thermal control function. As appropriate, such systems should also address functional capability in the microgravity environment that will be experienced prior to lunar surface operations.

Proposed technologies should also be extensible to human-class landers that will have variable heat loads and average loads between 2 and 6 kW. All technologies should support a minimum flight duration of 5 years and be compatible with the encountered aerospace environment.

This subtopic is different from S3.06 subtopic, which is focused on thermal control technologies for payloads and smaller robotic landers. Technologies directly applicable to that scale vehicle should consider reviewing the S3.06 Thermal Control Systems subtopic.

Embedded Cooling of Power Electronics

To optimize the performance of state-of-the-art power and propulsion systems, it is often advantageous to directly embed thermal control mechanisms within the packaged hardware. The key advantages are to enable a lower temperature drop between the
heat source and heat rejection to allow for higher rejection temperatures, to remove heat from concentrated areas (avoid localized hot spots), and to provide more uniform temperatures within the electronics package. Applications for such technologies range from very high power nuclear electric propulsion (NEP) systems, to compact laser diodes, to embedded cooling of rotating equipment. Here we specifically desire concepts that have the potential to efficiently manage high-performance power electronics in common compact packages.

At the device level, applications such as low-inductance GaN packages rely on low thermal impedance heat-sinking strategies which also facilitate mechanical compliance and often electrical isolation. Current state-of-the-art thermal gap fillers have functional thermal impedances of 1.5 to 11 K/W for 12-mm\(^2\) GaN devices with thermal transfer of 200 to 400 mW/mm\(^2\) [Ref. 6]. Solutions that improve these thermal impedances values by >50% are sought.

At the system level, NASA has interest in the cooling of standard 3U boards to assist in the Advanced Modular Power Systems (AMPS) program. This program calls for semiconductor to circuit board power transfer of >200 mW/mm\(^2\), circuit board to backplane interface >5mW/mm\(^2\), and backplane interface through wedgelock rail >15 mW/mm\(^2\) with minimum thermal impedance [Ref. 7].

Example solutions include but are not limited to single-phase liquid jet cooling, heat pipes, and evaporation techniques. Any proposed solution should consider the material compatibility with the heat source and heat delivery to the vehicle’s primary active thermal control system as well as any adverse effects on the cooled electronics. Here, solutions may consider integration with either a traditional single-phase (liquid) vehicle active thermal loop or a two-phase (liquid-vapor) mechanically pumped active thermal loop. Power requirements to operate active systems must be addressed with the goal to minimize power. The transient performance of the proposed mechanism should be considered within the scope of the award in order to identify any key limitations of the design.

Closed-Loop EVA Thermal Technologies

EVA thermal control has traditionally relied on the dissipation of water to space. The current suit relies on a water sublimator, whereas the next-generation exploration spacesuit will include a water evaporator. In either case, water is consumed at an average rate of ~1 lb/hr over the course of the spacewalk. Here, NASA seeks novel closed-loop EVA thermal control technologies that have general potential for integration into future iterations of spacesuit design.

Concepts should address the following key performance parameters, at a minimum:

- Nominal average heat rejection >350 W.
• Accommodate peak heat rejection of at least 700 W for 15 min, with little or no consumable loss.
• Support EVA duration of at least 4 hr, stretch goal of 8 hr.
• Demonstrate viability of integration with the liquid cooling garment operating at a minimum continuous temperature between 8 and 10 oC.
• Time to regenerate/recharge the system <12 hr.
• Any regeneration/recharge impacts to the spacecraft should be addressed within the scope of the award (vehicle mass, power, volume impact assessment).
• Mechanism power <20 W including any controller electronics.

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

**Primary Technology Taxonomy:**
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.2 Thermal Control Components and Systems

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

• Analysis
• Prototype
• Hardware
• Software

**Desired Deliverables Description:**

Phase I awards in this area are expected to demonstrate analytical and/or empirical proof-of-concept results that demonstrate the ability of the organization to meet the goals stated in the solicitation.

At the conclusion of a Phase II contract, deliverables are expected to include a functioning prototype (or better) that demonstrates the potential to meet the performance goals of the technology. Any delivered math models should include supporting data that validates the assumptions used within the model.

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

These focus areas strive to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human-class spacecraft. Additionally, the exploration of embedded thermal control technologies may have a direct impact on the AMPS program in the near term and provide valuable insight into techniques for other embedded cooling applications. These improvements may come through either novel hardware solutions or modernization of software tools used to assess human vehicle interactions. The current state of the art in thermal control results in vehicle power and mass impact of greater than 25% to 30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.), the need for intelligent control (both actively and passively) within the thermal control system becomes more apparent. Science payloads will continue to decrease in size, increase in power, and require precise temperature control, all of which cannot be readily provided by traditional thermal control methods due to vehicle-level impacts of overall performance, mass/volume, and power.
Relevance / Science Traceability:

- Advanced Modular Power System
- Europa Clipper/Lander
- Lunar Lander
- Long-duration habitats (Moon, Mars, etc.)
- EVA

References:


Z2.02 High-Performance Space Computing Technology
Lead Center: JPL
Most current NASA missions utilize 20-year-old space computing technology that is inadequate for future missions. Newer processors with improved performance are becoming available from industry but still lack the performance, power efficiency, and flexibility needed by the most demanding mission applications. The NASA High-Performance Spaceflight Computing (HPSC) project is addressing these needs. This subtopic solicits technologies that can enable future high-performance, multicore processors, along with the supporting technologies needed to fully implement avionics systems based on these processors.

- Runtime system software security: Software support to enable secure boot, signed applications, and runtime system monitoring is needed to ensure the integrity of onboard, real-time computing systems.
- Compilers that support software-implemented fault tolerance (SIFT) capabilities (e.g., control flow checking, coordinated checkpoint/rollback, recovery block) for multicore processors are desired.
- Technologies are needed to enable radiation-tolerant and fault-tolerant onboard networks with >10 Gbps bandwidth per lane, including intellectual property (IP) cores for endpoints and switches, software stack, and verification and test tools.
- A fault-tolerant RISC-V processor IP core is needed that is augmented to provide data parallelism, which is needed to accelerate image processing and science data processing.
- Solid-state data recorders are needed that are suitable for operation in the space environment, support the space extensions to Serial Rapid IO, and have redundant interfaces.

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

**Primary Technology Taxonomy:**
- Level 1: TX 02 Flight Computing and Avionics
- Level 2: TX 02.X Other Flight Computing and Avionics

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

**Desired Deliverables Description:**
Phase I Deliverables:
For software and hardware elements, a solid conceptual design, plan for full-scale prototyping, and simulations and testing results to justify prototyping approach. Detailed specifications for intended Phase II deliverables.

Phase II Deliverables:
For software and hardware elements, a prototype that demonstrates sufficient performance and capability and is ready for future development and commercialization.

State of the Art and Critical Gaps:
Most NASA missions utilize processors with in-space qualifiable high-performance computing that has high power dissipation (approximately 18 W), and the current state of practice in Technology Readiness Level 9 (TRL-9) space computing solutions have relatively low performance (between 2 and 200 DMIPS (Dhrystone million instructions per second) at 100 MHz). A recently developed radiation-hardened processor provides 5.6 GOPS (giga operations per second) performance with a power dissipation of 17 W. Neither of these systems provide the performance, the power-to-performance ratio, or the flexibility in configuration, performance, power management, fault tolerance, or extensibility with respect to heterogeneous processor elements. Onboard network standards exist that can provide >10 Gbps bandwidth, but not everything is available to fully implement them.

Relevance / Science Traceability:
The HPSC ecosystem is enhancing to most major programs in the Human Exploration and Operations Mission Directorate (HEOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by HEOMD, including the Safe and Precise Landing - Integrated Capabilities Evolution (SPLICE) project. Within the Science Mission Directorate (SMD), strong mission pull exists to enable onboard autonomy across Earth science, astrophysics, heliophysics, and planetary science missions. There is also relevance to other high-bandwidth processing applications within SMD, including adaptive optics for astrophysics missions and science data reduction for hyperspectral Earth science missions.

References:


and Metal Recycling Technologies for On-Orbit Manufacturing

Lead Center: GSFC

Participating Center(s): GSFC, LaRC

Scope Title:

Development of Advanced Joining Technologies for On-Orbit Manufacturing

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material welding capability is an important supporting technology for the long-duration, long-endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically, structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. An in-space welding capability will greatly reduce constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures. Welding is an essential complementary capability to large-scale additive manufacturing technologies being developed by NASA and commercial partners. Welding is also a critical capability for repair scenarios (e.g., repair of damage to a structure from micrometeorite impacts).

This subtopic seeks innovative engineering solutions to robotically weld materials, both fully autonomous and semiautonomous, for manufacturing in the unpressurized space environment. Current state-of-the-art (SOA) terrestrial welding methods such as laser beam, electron beam, and friction stir should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for on-orbit manufacturing applications. Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors. The need to repair a damaged structure or build new structures may require the need to not only weld material but to cut and remove material. A process that can weld material is the priority, but a robust process with cutting and removal capabilities adds value. The Phase I effort should provide a laboratory demonstration of the welding process and its applicability to aerospace-grade metallic materials and/or thermoplastics, focusing on joint configurations that represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios—for example, repair of a metal panel following micrometeorite damage, longitudinal welding of two metal curved panels, and welding of a truss to an adjacent truss. The Phase I effort should also provide an assessment of the proposed process operational capabilities (e.g., classes of materials that can be welded with the process, joint configurations that can be accommodated, and any expected impacts of the microgravity environment on joint efficiency relative to terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be welded may also be included in the Phase I effort.

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

Primary Technology Taxonomy:

Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I requires laboratory demonstration/proof of concept that (a) the system enables high-value applications of repair and assembly and (b) the system shows potential for being operated remotely with very little intervention/setup. A preliminary design and concept of operations are also deliverables under Phase I.

Phase II includes finalization of the design and demonstration of a ground-based prototype system.

Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Exploration Crew Module (ECM), Gateway, OSAM-1, OSAM-2, lunar lander payload, or as a free-flyer.

State of the Art and Critical Gaps:

Unpressurized environment in-space manufacturing has primarily focused on fabrication of structures in the space environment. Welding is an essential supporting technology to these capabilities. Research on welding tapered off to some extent following the cancellation of the In-Space Welding Experiment (ISWE) for the space shuttle. With the emergence of the OSAM initiative, a renewed interest and focus on manufacturing structures in the space environment as an enhancing capability for long-duration missions, and as a way to remove design constraints imposed by payload fairings and launch loads, additional work on development of an in-space welding capability should be a priority. In-space welding represents an essential complementary technology to in-space fabrication techniques.

Relevance / Science Traceability:

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module (ECM), Gateway, Lunar Base Camp, OSAM-1 and OSAM-2, in-Space Assembled Telescope (iSAT) and SmallSat.

References:


Scope Title:

Development of Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM)
for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

The ability to additively manufacture large-scale structures in-space is an enabling capability needed to fully realize the game-changing impacts of OSAM. Current state-of-the-art (SOA) on-orbit manufacturing systems are constrained to a build volume similar to terrestrial additive manufacturing processes, and others are focused on linear beam and truss designs. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. Large-scale, free-form additive manufacturing capabilities can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures.

This subtopic seeks innovative engineering solutions to fabricate and/or repair large structures, using fully autonomous or semi-autonomous systems, in the unpressurized space environment. Current SOA terrestrial large-scale additive manufacturing processes such as wire-fed directed energy deposition, pellet-fed extruder systems, and additive friction stir deposition should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic large-scale additive manufacturing process and system for unpressurized in-space manufacturing applications. Targeted applications for this technology include fabrication of truss structures, build-up of structural material for retrofitting spent tanks to habitat modules, and/or solar array back planes. Additional targeted applications include the repair of structures such as spacecrafts and/or payloads damaged during the ascent stage, habitat modules with micrometeoroid impact, and out-of-service components due to unforeseen circumstances and/or scheduled repairs. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace-grade metallic materials, focusing on structures that represent the priority in-space manufacturing applications identified above. Work under Phase I will inform preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment. The Phase I effort should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Gateway, OSAM-1, OSAM-2, a lunar lander payload, or as a free-flyer.

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

**Primary Technology Taxonomy:**
- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.4 Manufacturing

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

- Prototype
- Analysis
- Hardware
Desired Deliverables Description:

Phase I requires a demonstration/proof of concept that (a) the system enables high-value applications of in-space fabrication of large-scale structures and (b) the system shows potential for being operated remotely with very little intervention/setup. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace-grade metallic materials, focusing on structures that represent the priority in-space manufacturing applications identified above. The Phase I effort should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase II includes finalization of the design and demonstration of a ground-based prototype system including autonomous capability.

Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Gateway, OSAM-1, OSAM-2, a lunar lander payload, or as a free-flyer.

State of the Art and Critical Gaps:

Unpressurized structure in-space manufacturing has primarily focused on fabrication of 3D-printed truss structures and beams. The OSAM-1 and OSAM-2, funded by the STMD (Space Technology Mission Directorate) Technology Demonstration Mission Program, are planning the demonstration of 3D-printed truss structures and beams. The technology advancement to multiple degrees of freedom, large-scale fabrication of structures is a priority for on-orbit manufacturing.

Relevance / Science Traceability:

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module, Gateway, Lunar Base Camp, OSAM-1, OSAM-2 and In-Space Assembled Telescope (iSAT).

References:


Scope Title:

Development of Metal Recycling Processes for On-Orbit Manufacturing

Scope Description:

Deep space missions will require a shift in the logistics paradigm to enable reuse and recycling of materials. Recycling is a significantly enhancing capability for space missions and would enable what would otherwise be nuisance material (spent components, waste items) to be utilized as feedstock for further manufacturing. This subtopic seeks innovative engineering solutions to facilitate recycling of metals commonly used in space systems in either an intravehicular (IVA) or extravehicular (EVA) environment. In an IVA use scenario, technologies might be used inside a habitat to process spent components by breaking down the structure, generating chips, and consolidating the chips into feedstock that can be used to generate new components through various in-space manufacturing processes. In an EVA use scenario, recycling technologies might be used to take metal material
scavenged from large structures (such as space habitats, satellites, and spent upper stages) and reprocess it into material feedstock for on-orbit servicing, assembly, manufacturing, and repair applications. High-value materials for metal recycling include those commonly used in large-scale space structures and components of space systems: aluminum alloys, stainless steel, and titanium.

Current state of the art (SOA) includes metal recycling technologies commonly applied in industry (e.g., shredding, melting, solidification), but these must be modified to fit the physical footprint, power, and mass requirements for on-orbit applications. For an IVA environment, the system for initial demonstration would be constrained to an EXPRESS* rack, occupying some portion of its 0.45-m³ volume. An EXPRESS rack is designed to support up to eight individual payloads, each occupying one EXPRESS locker (each locker has an internal volume of approximately 0.057 m³, with the total rack of eight lockers providing in excess of 0.45 m³ of payload volume). The width of a single locker is 0.44 m, the height is 0.25 m, and the depth is 0.52 m. The full rack can accommodate approximately 260 kg. In an EVA environment, the metal recycling capability would likely operate as a free-flyer platform.

*EXPRESS is an acronym for "EXpedite the PRocessing of Experiments to the Space Station."

Expected TRL or TRL Range at completion of the Project: 3 to 5
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:
   • Analysis
   • Prototype
   • Hardware

Desired Deliverables Description:

Phase I is a feasibility study and proof of concept of a system for in-space recycling of one or more metal materials. Targeted applications for the technology include processing of spent components into feedstock for in-space manufacturing and/or processing of large-scale structures (such as spent upper stages) into material forms for further use. While the focus should be on material processing (which may include shredding, melting, solidifying, and other processes necessary to obtain a final feedstock form), other ancillary techniques such as sorting, purification, and material delivery/transport may also be considered as part of an overall concept of operations. How the system will be deployed and operated in either an IVA or EVA environment should also be considered. The Phase I effort should also include a laboratory demonstration of the core recycling technique with an aerospace-grade metallic material and some characterization of properties post-recycling. Relevant metrics such as power consumption, system footprint, and mass of system should also be reported, with an emphasis on scalability and adaptation to the relevant space environment. This work will collectively inform preliminary design of a metal recycling capability for in-space use. An additional constraint is that the system must be operated remotely with very little intervention/setup. Even in an IVA environment with crew, the availability of crew time to tend or service a recycling system will be very limited. An EVA environment would require fully remote operation.

Phase II would include finalization of the design and demonstration of a ground-based prototype system.

Phase III would seek to evolve the technology to a flight demonstration for ISS (internal or external payload) or as a free-flyer.

State of the Art and Critical Gaps:
The current SOA is terrestrial systems for metal recycling, but these processes must be adapted to operate in the relevant space environment and comply with the system constraints of their intended use (for example, in an IVA environment as a payload). The capability to break down spent components and larger structures and repurpose them into a useful product is needed on long-duration space missions where logistics are constrained. Recycling of polymer materials on the International Space Station (ISS) into manufacturing feedstock (for 3D printing) has been previously demonstrated, but there are no current recycling capabilities for metals on the ISS. For external applications of metal recycling, NASA has funded some Next Space Technologies for Exploration Partnerships (NextSTEP) work previously on repurposing of spent rocket stages left in-orbit. Recycling, reuse, and repurposing of metals is seen as a critical gap for on-orbit servicing, assembly, and manufacturing (OSAM) and shifting the logistics paradigm from pre-positioning of spare parts to point-of-use manufacturing.

Relevance / Science Traceability:

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module, Gateway, Lunar Base Camp, OSAM-1, OSAM-2 and in-Space Assembled Telescope (iSAT).

References:


Z3.04 Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly, and Manufacturing (OSAM)

Lead Center: GSFC

Participating Center(s): MSFC

Scope Title:

Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly, and Manufacturing (OSAM)

Scope Description:

As NASA seeks to extend its presence into deep space, ground-based human intelligence applied to supervision, control, and intervention of operations will no longer be viable due to system and mission complexity and communication delays. Therefore, trusted and certified-safe autonomous systems with machine intelligence and robotic capabilities of responding to both nominal and unexpected situations will be needed. These systems should be capable of:

- Sensing and perception.
- Acquiring measurements on-orbit or on planetary surfaces.
- Achieving situational awareness.
- Making decisions.
- Taking action.
- Teaming with humans and other machine agents.
- Using experiential data to update capabilities.
- Verifying autonomy algorithms and behavior.
- Validating as-assembled structure shape and interface integrity.

As such, autonomy, system modularity, metrology, and modeling and simulation are four critical aspects required to enable OSAM. The hardware and software components of an in-space assembled structure must be modular to facilitate servicing, component replacement, and reconfiguration of the spacecraft. Assembly by autonomous robots can reduce the workload of astronauts and ground crew and can mitigate inefficiencies due to communication delays associated with teleoperation. The OSAM paradigm requires multiple autonomous agents to collaborate in a complex, dynamic environment. These agents will need to accurately perceive both their environment (the worksite) and each other in order to efficiently allocate tasks, plan trajectories, and respond to disturbances—all in the presence of uncertainties such as unknown payload characteristics and unmodeled effects.

Modular structures will increase ease of access to space. Modular platforms could host flight hardware and share power, data, GN&C (guidance, navigation, and control), and thermal regulation capabilities. Under this paradigm, technology demonstrations could be performed without the need to design and operate an entire spacecraft. Modules could simply occupy space on an already existing platform. This constitutes a plug-and-play architecture that will require a common interface between modules such that required structural loads can be supported as well as power, data, and other services.

Modeling and simulation of structures and assembly agents is necessary for verifying autonomous agent algorithms and behavior used for structures that cannot be assembled on the ground. Accurate sensing of complex and uncertain environments is necessary to provide autonomous agents with situational awareness to accomplish assembly tasks. Validation of the autonomous system behavior and in-space assembled structure accuracy in situ will require in-space metrology capabilities.

The scope of this subtopic includes modular hardware and software systems:

- Element 1: Algorithms and software for sensing, planning, and control of both autonomous robots and mission/task management agents.
- Element 2: Novel hardware designs (modular robots and structures).
- Element 3: Hardware and software for global (worksite-scale) metrology systems for accurately sensing agent and structure pose within an on-orbit or lunar assembly worksite.
- Element 4: Novel approaches to dynamics-based mathematical modeling for
complex rigid-body connections and independent verification and validation for dynamics-based rigid multi-body mathematical models.

A solution for autonomous modular technologies for OSAM will be built on the following foundational areas:

- Heterogeneous multi-agent planning and control: Algorithms for collaboration on shared tasks for assembly of large modular space structures; task allocation among multiple agents; trajectory planning through the worksite and real-time updating of tasks and trajectories to respond to unplanned scenarios; robust and adaptive control for guaranteed performance or graceful degradation of performance for robotic manipulators and/or novel assembly agents; and teaming of humans and machines for planning, validation, and post-assembly analysis.

- Strategies and solutions for error detection and correction during the assembly process: Perception systems and/or classification algorithms independent from the assembly agent for verifying assembly steps and characterizing assembly errors. Fault/anomaly detection, diagnosis, and response to restore nominal operations or derive an acceptable alternative goal.

- Metrology systems: Global metrology systems or sensing tools that can map a worksite to facilitate agent and structure assembly path-planning for real-time task management and situational awareness and facilitate verification and validation of assembly tasks. A scalable system that can accurately measure structures at an in-space (orbital or surface) worksite with a focus on minimal supporting infrastructure is desired. Concepts with potential for integration and repurposing after construction are favored.

- Modular structures, systems, and tools: Deployables that are rigidizable by an accompanying in situ system (i.e., trusses or functional modules), can be serviced (due to modularity), are capable of moving along truss structures of variable geometries, and/or can interface with agents or be stored/stowed at a worksite where the agent mostly acts as a driver for a mobility system. Of particular interest are approaches to efficiently connect truss modules together—hardware concepts that support the interconnection of modules in the 100- to 5,000-kg range using some form of space robotics. The objective is to minimize the parasitic mass of the completed spacecraft from the modularity features that are required for intermodule assembly. Features can be added and removed to reduce this parasitic mass. Proposals are preferred that include features to connect both electrical (power and data) and structural features, noting that the connections can occur sequentially. Joining strategies that support fluid connections are of interest but are not necessary to be responsive to this subtopic area. The structural connection should occur at a minimum of three discrete locations, fixing the rigid-body motion of the two modules in all six degrees of freedom while isolating (minimizing) forces resulting from thermal-induced strain between the modules consistent with a low Earth orbit (LEO) orbit. The three (or more) connections do not have to occur simultaneously.

- Modeling and simulation: Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections with nonlinear effects (for example,
slider, ball, or slot connections) and independent verification and validation for dynamics-based rigid multibody mathematical models. Of particular interest are accurate dynamics-based models for joining of modules on-orbit or in planetary environments.

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

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.X Other Autonomous Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software

Desired Deliverables Description:

Phases I and II should both result in the following deliverables:

- Software implementations of designed algorithms.
- Documentation verifying the efficacy of the designed algorithms.
- Physical prototypes of designed hardware.
- Design documentation for any designed hardware.

Level of detail in the documentation should be commensurate with project phase.

State of the Art and Critical Gaps:

As humans venture into deeper space, communication latency will increase to the point that autonomous operations are crucial. Current technologies for autonomous robots are low Technology Readiness Level (TRL), application specific, and fragile with respect to environmental uncertainties. To enable OSAM, these technologies must be made more resilient. Many interesting ideas exist in academia but have yet to be made into a viable product.

Existing interfaces for modular trusses are purely structural. A critical gap is the development of interfaces that can exchange power, data, and other services over the interface.

Relevance / Science Traceability:

Achieving a robust and resilient autonomous solution for OSAM requires the intersection of many disciplines, including mechanical and electrical systems, robotics, dynamics modeling, control theory, and computer science. NASA goals that would directly benefit from this work are future lunar exploration missions, including sustained human presence on the Moon and persistent space platforms.

References:

NASA in-Space Assembled Telescope (iSAT) Study: [9] https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/


[9]
[10]
[11]
Z3.05 Satellite Servicing Technologies

Lead Center: GSFC

Participating Center(s): LaRC, MSFC

Scope Title:

Adjustable End-of-Robot-Arm Force-Torque Sensor Technique

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets. An end-of-arm force-torque sensing technique that is adjustable is needed to enable a variety of OSAM mission-specific tasks to be performed. A ground-based demonstration of the technique is of interest.

Current state of the art in end-of-arm force-torque sensors is that they are not placed close enough to the sensing point to minimize the load distal of the sensor, do not work in both unrestricted 1g and 0g environments, and cannot simultaneously handle large (6× to 10×) full-range overload for launch loads while providing absolute accuracy stability for at least 30 min before zeroing. A sensing technique is needed that can provide the following:

- Range of 0 to 200-500 N, resolution of 2 N, and absolute accuracy of ±5 N for surface contact measurements.
- Range of ±120 N, resolution of 0.1 N to 0.2 N, and absolute accuracy of ±2 N for servicing tasks.
- Range of 0 to 20 N, resolution of 0.02 N, and absolute accuracy of ±0.1 N for payload determination measurements.

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

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

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

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Brassboard force-torque sensor.

Phase II deliverables include:

- Demonstration using the brassboard force-torque sensor.
- Environmental testing of key components.

State of the Art and Critical Gaps:

Current state of the art in end-of-arm force-torque sensors is that they are not placed close enough to the sensing point to minimize the load distal of the sensor, do not work in both unrestricted 1g and 0g environments, and cannot simultaneously handle large (6× to 10×) full-range overload for launch loads while providing absolute accuracy stability for at least 30 min before zeroing.

Relevance / Science Traceability:

An adjustable force-torque sensor is relevant to dexterous robotic missions such as OSAM-1, OSAM-2, International Space Station (ISS) robotics, robotic sample return missions, Gateway, and in-Space Assembled Telescope.

References:

On-Orbit Satellite Servicing Study Project Report, October 2010,

Scope Title:

Centralized Robot Actuator Servo Controller Board for MUSTANG (Modular Unified Space Technology Avionics for Next Generation) Form Factor

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets. A robot actuator servo control electronic board that fits in the Modular Unified Space Technology Avionics for Next Generation (MUSTANG) form factor is needed to enable a variety of OSAM and robotic sample return missions. A ground-based demonstration of the control electronics is of interest.

Current state of the art for robot actuator servo control electronic boards is that they do not read all of the sensors necessary for closed-loop control, are too big (>30 by 30 cm), and weigh too much (>2 kg). An actuator servo control electronic board is needed that fits the MUSTANG form factor, reads all of the necessary sensors (Hall effect sensor, resolver), and weighs less than 2 kg.

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

Primary Technology Taxonomy:

Level 1: TX 04 Robotics Systems
Level 2: TX 04.3 Manipulation

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

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

Deliverables include a ground-based demonstration of a robot actuator servo control electronic board in the MUSTANG form factor commanding a robot actuator.

**Phase I deliverables include:**

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Brassboard robot actuator servo control electronic board.

**Phase II deliverables include:**

- Demonstration using the brassboard robot actuator servo control electronic board.
- Environmental testing of key components.

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

Existing centralized robot actuator servo control electronics do not fit the MUSTANG form factor or require additional resources other than those provided by the rest of the MUSTANG avionics platform.

**Relevance / Science Traceability:**

Robot actuator servo control electronics are relevant to dexterous robotic missions such as OSAM-1, OSAM-2, International Space Station (ISS) robotics, robotic sample return missions, Gateway, and in-Space Assembled Telescope.

**References:**

On-Orbit Satellite Servicing Study Project Report, October 2010,

MUSTANG (Modular Unified Space Technology Avionics for Next Generation): [https://ntrs.nasa.gov/citations/20190028692](https://ntrs.nasa.gov/citations/20190028692) [18]

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Z4.04 Real-Time Defect Detection, Identification, and Correction in Wire-Feed and Fused-Filament Additive Manufacturing

**Lead Center:** LaRC

**Participating Center(s):** MSFC
Additive manufacturing (AM) (also referred to here as 3D printing) offers the ability to build lightweight components that are optimally suited for use in aerospace applications. AM can also support sustainable exploration of the surfaces of the Moon and Mars by enabling needed components to be fabricated onsite. Significant strides have been made in the development of AM, with 3D-printed components now being part of active aircraft and spacecraft. While the use of AM has enabled nontraditional designs and decreased part counts, full inspection of each component is typically required postbuild to determine fitness for the final application. Complex geometries, rough as-built surface finishes, and porosity can hinder inspection. If 100% inspection is not possible, proof test logic or some other method of proving fitness for use must be applied. Defects that occur can force a complete reprint. The ultimate promise of AM is to enable on-demand production of customized unique components. For utility in space applications, printed parts have to be fully functional, with zero to minimal postprocessing. Ideally, parts need to be built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service. To enable the full realization of the potential of 3D printing, a capability for closed-loop control of the process that integrates in situ monitoring, real-time defect detection and identification, and print parameter modification is required.

Wire-feed or extrusion-type AM, with its relative simplicity, wide range of feedstocks, and build volume flexibility, is a popular 3D-printing technique that is well suited to space applications. Fused filament fabrication (FFF) of thermoplastics and electron beam free-form fabrication (EBF3) of metals are useful examples of wire-feed processes to illustrate the limitations placed on AM by presently available design and process control tools. After designing an object using 3D modeling software, the geometry is passed to a slicing and tool path planning code, which generates the list of instructions needed by the printing hardware. Once received by the printer, no further modifications or corrections can be made, and the process continues to completion.

Proposals are invited to advance the manufacturing technology by incorporating an in situ defect detection and correction capability into wire-feed processing of metallic parts and FFF or related extrusion processing of thermoplastic, thermoset, or composite components.

In Phase I, contractors should prove the feasibility of integrating sensor feedback with appropriate software tools and computation resources to be able to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects to the part performance and the correction of those defects. Solutions sought include software that can be integrated into the 3D-printing workflow, hardware
requirements to run that software for real-time data processing, and sensors capable of operating in the build environment to provide data, also in real time. The proposed approach should be demonstrable at least on the coupon scale for shapes such as circles or boxes.

The proposed solution must include all of the following: (1) defect sensing and detection, (2) assessment of the impact of the defect on part performance, and (3) corrective actions other than scrapping of the build. Proposals that do not clearly include these three elements will be considered out of scope.

Phase II should demonstrate the feasibility of Phase I concepts to arrive at closed-loop solutions to build parts in which information on the processing generated from gathering and analyzing sensor data is used for the prediction of part performance, unique to each individual part, as it is being built. Incorporation of defect correction during fabrication, rather than requiring a print to be scrapped and restarted, should be demonstrated on sample parts.

**Expected TRL or TRL Range at completion of the Project:** 2 to 3

**Primary Technology Taxonomy:**

Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing  
Level 2: TX 12.4 Manufacturing

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

- Hardware  
- Software  
- Prototype  
- Research  
- Analysis

**Desired Deliverables Description:**

Phase I: Concept studies documenting the feasibility of incorporating sensor data feedback and appropriate software tools and computation resources to be used to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects on the performance of the parts and the correction of those defects.

The proposed solution must include all of the following: (1) defect sensing and detection, (2) assessment of the impact of the defect on part performance, and (3) corrective actions other than scrapping of the build. Proposals that do not clearly include these three elements will be considered out of scope.

Phase II: Scale demonstration of a printer with closed-loop control that incorporates defect detection, identification, and correction during fabrication. The complexity of defects that are detected and corrected, as well as the size of the parts, should demonstrate the challenges that would come up in full-scale use of the control processes. Printed part sizes should be at least 10 cm per side for cubes, with detectable defects down to the mm scale or smaller. The defects should have a demonstrable effect on the part performance, such as a decrease in mechanical properties, that is then corrected for by the process.
State of the Art and Critical Gaps:

AM is seeing rapidly expanding applications in many areas, including in aerospace. Despite this growth in AM, filling its full potential has always been limited by quality-control issues and certification of the manufactured parts, as each component that is built is unique. Some work has begun to add defect detection and correction to powder-based manufacturing processes, such as direct metal laser sintering (DMLS) and wire-feed AM. There has, however, not been the requisite advance in ensuring that defect detection and identification is coupled with the real-time correction of those defects and ensuring final performance of the manufactured part in a particular application.

Gap: Real-time defect detection, identification, and correction in AM processes that would ensure the performance of the as-printed parts without relying on postproduction inspection processes, with parts built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service, has not been demonstrated.

Relevance / Science Traceability:

This topic fits under STMD (Space Technology Mission Directorate). It supports Advanced Manufacturing of Lightweight Structures. Enhancing quality control in AM opens up its use in many industrial applications as well as its use by NASA. In particular, in-space use of AM in future Gateway, lunar, and Mars exploration missions will require that parts that are produced are ready for use as-produced, because there will be limitations in availability of material for reprinting as well as limitations on crew time and equipment for postprinting inspection.

References:

Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis

Lead Center: LaRC

Participating Center(s): ARC, GSFC

Scope Title:

Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis

Scope Description:

NASA’s NDE SBIR subtopic will address a wide variety of NDE disciplines. These disciplines include but are not limited to structural health monitoring (SHM), novel NDE sensor development, and NDE modeling and analysis. All three of these disciplines can be used on aerospace structures and materials systems, including but not limited to Inconel, titanium, aluminum, carbon fiber, Avcoat, ATB-8, Phenolic Impregnated Carbon Ablator (PICA), and thermal blanket structures. Sensor systems, SHM, and modeling can target any set of these materials in common aerospace configurations, such as micrometeoroid and orbital debris (MMOD) shielding, truss structures, and stiffened structures. In addition, NDE can target material and material systems in a wrought state in process, and NDE techniques that could be used to inspect additively manufactured components post production would be favored. Current NDE computational tools do not have sufficient resolution to provide representation on the order of finite-element models (FEMs) allowing for a digital twin. Depending on the size of the critical flaw in the material system/structure, this resolution can range from 500 nm to 100 cm realistically. As NDE tool resolution grows, larger volumes of data are created, and thus new computational tools are required. At the same time, low-cost emerging computational hardware, such as graphics processing units (GPUs), is enabling the growing use of advanced physics-based models for improved NDE inspection and for advanced data analysis methods such as machine learning. In addition, as NASA strives to go deeper and longer, new tools need to be developed in order to support long-duration spaceflight.

NDE Sensors and Data Analysis

Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight.
hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface.

Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to automatically register NDE results to precise locations on the structure. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged that proposals provide an explanation of how the proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multiwall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) radiators, or aerospace structural components.

Additionally, techniques for quantitative data analysis of sensor data are desired. It is also considered highly desirable to develop tools for automating detection of material foreign object debris (FOD) and/or defects and evaluation of bondline and in-depth integrity for lightweight rigid and/or flexible ablative materials. Typical internal void volume detection requirements for ablative materials are on the order of less than 6 mm, and bondline defect detection requirements are less than 25 mm.

Additive manufacturing is rapidly becoming a manufacturing method targeting fracture-critical components; as such, NDE requirements will become more stringent. Additively manufactured components represent a novel challenge for NDE due to the layering nature of the process and its effect on diffracting energy sources. Development of NDE techniques, sensors, and methods addressing these issues would be highly desired, but techniques addressing weld inspection will also be considered. Most of the aerospace components will be metallic in nature, and critical flaws are on the range of 1 mm or smaller and can be volumetric or fracture-like in nature.

Structural Health Monitoring (SHM)

Future manned space missions will require spacecraft and launch vehicles that are capable of monitoring the structural health of the vehicle and diagnosing and reporting any degradation in vehicle capability. This subtopic seeks new and innovative technologies in SHM and integrated vehicle health management (IVHM) systems and analysis tools.

Techniques sought include modular/low mass-volume systems; low-power, low-maintenance systems; and systems that reduce or eliminate wiring, as well as standalone smart-sensor systems that provide processed data as close to the sensor as practical and systems that are flexible in their applicability. Examples of possible systems include surface-acoustic-wave- (SAW-) based sensors, passive wireless sensor tags, flexible sensors for highly curved surfaces, and direct-write film sensors. Damage detection modes include leak detection, ammonia detection, micrometeoroid impact, and others. Reduction in the complexity of standard wires and connectors and enabling sensing functions in locations not normally accessible with previous technologies is also desirable. Proposed techniques should be capable of long-term service with little or no intervention. Sensor systems should be capable of identifying material state awareness and distinguishing aging-related phenomena and damage-related conditions. It is considered advantageous that these systems perform characterization of age-related degradation in complex composite and metallic materials. Measurement techniques and analysis methods related to quantifying material thermal properties, elastic properties, density, microcrack formation, fiber buckling and breakage, etc., in complex composite material systems and in adhesively bonded/built-up and/or polymer-matrix composite sandwich structures are of particular interest. Some consideration will be given to the IVHM/SHM ability to survive in on-orbit and deep space conditions, allow for additions or changes in instrumentation late in the design/development process, and enable relocation or upgrade on orbit. The system should allow NASA to gain insight into performance and safety of NASA vehicles as well as commercial launchers, vehicles, and payloads supporting NASA missions.
Inclusion of a plan for detailed technical operation and deployment is highly favored.

**NDE Modeling**

Technologies sought under this SBIR include near real-time realistic NDE and SHM simulations and automated data reduction/analysis methods for large datasets. Simulation techniques will seek to expand NASA’s use of physics-based models to predict inspection coverage for complex aerospace components and structures and to utilize inverse methods for improved defect characterization. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/characterization of critical flaws in space-flight structures and components, and may involve methods such as machine learning and domain transformation. NASA’s interest area is lightweight structural materials for spaceflight, such as composites and thin metals. Future purposes will include application to long-duration space vehicles as well as validation of SHM systems.

Techniques sought include advanced material-energy interaction (i.e., NDE) simulations for high-strength lightweight material systems and include energy interaction with realistic damage in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals, but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, laser, microwave, terahertz, infrared, x-ray, x-ray computed tomography, fiber optic, backscatter x-ray, and eddy current. It is assumed that any data analysis methods will be focused on NDE techniques with high-resolution, high-volume data. Modeling efforts should be physics-based, and it is desired that they can account for material aging characteristics and induced damage, such as micrometeoroid impact. Examples of damage states of interest include delamination, microcracking, porosity, and fiber breakage. Techniques sought for data reduction/interpretation will yield automated and accurate results to improve quantitative data interpretation to reduce large amounts of NDE/SHM data into a meaningful characterization of the structure. It is advantageous to use coprocessor/accelerator-based hardware (e.g., field-programmable gate arrays (FPGAs) and GPUs) for simulation and data reduction. Combined simulation and data reduction/interpretation techniques should demonstrate ability to guide the development of optimized NDE/SHM techniques, lead to improved inspection coverage predictions, and yield quantitative data interpretation for damage characterization.

**Expected TRL or TRL Range at completion of the Project:** 1 to 6

**Primary Technology Taxonomy:**
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

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

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

**Phase I Deliverables:** For proposals focusing on NDE sensors: Lab prototype and feasibility study or software package, including applicable data or observation of a measurable phenomenon on which the prototype will be built. For proposals focusing on NDE modeling: Feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (Technology Readiness Level (TRL) 2 to 4). Inclusion of a proposed approach to develop a given methodology to a TRL of 2 to 4. All Phase I proposals will include minimum of short description for Phase II prototype/software. It will be highly favorable to include a description of how the Phase II prototype or methodology will be applied to structures.

**Phase II Deliverables:** Working prototype or software of proposed product, along with full report of development, validation, and test results. Prototype or software of proposed product should be of TRL 5 to 6. Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.
State of the Art and Critical Gaps:

NDE tools for flight still do not have sufficient resolution to provide representation on the order of finite-element models (FEMs) allowing for a digital twin. Also, as NDE tools grow and sensors get faster, larger volumes of data are created and thus new computational tools are required. At the same time, low-cost emerging computational hardware, such as GPUs, is enabling the growing use of advanced physics-based models for improved NDE inspection and for advanced data analysis methods such as machine learning. Development of new techniques are enabling Orion to meet its 100% inspected mission directive. In addition, as NASA strives to go deeper and longer, new tools need to be developed in order to support long-duration spaceflight.

Relevance / Science Traceability:

Several missions could benefit from technology developed in the area of NDE. Currently, NASA is returning to manned spaceflight. The Artemis program's Orion spacecraft and Space Launch System have had inspection difficulties, and continued development and implementation of NDE tools will serve to keep our missions flying safely. Currently, Orion is using several techniques and prototypes that have been produced under the NDE SBIR topic. The Space Launch System is NASA's next heavy-lift system, capable of sending hundreds of metric tons into orbit. Inspection of the various systems is ongoing and will continue to have challenges, such as verification of the friction stir weld on the fuel tanks. As NASA continues to push into deeper space, smart structures that are instrumented with SHM systems can provide real-time mission-critical information on the status of the structure.

References:


Cramer, K. E.: Current and Future Needs and Research for Composite Materials NDE. Presented at SPIE Smart
Z4.06 Manufacturability Assessment as a Design Constraint for Advanced Tailorable Composites

Lead Center: LaRC

Participating Center(s): MSFC

Scope Title:

Manufacturability Assessment as a Design Constraint for Advanced Tailorable Composites

Scope Description:

While use of composite material systems in space vehicle structures is increasing, their broader implementation is still facing multiple challenges. One of these challenges, especially relevant in the context of advanced tailorable composites, is a manufacturability assessment that could be leveraged as a design constraint early in the development. Absence of a reliable and comprehensive manufacturability assessment often restricts exploitation of the full potential of the composite material system and promotes conservative fabrication approaches that can negate potential mass benefits of composites. Suboptimal designs such as quasi-isotropic lamination stacking sequence treat the material as “black aluminum,” failing to permit tailored load paths possible with composites. Consequently, a material system that can enable large reductions in system mass ends up being used in the design process in a way that results in structural components that are much heavier than necessary.

This solicitation seeks to advance the analytical predictive manufacturability assessment capabilities for layered composites. Such an assessment is required as a constraint in the structural design and optimization process. Layered pre-impregnated composite materials reinforced with either continuous or short fibers, and with a broad spectrum of ply thicknesses, are in the scope of this solicitation. For the continuous-fiber composites, the typical fiber areal weights range from approximately 30 grams per square meter (gsm) to just under 200 gsm. For short-fiber applications, the ultrathin plies in the single-digit gsm range are also of interest. Since a broad variety of composite material systems is within the scope of this solicitation, the scope of related manufacturability constraints...
can be tailored to the proposed material system. Consequently, the examples of manufacturability considerations provided in this solicitation are not all-inclusive, and parameters not listed below can be offered up for investigation when a compelling rationale is presented. The list of potential implementations of advanced tailorable composites is also provided to aid in the determination of manufacturing constraints of primary importance. The overarching approach should be based on recognizing that the more aggressive the tailoring of a composite material system, the greater the risk of developing defects in the manufacturing process. While avoiding any defects can be one countermeasure, quantifying the effects of defects can provide additional insights. Specifically, if the effect of defect can be quantified and it can be demonstrated that the benefits gained from the associated design tailoring can overcome the adverse effect of a small defect, then a rationale for the more aggressive tailoring can be justified. Examples of defects include, but are not limited to, tow gaps, overlaps, foldovers, or poor compaction/separation from the underlying plies. In cases where a placement imperfection can be subjected to restorative actions, analysis of how successful such actions can be is also of value.

The manufacturability assessment shall be based on analytical tools validated with experimentation/actual manufacturability trials. Examples of the performance-based manufacturing constraints for the continuous-fiber composites include, but are not limited to, determination of the minimum allowable steering radius, relative proximity of ply terminations such that no significant adverse interaction occurs, and minimizing thermal warping in the cure process when nonsymmetric lamination stacking sequence is present. For example, one of the important examples of the manufacturability assessment for short-fiber composites is determination of an initial preform thickness distribution that would produce a desired thickness distribution after forming that involves preform expansion and/or turning or steering (i.e., forming similar to deep-stamping or closed-cross-section forming with a clamshell tool and an expandable bladder). Similarly, estimation of the short-fiber orientation distortions in the forming process and predictive countermeasures to this behavior are also sought.

Subscale manufacturing demonstrations representative of the challenges that can be encountered in the full-scale applications are sought as the manufacturability predictive analysis validation cases. The full-scale structures of interest that can be scaled down for the manufacturing demonstrations include cryogenic tanks, crew modules, pressurized habitats, and other dry and unpressurized primary structural components or portions of thereof. Discrete features such as hatches, access and windows cutouts, and hard point attachments can be considered as manufacturability challenges to be encountered in the full-scale applications in addition to the general acreage considerations. Furthermore, manufacturability assessment for short-fiber composites is expanded to allow smaller size demonstrations, for example, those representative of hard point attachment brackets, hinges, clevises, etc.

Expected TRL or TRL Range at completion of the Project: 5 to 6
Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

In Phase I, a comprehensive identification of manufacturability constraints shall be conducted for a selected material system and application. Analytical and experimental results shall be obtained for at least one selected aspect of the manufacturability assessment.

In Phase II, the analytical tool capabilities and related manufacturability trials shall be expanded to a more comprehensive and exhaustive list of manufacturability constraints identified in Phase I. A manufacturing demonstration article and the computational tool available for release shall be delivered at the conclusion of Phase II.
State of the Art and Critical Gaps:

Present composite designs are typically limited to straight fiber arrangements and lamination stacking sequences resulting in quasi-isotropic material properties. Apart from the lack of structural design and optimization tools, highly tailored fabrication of composites presents manufacturing challenges and is prone to introducing manufacturing defects. Manufacturability assessment is often performed via the trial-and-error approach, which is costly, time consuming, and very limited in scope. A validated computational manufacturability assessment tool would enable more rapid and comprehensive manufacturability assessment that can inform the design effort in its early stages.

Relevance / Science Traceability:

- Space Technology Mission Directorate (STMD), Artemis/HLS (human landing systems) programs, developers of air-launched systems, e.g., Generation Orbit Launch Services.
- Aeronautics Research Mission Directorate (ARMD), next-generation airframe technology beyond "tube and wing" configurations, e.g., hybrid/blended wing body.
- Developers of the in situ nondestructive evaluation inspection capabilities within both space and aeronautics programs.

References:


Z5.04 Technologies for Intravehicular Activity Robotics

Lead Center: ARC

Participating Center(s): JSC

Scope Title:

Improve the Capability or Performance of Intravehicular Activity Robots

Scope Description:

To support human exploration beyond Earth orbit, NASA is developing Gateway, which will be an orbiting facility near the Moon. This facility will serve as a starting point for missions to cis lunar space and beyond. It could enable assembly and servicing of telescopes and deep space exploration vehicles. It could also be used as a platform for astrophysics, Earth observation, heliophysics, and lunar science.

In contrast to the International Space Station (ISS), which is continuously manned, Gateway is expected to be occupied by humans only intermittently—perhaps only 1 month per year. Consequently, there is a significant need for Gateway to have autonomous capabilities for performing payload operations and spacecraft caretaking.
particularly when astronauts are not present. Similar capabilities are needed for future lunar or planetary surface habitats. Intravehicular activity (IVA) robots can potentially perform a wide variety of tasks, including systems inspection, monitoring, diagnostics and repair, logistics and consumables stowage, exploration capability testing, aggregation of robotically returned destination surface samples, and science measurements and operations.

The objective of this subtopic is to develop technologies that can improve the capability or performance of IVA robots to perform payload operations and spacecraft caretaking. Proposals are specifically sought to create technologies that can be integrated and tested with the NASA Astrobee, Robonaut 2, or other NASA robots in the following areas:

- Sensors and perception systems for performing contact tasks; manipulation; and/or interior environment monitoring, inspection, modeling, and navigation.
- Robotic tools for manipulating logistics and stowage or performing maintenance, housekeeping, or emergency management operations (e.g., fire detection and suppression in multiple constrained locations or cleaning lunar dust out of air filters).
- Operational subsystems that enable extended robot operations (power systems, efficient propulsion, etc.); increase robot autonomy via computationally efficient methods (planning, scheduling, and task execution); or improve human-robot interaction between IVA robots and human teams on the ground under communications constraints, including low bandwidth and extended loss-of-signal periods (software architecture, remote operations methods, etc.).

This subtopic also seeks to advance technologies that will enable the next generation of IVA robots to operate in lunar surface habitats, including:

- Novel robotic end effectors capable of reliably performing fine grasping tasks, such as plugging and unplugging MIL-STD-38999 electrical connectors and fluid quick-disconnect connectors.
- Compact, reliable, modular robotic actuators and controllers for IVA robots.
- Software that enables autonomous management of robot operational and hardware faults such that the robot can “fail operational.” For example, the software may use algorithms to determine how to automatically respond to a failure in a motion planner for move to a commanded location by taking into account a projected collision and replanning to the next closest point not in collision.

Expected TRL or TRL Range at completion of the Project: 4 to 5
Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.X Other Robotic Systems
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
• Software

Desired Deliverables Description:

Proposals must describe how the technology will make a significant improvement over the current state of the art, rather than just an incremental enhancement, for a specific IVA robot application.

Deliverables should focus on prototype components, subsystems, and the demonstration thereof. Specifically, Phase I awards shall deliver an interim and final report discussing these results. Phase II awards shall deliver demonstration reports along with supporting software, design information, and documentation.

State of the Art and Critical Gaps:

The technology developed by this subtopic would both enable and enhance the Astrobee free-flying robot and Robonaut 2 humanoid robot, which are the state of the art for IVA robots. SBIR technology would improve the capability and performance of these robots to routinely and robustly perform IVA tasks, particularly internal spacecraft payload operations and logistics. New technology created by 2021 SBIR awards could potentially be tested with these, or other, robots in ground testbeds at Ames Research Center (ARC) and Johnson Space Center (JSC) in follow-on awards. Likewise, on-orbit testing on ISS may be possible during follow-on awards.

The technology developed by this subtopic would also fill technical gaps identified by the proposed Game Changing Development (GCD) Integrated System for Autonomous and Adaptive Caretaking (ISAAC) project, which will mature autonomy technology to support the caretaking of human exploration spacecraft. In particular, the SBIR technology would help provide autonomy and robotic capabilities that are required for in-flight maintenance (both preventive and corrective) of Gateway during extended periods when crew are not present.

Relevance / Science Traceability:

This subtopic is directly relevant to the following STMD (Space Technology Mission Directorate) investments:

• Astrobee freeflying robot, GCD
• Integrated System for Autonomous and Adaptive Caretaking (ISAAC), GCD
• Smart Deep Space Habitats (SmartHabs), Space Technology Research Institutes (STRI)

This subtopic is directly relevant to the following HEOMD (Human Exploration and Operations Mission Directorate) investments:

• SPHERES (Synchronized Position Hold, Engage, Reorient, Experimental Satellite)/Astrobee facility, ISS
• Robonaut 2 humanoid robot, ISS
• Gateway program, Advanced Exploration Systems (AES)
• Logistics Reduction project, AES
• Autonomous Systems Operations project, AES

References:

What is Astrobee? https://www.nasa.gov/astrobee [29]

What is a Robonaut? https://www.nasa.gov/robonaut2 [30]


Z7.01 Entry, Descent, and Landing Flight Sensors and Instrumentation

Lead Center: MSFC

Participating Center(s): ARC, GSFC, JPL, LaRC

Scope Title:

High-Accuracy, Lightweight, Low-Power Fiber-Optic or Recession Sensing System for Thermal Protection Systems and Low-Cost Data Acquisition System

Scope Description:

Current NASA state-of-the-art entry, descent, and landing (EDL) instrumentation and associated data acquisition are very expensive to design and incorporate on planetary missions because they must meet functional and performance requirements during and after exposure to loads and environments associated with spaceflight and atmospheric entry.

Commercial fiber-optic systems offer an alternative to traditional sensors that could result in a lower overall cost and weight reduction while actually increasing the number of measurements. Fiber-optic systems are also immune to electromagnetic interference (EMI), which reduces design and qualification efforts. This would be highly beneficial to future planetary missions requiring thermal protection systems (TPSs). In addition, as NASA looks to
the future of science missions to the outer planets, extreme entry environments will require the new, 3D-woven Heatshield for Extreme Entry Environment Technology (HEEET) TPS recently matured within the Agency. Gathering flight performance data on this new material will be key—particularly the measurement of recession, which was so very important on the Galileo probe mission to Jupiter. Minimizing the sensor intrusion of the outer mold line is critical in this case because the extreme environment dictates that the TPS be as aerothermally monolithic as possible. In applications to planetary entry vehicles greater than about 1 m in diameter, however, the HEEET TPS is expected to contain seams that might be used for accommodating instrumentation.

Recession measurements in carbon fiber/phenolic TPSs such as Phenolic Impregnated Carbon Ablator (PICA) and AVCOAT are also of interest. When ablation is not severe and/or rapid, accurate measurements have proven difficult with the historic Galileo-type sensor, which was based on the differential resistance resulting from sensor materials that have charred.

To be considered against NASA state-of-the-art TPS sensing systems for future flight missions, fiber-optic systems must be competitive in sensing capability (measurement type, accuracy, and quantity) and associated data acquisition system mass, size, power, and cost. Therefore, NASA is looking for a fiber-optic system that can meet the following requirements:

- **TPS Temperature**
  - Measurement Range: -200 to 1,250 °C (up to 2,000 °C is preferred).
  - Accuracy: +/-5 °C desired.
- **Surface Pressure**
  - Measurement Range: 0 to 15 psi.
  - Accuracy: < +/-0.5%.

Destinations such as Mars, Venus, and Titan pose many challenges for EDL data acquisition systems, including radiation, g-loading, and volume constraints. Recent notable examples of such systems are the Mars Entry, Descent, and Landing Instrument (MEDLI) sensor suite, which successfully acquired EDL data in 2012, and the upcoming MEDLI2 system, which will gather data during EDL at Mars in February of 2021. The NASA MEDLI and MEDLI2 data systems are very well designed and robust to the extreme environments of space transit and EDL, but this comes at a great financial burden to these missions. The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limiting the EDL science that can be conducted by NASA. In an effort to bring EDL instrumentation to all missions, NASA is seeking a low-cost, robust, high-accuracy data acquisition system that can meet the following requirements:

- Performs instrument signal conditioning and analog-to-digital conversion, and includes a spacecraft bus serial interface.
- Weight: 5 kg or less.
- Size: Modularity encouraged; maximum module size 10 cm³; 4 modules maximum.
- Power: 16 W or less.
- Measurement Resolution: 12-bit or higher.
- Accuracy: +/-0.5% of full-scale output.
- Acquisition Rate per Measurement: 8 Hz or higher.
- Radiation Tolerant by Design: Minimum of 10 kRad (30 kRad or better desired).
- Axial Loading Capability: Minimum 15g (Venus missions could require 100g to
400g).

- Operating Temperature Capability: -40 °C to 85 °C.
- Cost: Fully qualified target of ~$1M (recurring).
- Sensor Compatibility.
  - Minimum 15 thermocouples with at least 2 Type R and 8 Type K.
  - Minimum 8 pressure transducers (120 or 350 ohm bridge).

For recession measurements acquired in extreme entry environments requiring 3D woven TPSs, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above and meet the following requirements:

- Up to 5,000 W/cm$^2$ total heat flux (convective plus radiative).
- Up to 5 atmospheres of pressure on the vehicle surface.
- Minimum recession measurement accuracy within +/-1 mm.

For recession measurements in moderate entry environments requiring carbon fiber/phenolic TPSs, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above, and meet the following requirements:

- 150 to 2,000 W/cm$^2$ total heat flux (convective plus radiative).
- Up to 1 atmosphere of pressure on the vehicle surface.
- Minimum recession measurement accuracy within +/-1 mm.

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

**Primary Technology Taxonomy:**
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.X Other Entry, Descent, and Landing

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

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

Phase I Goals: Design and proof of concept, including the production approach to achieve the cost goals.

Phase II Goals: Prototype/breadboard validation in laboratory environment.

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

NASA now requires instrumentation on all EDL missions, including competed science missions, and these cost- and mass-constrained missions cannot use the state-of-the-art instrumentation.

**Relevance / Science Traceability:**
EDL instrumentation directly informs and addresses the large performance uncertainties that drive the design, validation, and in-flight performance of planetary entry systems. Improved understanding of entry environments and TPS performance could lead to reduced design margins, enabling a greater payload mass-fraction and smaller landing ellipses. Improved real-time measurement knowledge during entry could also minimize the landing dispersions for placing advanced payloads onto the surface of atmospheric and airless bodies.

NASA science missions are frequently proposed that include high-speed Earth return (New Frontiers, Discovery, and Mars Sample Return) and Venus and Mars entry. Capsules used for these missions must withstand both convective and radiative aeroheating, and NASA now requires EDL instrumentation for these missions. Current radiative measurement techniques (radiometers) provide only an integrated heating over a limited wavelength range; past interpretation of such flight data [Ref. 3, 4] shows the need for spectrally resolved measurements from spectrometers. For Earth and Venus, the radiative component may be the dominant source of heating, and emission comes from the vacuum ultraviolet (VUV), which NASA currently has no capability to measure. For Mars and Venus, the aftbody radiation is dominated by midwave infrared (MWIR). Again, NASA does not have a method to measure MWIR radiation in flight; the current radiometers integrate across several band systems. Miniaturized spectrometers that can measure in VUV and MWIR would have immediate application to Science Mission Directorate (SMD) planetary missions. Such spectrometers may also inform what ablation species are emitted from the heat shield and backshell during entry.

References:


Scope Title:

Novel Lidar Component Technologies Applicable to Guidance, Navigation, and Control (GN&C) for Precise Safe Landing

Scope Description:

NASA is seeking the development of component technologies for advanced lidar sensors that will be utilized within Entry, Descent, and Landing (EDL) and Deorbit, Descent, and Landing (DDL) Guidance, Navigation, and Control (GN&C) systems for precise safe landing on solid solar system bodies, including planets, moons, and small celestial bodies (e.g., asteroids and comets). The EDL phase applies to landings on bodies with atmospheres, whereas DDL applies to landings on airless bodies. For many of these missions, EDL/DDL represents one of the riskiest flight phases. NASA has been developing technologies for precision landing and hazard avoidance (PL&HA) to minimize the risk of the EDL/DDL phase of a mission and to increase the accessibility of surface science targets through precise and safe landing capabilities. One flight instrumentation focus of PL&HA technology has been in the development of lidar technologies that either provide terrain mapping (range point cloud) capability or direct velocity measurement. The continued maturation of these technologies is targeting (1) further size, mass, and power reductions of components; (2) multicomponent integration; and (3) multimodal operation (i.e., combing mapping and velocimetry functions).
This solicitation is requesting specific lidar system components and not complete lidar solutions. To be considered, all component technologies proposed must show a development path to operation within the applicable EDL/DDL spaceflight environment (radiation, thermal, vacuum, vibration, etc.). The specific lidar component technologies desired include the following:

- **Dense focal plane arrays for simultaneous ranging and Doppler velocimetry, plus associated signal processing approaches including photonic integrated circuits (PICs),** with the following characteristics:
  - Simultaneous measurements from each pixel or from subsets of pixels.
  - Functionality (when integrated into a lidar system) that would operate up to 8 km range.
  - Functionality (when integrated into a lidar system) for measuring velocity from 0 m/sec along the line of sight (LOS) up to 200 m/sec or greater.
  - PICs approaches that integrate multiple components into a single device or provide a single component in a miniaturized robust package (e.g., master laser, modulator, and detectors).
  - Ability to reject false locks on dust plumes due to exhaust.
  - Implementation for low power, mass, and size.
  - Optical losses comparable with fiber-optic or bulk optical components.

- **High-speed (5 MHz) wavelength tuning laser modules with low power driving electronics,** which have random wavelength access or predefined wavelength-lookup-table tuning, and meet the following requirements:
  - Semiconductor laser module.
  - Tuning range: 1550 nm with tuning range of C-band.
  - Tuning speed: 5 MHz, and less than 100 ns settling time.
  - Wavelength grid: 10,000 evenly distributed over the whole tuning range.
  - Tuning fashion: Random wavelength grid access, or sequential predefined wavelength lookup table tuning.
  - High wavelength and power repeatability.
  - Low temperature or environmental dependency.

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

**Primary Technology Taxonomy:**
- Level 1: TX 09 Entry, Descent, and Landing
- Level 2: TX 09 X Other Entry, Descent, and Landing

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

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

The following deliverables are desired for Phase I: (1) Hardware demonstrations of
sensor components and applicable support hardware and/or (2) Analysis and software simulations of component proofs of concept within simulated environments. Responses must show a path for the proposed capabilities to be compatible with the environmental conditions of spaceflight.

The following deliverables are desired for Phase II: (1) Hardware demonstrations of sensor components and applicable support hardware and (2) Analysis of components in laboratory or relevant environment (depending on TRL). Phase II products will need to demonstrate a path for the capabilities to be compatible with the environmental conditions of spaceflight.

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

The EDL GN&C and sensors community has been developing for more than a decade the technologies to enable precise safe landing. Infusion of these capabilities into spaceflight missions and spinoff into the commercial sector remains the critical gap. Bridging this gap requires additional component technology advancements for specific lidar sensors that enhance operational performance, increase dynamic envelope, reduce size/mass/power/cost, and enable spaceflight qualification.

**Relevance / Science Traceability:**

GN&C/PL&HA technologies for precise safe landing are critical for future robotic science and human exploration missions to locations with hazardous terrain and/or pre-positioned surface assets (e.g., cached samples or cargo) that pose significant risks to successful spacecraft touchdown and mission surface operations. The PL&HA technologies enable spacecraft to land with minimum position error from targeted surface locations, and they implement hazard-avoidance diverts to land at locations safe from lander-sized or larger terrain hazards (e.g., craters, rocks, boulders, sharp slopes, etc.). PL&HA has maintained consistent prioritization within the NASA and National Research Council (NRC) space technology roadmaps for more than a decade, and multiple near-term science missions, such as Mars 2020, are starting to infuse some of the PL&HA capabilities.

**References:**

Z7.03 Entry and Descent System Technologies

Lead Center: MSFC

Participating Center(s): ARC

Scope Title:

Entry and Descent System Technologies

Scope Description:

Background: NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan, as well as payload return to Earth from low Earth orbit. The benefit of deployable decelerators is that the entry vehicle structure and thermal protection system are not constrained by the launch vehicle shroud. They have the flexibility to more efficiently use the available shroud volume and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. For Mars, this technology also enables delivery of very large (20 metric tons or more) usable payload, which will likely be needed to support human exploration. The technology also allows for reduced cost access to space by enabling the recovery of launch vehicle assets. This subtopic area solicits innovative technology solutions applicable to deployable entry concepts. Specific technology development areas include:

1. Advancements in textile manufacturing technologies that can be used to simplify production, reduce the mass, or reduce the stowed volume of mechanically deployed structures, inflatable structures, or their flexible thermal protection system. Thermal protection concepts can also lead to improvements in thermal management efficiency of radiant and conductive heat transport at elevated temperatures (exceeding 1,200 °C). Concepts can be either passive or active dissipation approaches. For smaller scale inflatable systems for small-spacecraft/satellite applications, less than 5 m in diameter, thin-ply or thin-film manufacturing approaches that can be used to reduce the minimum design gauge are of particular interest for inflatable structures.

2. High-temperature-capable structural elements to support mechanically deployable decelerators that surpass the performance capability of metallic ribs, joints, and struts. Anticipated systems would include composite elements or hybrid approaches that combine metallic structures with high-temperature-capable interface materials to improve thermal performance. Minimum-mass approaches that address volumetric/packing efficiencies at small-scale (approx. 1 to 2 m) implementations are of interest for small-satellite applications.

3. Development of gas-generator technologies used as inflation systems that result in improved mass efficiency and system complexity over both current pressurized...
cold gas systems and present state-of-the-art gas generators for inflatable structures. Inflation gas technologies can include warm or hot gas generators, sublimating powder systems, or hybrid systems; however, the final delivery gas temperature must not exceed 200 °C. Lightweight, high-efficiency gas inflation technologies capable of delivering gas at 250 to 10,000 standard liters per minute (SLPM) are sought. This range spans a number of potential applications. Thus, a given response need not address the entire range. Additionally, the final delivery gas and its byproducts must not harm aeroshell materials, such as the fluoropolymer liner of the inflatable structure. Minimal solid particulate is acceptable as a final byproduct. Water vapor as a final byproduct is also acceptable for lower flow (250 to 4,000 SLPM) and shorter duration missions, but it is undesirable for higher flow (8,000 to 10,000 SLPM) and longer duration missions. Chillers and/or filters can be included in a proposed solution, but they will be included in assessing the overall system mass versus amount of gas generated.

Expected TRL or TRL Range at completion of the Project: 1 to 4
Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Reports documenting analysis and development results, including description of any hardware or prototypes developed. Focus for Phase I development should be material coupon up to subscale manufacturing demonstration articles that demonstrate proof of concept, and lead to Phase II manufacturing scaleup and testing in relevant environments for applications related to Mars entry, Earth return, launch asset recovery, or the emergent small-scale satellite community.

State of the Art and Critical Gaps:

The current state of the art for deployable aerodynamic decelerators is limited due to the novelty of this technology. Developing more efficient, lighter, and thinner flexible thermal protection system component materials with higher temperature capability could potentially enable more efficient designs and extend the maximum range of use of the concepts. Novel and innovative high-temperature structural concepts are needed for the mechanically deployed decelerator. Development of gas generator technologies that improve mass efficiency over current pressurized cold gas systems for inflatable structures is needed.
Relevance / Science Traceability:

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan, as well as payload return to Earth from low Earth orbit. The Human Exploration and Operations Mission Directorate (HEOMD), Space Technology Mission Directorate (STMD), and Science Mission Directorate (SMD) can benefit from this technology for various exploration missions.

References:


Z7.04 Landing Systems Technologies

Lead Center: MSFC

Participating Center(s): GRC, LaRC

Scope Title:

Landing Systems Technologies

Scope Description:

Plume-Surface Interaction (PSI) Instrumentation, Ground Testing, and Analysis

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon, and eventually Mars, characterization of landing environments is critical to identifying requirements for landing systems and engine configurations, instrument placement and protection, and landing stability. The ability to predict the extent to which regolith is liberated and transported in the vicinity of the lander is also critical to understanding the effects on precision landing sensor requirements and landed assets located in close proximity. Knowledge of the characteristics, behavior, and trajectories of ejected particles and surface erosion during the landing phase is important for designing effective sensor systems and PSI risk mitigation approaches. Mission needs to consider include landers with single and multiple engines, both pulsed and throttled systems, landed mass from 400 to 40,000 kg, and both lunar and Mars destinations.
NASA is seeking support in the following areas:

1. Ground test data, test techniques, and diagnostics across physical scales and environments, with particular emphasis on nonintrusive approaches and methodologies.
2. PSI-specific flight instrumentation, with particular emphasis on in situ measurements of particle size and particle velocity during the landing phase.
3. Solutions to alleviate or mitigate the PSI environments experienced by propulsive landers.
4. Validated computational fluid dynamics (CFD) models and tools for predicting PSI physics for plumes in low-pressure and rarefied environments, time-evolving cratering and surface erosion, and near-field and far-field ejecta transport.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services [35]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020, and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

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

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.3 Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Deliverables of all types can be infused into the prospect missions due to early design maturity.

For PSI ground test data, flight instrumentation, diagnostics, and mitigation approaches, Phase I deliverables should include detailed test plans, with prototype and/or component demonstrations as appropriate. Phase II deliverables should include complete data
products, fully functional hardware, and validated performance in relevant environments.

For PSI modeling and simulation, Phase I deliverables should demonstrate proof of concept and a minimum of component-level verification, with detailed documentation on future data needs to complete validation of the integrated model and uncertainty quantification methodology. Phase II deliverables must demonstrate verification and validation beyond the component level, with validation demonstrated through comparisons with relevant data and documented uncertainty quantification.

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

The characteristics and behavior of airborne particles during descent is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere and the characteristics of the regolith are different for the Moon, the capability to model PSIs on the Moon will feed forward to Mars, where it is critical for human exploration.

Currently, flight data are collected from early planetary landing, and those data are fed into developmental tools for validation purposes. The validation dataset, as well as the expertise, grows as a result of each mission and is shared across and applied to all other missions. We gain an understanding of how various parameters, including different types of surfaces, lead to different cratering effects and plume behaviors. The information helps NASA and industry make lander design and operations decisions. Ground testing (“unit tests”) is used early in the development of the capability in order to provide data for tool validation.

The current post-landing analysis of planetary landers (on Mars) is performed in a cursory manner with only partially empirically-validated tools, because there has been no dedicated fundamental research investment in this area. Flight test data does not exist in the environments of interest.

**Relevance / Science Traceability:**

Current and future lander architectures will depend on knowledge of PSI, such as:

- Artemis Human Lander System (HLS)
- Commercial robotic lunar landers (CLPS or other)
- Planetary mission landers (Mars Sample Retrieval Lander and others)
- Human Mars landers

**References:**

Lander Technologies: [https://www.nasa.gov/content/lander-technologies](https://www.nasa.gov/content/lander-technologies) [36]


Z7.06 Entry, Descent, and Landing (EDL) Terrestrial Testing Technologies

Lead Center: MSFC

Participating Center(s): LaRC

Scope Title:

Optical and Laser-Spectroscopic Imaging Techniques for High-Enthalpy Arc-Heated Test Facilities

Scope Description:

Arc-heated high-enthalpy test facilities at NASA’s Ames and Langley Research Centers are used for evaluation and certification of high-temperature materials and structures of an entry vehicle’s thermal protection system (TPS). Future exploration missions will utilize new ablative TPS materials that release decomposition products into the gas stream ahead of the vehicle, influencing flow-field behavior. Data and observations from materials testing programs using NASA’s arc jet facilities are critical for validation of high-fidelity modeling and simulation tools used to design and margin TPS specifications for entry vehicles. However, the complex multiphysics processes that manifest as entry aeroheating of ablative TPSs present formidable challenges for model validation. The available diagnostic techniques for arc jet testing provide little direct evidence of the subject aerothermal and thermophysical processes.

NASA is seeking advanced and new optical and laser-spectroscopic techniques applied to arc jet testing programs. Experimental methods for arc jet facility characterization strive to quantify thermodynamic and gas dynamic properties of the arc jet stream and serve multiple purposes, such as verification of test conditions (facility operations), validation of arc heater and flow-field simulations, and measurement of incident/boundary conditions for material response simulations. Of equal importance are methods that can detect and identify pyrolysis gases and particles injected into the shocked gas region ahead of TPS material test articles, providing needed insight to the complex interactions of the flow field with material response. Experimental methods that measure recession, temperature, and optical properties of the TPS surface enable characterization of surface thermal response phenomenology.

The off-body gas phase diagnostics are to detect and quantify:

- Major species in the arc jet stream (N, O, N\textsubscript{2}, NO for air; CO and CO\textsubscript{2} for facilities capable of operating with CO\textsubscript{2} mixtures).
- Ablation species and recombination products in the shock layer (C, CN, CH, H, Ca).
- Spalled particles from test articles penetrating the shock layer.
Also of importance are measurements of velocity and free stream and shock layer temperatures, including vibrational temperature. Planar or line imaging techniques are desired to characterize spatial distributions with 1-mm or smaller resolution at kHz data rates. Burst mode (>100 kHz) imaging approaches that enable correlation of temporal-spatial intermittencies are of particular interest.

The requested surface imaging diagnostics are to measure test-article temperature and spectral emissivity, topology, and recession rate. Hyperspectral techniques are preferred if they enable characterization of multiple surface properties simultaneously while discriminating from shock layer radiation. Spatial resolutions and acquisition rates of <1 mm and >30 Hz, respectively, are desired. Adaptation of standoff surface spectroscopy techniques may hold promise for time-resolved species detection and identification.

Spallation characterization requires measurements of ejected particle size distributions, 2D and 3D trajectories, and velocity distributions. Techniques for both stagnation and shear testing configurations are desired. Imaging spatial resolution and field of view needs to account for particle trajectories that travel upstream and penetrate shock waves. Methods that provide insight to the chemical composition of spalled particles would be particularly valuable. Anticipated particle size and speeds are 1 to 100 µm and 1 to 200 m/s, respectively.

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

**Primary Technology Taxonomy:**
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

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

**Desired Deliverables Description:**
Phase I: Assessment study of potential diagnostic techniques.
Phase II: Prototype instrument demonstration in relevant environment with hardware delivery to NASA.

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

The requirements for spatially resolved, species-specific measurements of high-temperature-reacting gas properties necessitate the use of optical-spectroscopic methods. The state of the art at NASA’s arc-heated facilities are techniques based on nanosecond-pulsed laser-induced fluorescence (ns-LIF). Pointwise flow property measurement requires approximately 60 to 90 sec per acquisition to recover properties calibrated to engineering units (velocity, temperature, species densities) at one location. The low sensitivity and long standoff distances in arc-heated facilities preclude line or planar imaging. The long acquisition times result in a poor use of expensive testing resources. The ns-LIF approach is not suitable for post-shock and near-surface regions, as the moderate pressures, high temperatures, and strong gas and surface luminosity confound signal interpretation, effectively prohibiting quantitative ablation species detection. Emission spectroscopy techniques for free-stream and shock-layer measurements have been used with success for many years, but these are limited to observation of excited-state populations along integrated lines of sight. Tunable laser absorption spectroscopy can target ground-state or excited-state populations of certain species of interest; however, the low-density/high-temperature test conditions and the short path lengths yield absorbances too low for detection with demonstrated laser absorption techniques.

Recent advances in tunable amplified sources pumped by kHz and burst-mode femtosecond-pulse lasers has enabled the development of several nonlinear laser spectroscopy techniques. These new techniques have capabilities that directly address the sensitivity, temporal, and spatial resolution shortcomings identified above.
For spallation diagnostics, both active interrogation/response and passive imaging techniques have potential for characterizing size distributions, trajectories, and velocity distributions. NASA’s current capability for observing and quantifying spallation is the use of high-speed gated video, which is limited to situations where particle luminosity can be distinguished from background sources.

Relevance / Science Traceability:

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have ED/EDL (entry and descent or entry, descent, and landing) architectures: Mars Sample Return, high-speed crewed return, high-mass Mars landers, Venus, and gas/ice giant probes. With few exceptions, entry vehicle TPS for these missions will be composed of materials currently under development and without certification heritage in multiple gases. Arc jet testing at conditions relevant for certification will invariably be required for each of these proposed missions. Ground testing at more extreme environments for future missions will challenge existing capabilities. There is a compelling need now to bring research-level diagnostic technologies forward to ensure that facility operations can confidently demonstrate required performance to TPS technology projects.

Conventional instrumentation will continue to be the primary source of facility characterization data. The purposes of the advanced techniques are to provide validating evidence for the conventional instrumentation, reveal error and bias in interpretation of heat flux measurements, and ultimately reduce uncertainty in facility performance data provided to test programs.

References:


Scope Title:
Advanced Instrumentation for NASA’s Shock Tube and Ballistic Range Facilities

Scope Description:

NASA Ames Research Center operates two specialized-use impulse test facilities for aerodynamic and aerothermodynamic research investigations that support atmospheric entry systems modeling and validation. The Electric Arc Shock Tube (EAST) facility replicates shocked gas environments encountered by entry vehicles.
transiting planetary atmospheres at hypersonic velocities. EAST creates these environments through calibrated gas mixtures of target atmospheres (Earth, Venus, Mars, Titan, gas giants, etc.) and prescribed preshock pressures and shock speeds. Radiative heating of both fore- and after-body surfaces of an entry vehicle can influence, and in some cases dominate, the design requirements for thermal protection systems. Spectroscopic instrumentation is used to characterize the absolute radiance and gas kinetics behind a traveling shock wave. The Hypervelocity Free Flight Aerodynamic Facility (HFFAF), an enclosed aeroballistic range, is used for the study of dynamically similar supersonic and hypersonic aerodynamics, transition to turbulence, and laminar and turbulent convective heat transfer. Optical imaging instrumentation is used to characterize aerodynamic forces and moments of scaled models launched through the range. Thermographic and spectral imaging instrumentation is used to characterize spatially resolved heating rates to scaled models.

NASA is seeking innovative imaging and spectroscopic measurement techniques for these two facilities. New electro-optic products and methods will enable measurement of quantities unattainable with current capabilities as well as improve current practices.

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Assessment study of potential diagnostic techniques or technology upgrades.
Phase II: Prototype instrument demonstration in relevant environment (preferably with hardware delivery to NASA).

State of the Art and Critical Gaps:

The EAST facility’s instrumentation acquires data for shocked gas phenomenology and facility performance characterization. Measurements of radiance, absorbance, electron density, and temperature are used for validation of comprehensive radiation transport simulations of planetary atmospheres. Those measurements are primarily acquired using calibrated optical-spectroscopic instruments with sufficient temporal and/or spatial resolution to correlate observed magnitudes with localized, spectrally resolved absolute radiant fluxes or columnar property densities (including electron densities). Ancillary instrumentation is used to measure shock arrival times and transient pressures at the tube wall to establish shock speeds adjacent to the science instruments.

Measurement techniques that correlate observables to atomic and molecular state populations and radiance magnitudes enable validation of radiance models. Emission spectroscopy techniques, which capture the transient characteristics of excited atomic and molecular state populations, have reached a high degree of maturity and performance.

However, post-shock electron and ground-state or other dark-state population dynamics also influence shock radiance. Measurement of these states rely on more complicated absorption, induced fluorescence, or scattering (spontaneous and coherent) techniques. The lack of light sources and/or detectors with suitable spectral and temporal characteristics, or the challenges of implementation in impulse facilities, have limited the opportunities for such measurements. Techniques that enable measurement of these states would greatly expand opportunities for radiation transport model validation, particularly for conditions in which self-absorption would influence emission spectroscopy measurements. Specific quantities of interest are rotational/translation and vibrational temperatures, electron temperatures, and ground-state population densities of $\text{N}_2$, $\text{N}_2^+$, N, O, CO, CN, $\text{H}_2$, H.
Spatiotemporal resolution is necessary to discern nonequilibrium relaxation processes behind a traveling shock wave and is the key requirement for EAST diagnostics. Field imaging at a single instant in time, or time-resolved imaging of a single point in space, must have resolutions equivalent to >1 mm and >1 μs to capture these relaxation processes.

For the HFFAF, shadowgraph and schlieren photography are used to provide time-resolved imagery for aerodynamic force and moment analyses of scaled flight vehicles in free flight. A high-speed shutter (40-ns duration) and a spark-gap light source enable images to be captured without motion blur or image fogging from shocked gas radiance enveloping a test model. The shuttering system relies on Kerr cells filled with benzonitrile and a 35 kV pulse-shaping and switching network. Advances are sought for the eventual replacement of the 32 heritage light source/shutter systems with components that offer equal or greater performance as well as improved safety and reliability.

Relevance / Science Traceability:

Several potential future missions outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses have ED/EDL (entry and descent or entry, descent, and landing) architectures: Mars sample return, high-speed crewed return, high-mass Mars landers, and Venus and gas/ice giant probes. Entry vehicles to these destinations will encounter radiative heating to varying degrees. Radiative heating of a vehicle’s backshell has been recognized as a significant concern, so ensuring a full range of diagnostic techniques for expanding flows has become a high priority for the EDL community.

Characterizing the aerodynamic stability of emerging deployable drag devices for entry vehicles is also of high importance for future high-mass lander missions. The HFFAF will be a key ground-test facility for acquiring crucial free-flight aerodynamic data for study and simulation validation.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. Technology development projects supporting these programs are potential beneficiaries of new instrumentation for the EAST and HFFAF.

References:

1. Entry Systems Modeling Project: [https://gameon.nasa.gov/projects/entry-systems-modeling-esm/][37]
3. Many journal papers, conference proceedings, and technical reports describing the NASA Ames EAST and HFFAF test facilities and research are available in the open literature.

Z8.02 Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)

Lead Center: ARC

Participating Center(s): ARC, GSFC, JPL

Scope Title:

End-to-End Deep Space Communications
Scope Description:

Develop enabling communications technologies for small spacecraft beyond LEO. These technologies will be required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in communications technologies for distributed small spacecraft are essential to fulfill the envisioned science missions within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture [Ref. 11], it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include data relay from lunar surface to surface, data relay to Earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple small satellites may be necessary because of limited size, weight, and power (SWaP), but also to enhance coverage.

Technologies for specific lunar architecture are especially needed. For example, landers near the lunar South Pole may not have—and landers on the far side of the Moon will not have—direct line-of-sight to Earth-based ground stations and will need to send data through a relay satellite (or Gateway) to return data to Earth. Small surface systems (including rovers or astronauts on extravehicular activities (EVAs)) on the Moon will likely not have the necessary system resources to close a direct link to Earth. Human surface operations may require surface-to-surface over-the-horizon communications through an orbital relay. Deployment of sufficient traditional communications assets to maintain persistent global coverage of the lunar surface may be prohibitively expensive. Analogous to emerging LEO communications constellations, small spacecraft can operate as local relays in cislunar space.

Considerations of extension of the technologies and capabilities to the martian domain and other deep space applications are also solicited.

Interspacecraft networking is inherent to distributed mission and interoperable communications relay architectures. Enabling networking capabilities in small spacecraft requires low SWaP-C hardware for radio-frequency (RF) and optical cross links. While network protocols developed for interoperable communications relays may be interchangeable with those for distributed missions, relay networks may not be scalable to very large scale sensor webs of small spacecraft. As such, addressing interspacecraft networking gaps may require investment in both hardware cross links and networking protocols that scale to hundreds of nodes, and require robustness for loss of nodes or as new nodes enter the network.

An end-to-end system needs to be considered for the application of small satellites for deep space missions as described in preceding paragraphs. Therefore, enabling technologies also include non-NASA ground services that keep the operations cost commensurate with the lower costs of the small satellites themselves. Automation of the ground services as well as the small satellite constellations are needed.

Communications solutions can operate in optical or various RF bands; however, considerations must be given to bandwidth, public and Government licensing, and compatibility with referenced candidate architectures.

**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 05.2 Radio Frequency

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

- Prototype
- Hardware
Desired Deliverables Description:

Phase I: Identify and explore options for the deep space small-satellite missions, including ground services. Conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of communication technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:

Small-spacecraft missions beyond Earth require compact, low-power, high-bandwidth radios for use on the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. The current state of the art is the Iris radio (0.5U, 1.2 kg, and 35 W) [Ref. 12] that has been operationally used at Mars, and there is no known affordable, readily available competitor. Future missions require systems that are lower SWaP-C, can operate in multiple bands (S, X, Ka-band, and optical), and can reach uplink and downlink speeds in excess of 20 Mbps. Spectral, modulation, information layer, and protocol compatibility with current technologies (Space Communications and Navigation (SCaN)); licensing and spectrum approval; and planned Government or commercial deep space communication architecture must all be considered.

Communications among spacecraft in a distributed spacecraft mission (DSM) configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (10s to 100s of km apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- Uplinks (Earth-to-space) and downlinks (space-to-Earth): Alternatives for coordinated command and control of the DSM configuration and individual small spacecraft from Earth as well as return of science and telemetry data to Earth. Each spacecraft cannot rely on its own dedicated Earth link, consuming valuable ground infrastructure and operators.
- Integrated communications payload: Hardware and software designs for the common and unique capabilities of each small spacecraft in the DSM configuration. Spacecraft communication SWaP-C should be reduced by at least 25% from a non-DSM spacecraft.
- Small-spacecraft antennas: Development of antennas optimized for either intersatellite or uplink/downlink communications are sought across a broad range of technologies including but not limited to deployable parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning subsystems, and others suitable for use in high data rate transmission among small spacecraft over large distances. SWaP-C should be reduced from state of the art, such as the recent 6U CubeSat MarCO mission, which used a 0.2m² X-band reflectarray to achieve 29 dBiC gain and 42% efficiency [Refs. 13, 14]. Operations compatible with NASA’s space communications infrastructure [Ref. 9] and Government exclusive or Government/non-Government-shared frequency spectrum allocations is required [Refs. 6, 7, 8].
- Compatibility and interoperability with lunar communications and navigation architecture plans [Refs. 1, 2, 3]. Application of the emerging lunar standards includes frequency allocations per link functionality,
modulation, coding, and networking protocol standards. Ka-band frequencies and above are highly desired.

Relevance / Science Traceability:

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, Commercial Lunar Payload Services (CLPS); Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE); human exploration (Artemis) landing site and resource surveys; lunar communications and navigation infrastructure, including LunaNet, Mars communications relay, etc. Commercial and NASA small spacecraft, lunar surface assets, and manned vehicles in cislunar space and beyond will multiply within the decade. All of these missions will depend on small-spacecraft communications relays, time reference transmissions, and navigation capabilities.

References:


Relative and Absolute Deep Space Navigation

Scope Description:

Develop enabling technologies for beyond low Earth orbit (LEO) relative and/or absolute position knowledge. This situational awareness allows for autonomous control of small spacecraft as well as determining and maintaining position within a swarm or constellation of small spacecraft. In addition, timing distribution solutions for the SmallSats are important. Earth-independent and Global Positioning System- (GPS-) independent navigation and timing are enabling capabilities required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in navigation technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions.

Multiple small spacecraft operating in coordinated orbital geometries or performing relative stationkeeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small-spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets. Realizing these capabilities on affordable small spacecraft requires sensors and maneuvering systems that are low in mass, volume, power consumption, and cost.

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth-centric aids. Exploration mission operations that involve multiple-element distributed-mission architectures may involve 30 to 100 spacecraft, and the general expansion of the number of cislunar and deep space missions will stress or exceed current capacity of the Deep Space Network (DSN). Access to DSN ranging may not be available for multiple concurrent missions, may be blocked by terrain for surface operations, or may be limited by the radio capabilities of smaller missions. In concert with other available signals of opportunity and landed beacons, small spacecraft can provide relative ranging or triangulation to aid lunar navigation. Knowledge at the spacecraft of relative (between-spacecraft) situational awareness is needed for real-time stationkeeping/relative position control where required rapid reaction speeds preclude human-in-the-loop operation.

Future small-spacecraft missions will need to autonomously determine and transmit relative and absolute position as well as keep and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions and for distributed missions composed of small spacecraft beyond Earth. Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities (e.g., dual use of star-tracking instruments for relative navigation using surface features or other nearby spacecraft), x-ray emissions (from pulsars), and laser ranging to other spacecraft or surface landmarks. For use with small spacecraft, these systems must be compatible with the inherent size, weight, power, and cost (SWaP-C) constraints of the platforms.

Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data collection. Internetworked small spacecraft can help synchronize timing across multiple mission assets using an external timing source. Improvements in chip-scale atomic clocks that can be carried by the small spacecraft themselves can augment this capability to reduce the accumulation of errors over time or serve as the primary clock when other larger but more accurate reference sources are not available or feasible. The vast majority of current commercial interests and Government missions operate in near-Earth orbits. To date, both NASA and the commercial spaceflight industry have enjoyed strong investment in near-Earth situational awareness made possible by tracking and identification capabilities provided by the Department of Defense. As the number of cislunar missions grows and NASA encourages the development of the lunar service economy, similar investments in situational awareness capabilities in these new orbital regimes will be needed to help support NASA and commercial operations.
Primary applications include navigational aids to lunar surface and orbiting users. Distributing these capabilities across multiple SmallSats may be necessary because of limited SWaP, but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the martian domain are also solicited. Navigation solutions for deep space distributed spacecraft missions (DSMs) may be addressed via hardware or software solutions or a combination thereof.

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

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:

- Prototype
- Software
- Hardware

Desired Deliverables Description:

Phase I: Identify and explore options for the deep space navigation technology, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated navigation payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated navigation system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of navigation technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:

Science measurements of distributed satellite missions (DSMs) are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft are involved. State of the art (SOA) for attitude is the Jet Propulsion Laboratory's ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) 6U CubeSat demonstrated pointing stability of 0.5 arcsec (0.1 microdeg) rms over 20 min using guide stars. For position knowledge, missions still primarily use ranging transponders relying on a two-way Earth link. Examples of SOA for this ranging are the Iris transponder and the Small Deep Space Transponder (SDST) [Ref. 13].

Global navigation satellite services like the United States' Global Positioning System (GPS) provide very limited services beyond Geostationary Earth Orbit distances, and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs. Critical areas for advancement are:

- Long-term, high-accuracy attitude determination: In particular, low-SWaP absolute attitude determination using star trackers, etc., to achieve sub-arcsec accuracy.
- Optical navigation: Solutions are sought for visual-based systems that leverage advances in optical sensors (e.g., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. Opportunities for innovation include methods that do not require the execution of satellite maneuvers and/or the design of external satellite features that enhance observability. Innovations
may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various lunar and deep space mission operations concepts are of interest.

- Other novel navigation methods: Stellar navigation aids, such as navigation via quasars, X-rays, and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited.
- Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters and provide control for individual spacecraft. Opportunities for innovation include the application of optimization techniques that are feasible for small satellite platforms and do not assume particular orbit eccentricities.

State-of-the-art in this area is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), the first spacecraft to attempt to navigate to and maintain a near-rectilinear halo orbit around the Moon as a precursor for Gateway [Ref. 11]. NASA is also partnering with universities for use of surface-feature-based navigation and timing [Ref. 12].

NOTE: Small-spacecraft propulsion technologies are not included in this subtopic.

**Relevance / Science Traceability:**

Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of distributed spacecraft missions (DSMs) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, CLPS; human exploration (Artemis) landing site and resource surveys; and lunar communication and navigation infrastructure, including LunaNet, Mars communications relay, etc. All of these missions will benefit from improved communications and navigation capabilities.

**References:**


Z8.08 Technologies to Enable Cost and Schedule Reductions for Optical System for CubeSats

Lead Center: ARC

Participating Center(s): GSFC, JPL

Scope Title:

Technologies to Enable Cost and Schedule Reductions for Optical System for CubeSats

Scope Description:

Concepts for optical systems are sought that will enable larger apertures or longer focal lengths than currently available systems, to be deployed from within small spacecraft. Relatively inexpensive small spacecraft offer several advantages over larger, more expensive spacecraft: small spacecraft can perform inspection and repair of larger spacecraft, several can be deployed for more frequent revisit rates over Earth's surface or planetary objects, and multiple craft can achieve affordable mission reliability through redundancy. To date, the utility of small spacecraft in missions involving remote sensing (in any spectral band) has been constrained by their low budget and compact size; optical sensitivity is limited in proportion to the diameter of a telescope's aperture, and magnification is limited by the effective focal length. The cost to produce one-of-a-kind optical assemblies is disproportionate and the production times too long to incorporate into the tight budgets and schedules typical of small-spacecraft missions.

The objective of this subtopic is to receive proposals that articulate a demonstrable ability to manufacture, test, and control ultra-low-cost observing systems that can meet the reference mission performance requirements (including infrastructure issues) within a time frame and budget compatible with a small-spacecraft development cycle. For the purposes of this subtopic, small spacecraft are defined as CubeSats of 12U volume. Proposals are sought that will

- Specify observing systems figures of merit for a potential small-spacecraft mission, for example:
  - Earth resource management (commercial).
  - Maritime traffic monitoring.
  - Observations for agricultural industry.
  - Fire, flood, or other emergency monitoring.
  - Lunar exploration precursors or observation of human activity at the Moon.
Remote spacecraft health inspection.
Near-Earth object detection.
In-space or lunar-to-Earth optical communications.
Other reference mission to be specified by proposer.

- Include discussion of current state of the art for telescope optical parameters (sensitivity, resolution, and magnification within a spectral band).
- Include production cost and schedule significantly improved by the proposed system design.

Significant areas for proposals are:

- Concept systems that are modular in nature that can be produced in quantities larger than the single-unit production typical of spaceflight hardware builds (for instance, batch or lot production yielding flight units in the quantity range of 30 to 50).
- Concepts that will enable large deployable apertures (optical and related, such as sun shades enabling larger apertures) and/or longer focal lengths than currently available systems that can be implemented from within a 12U small spacecraft. The concepts of large deployable optical apertures and focal lengths for small spacecraft address the fact that small spacecraft are inherently size constrained.

Requirements to be addressed in the project should include specific needs for each wavelength application region, for example:

- For UV/Optical:
  - Wavefront Figure <5 nm rms
  - Wavefront Stability <1 nm/10 min
  - First Mode Frequency >500 Hz
  - Actuator Resolution <1 nm rms

- For EUV:
  - Slope <0.1 microrad

Also needed is ability to fully characterize surface errors and predict optical performance.

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

**Primary Technology Taxonomy:**
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

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

- Prototype

**Desired Deliverables Description:**
Prototype optical system appropriate for inclusion in a 12U CubeSat with up to 8U available for optics. A CubeSat-class precision optical system with an undeployed aperture constrained by a 0.2-m diameter (fits within a 12U volume). For Phase I, deliverables should include a design reference mission relevant to the optical system design, with key performance parameters identified. Identification of key relevant subcomponents of a telescope system that require a prototype demonstration for fabrication, test, or control technology required for a successful Phase II delivery of a prototype.

Ideally, Phase I includes a reviewed preliminary design and manufacturing plan that demonstrates production feasibility, appropriate material behavior, process controls, and optical performance. Mounting/deploying issues, especially with consideration to small spacecraft, should be resolved and demonstrated. While final manufacturing and assembly will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analysis will be done to show compliance with proposed performance measures, survival of the launch environment, and performance in the space environment (Earth orbiting or deep space).

In Phase II, the project could build a prototype and complete environmental qualification testing of the optical system (or a single node in the case of a multi-element system), including measuring optical figure before and after vibration testing, acoustic testing, and thermal cycling. It would also demonstrate that the telescope maintains optical figure in a reference thermal environment including thermal gradients.

A successful mission-oriented Phase II would yield a credible plan to deliver (in Phase III) flight hardware within the allocated budget for a fully assembled and tested telescope assembly that can be integrated into the potential mission. This plan would demonstrate an understanding of how the engineering specifications of their system meet the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis). Cost and schedule goals and optical performance goals are listed under State of the Art and Critical Gaps.

Requirements to be addressed in the deliverables should include specific needs for each wavelength application region, for example:

- For UV/Optical:
  - Wavefront Figure <5 nm rms
  - Wavefront Stability <1 nm/10 min
  - First Mode Frequency >500 Hz
  - Actuator Resolution <1 nm rms
• For EUV:
  - Slope <0.1 microrad

Also needed is ability to fully characterize surface errors and predict optical performance.

State of the Art and Critical Gaps:

Technical Challenges
Ultrastable, normal incidence mirrors with low mass-to-collecting area ratios, affordably produced and delivered, modular and readily integrated into CubeSat-class form-factor, are desired.

Affordably Manufactured, Easily Integrated, Readily Available

After performance, affordability is the most important metric for an advanced optical system, and long telescope fabrication times add significant program cost. Current normal incidence space telescopes in the 0.2- to 0.5-m aperture class have lead times of 12 to 18 months and cost $1 million to $5 million. This research effort seeks a 10× reduction in schedule and cost for precision optical components: a lead time of 4 to 6 months and a cost of $100K to $500K for a 0.2- to 0.5-m aperture-class telescope. Options should be offered for modular and easy installation into a CubeSat-style payload enclosure, with considerations for maximizing aperture sizes, reliable deployment (if required), and reliable optical alignment.

Large Deployable Apertures for Small Spacecraft

Small spacecraft are inherently size constrained. Given the tight volume constraints of CubeSats and other small spacecraft, deployable systems for these platforms need to be highly volumetrically efficient and may employ novel configurations or deployment mechanisms relative to their larger brethren. Systems that can deploy a larger aperture then nominally available in a fixed system can address this constraint.

Affordably Manufactured, Easily Integrated, Readily Available

To accomplish NASA CubeSat-class missions, the mirrors and even entire optical assemblies must be delivered on CubeSat-class schedules after they have been specified. Earth-observing missions and astronomical applications often involve assembling and testing one or many spacecraft within a matter of months from concept to delivery. Optics that can be quickly procured as "catalog items" upon specification must be fabricated and ready for installation—preferably as an assembled module including optics bench and mounting hardware "plug and play" ready—or risk not being available on time for the tight mission schedules.

Relevance / Science Traceability:

A new class of low-cost, optically stable, wide-spectral-range telescopes designed specifically for small spacecraft have application in a variety of exploration, commercial, and science missions. Existing missions can be accomplished in novel and more affordable ways with small spacecraft, and new missions will be enabled by high-performance telescopes in small spacecraft. A few examples include:

• Earth resource management.
• Maritime traffic monitoring.
• Observations for agricultural industry from low Earth orbit.
• Satellite optical crosslinks or lunar satellite-to-Earth optical communications.
• Lunar exploration in situ resource utilization (ISRU) or landing site surveyors or manned surface mission operations observation.
- Remote spacecraft health inspection/monitoring.
- Near-Earth object detection or exoplanet transit detection in deep space.

References:

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Nautilus Observatory: a space telescope array based on very large aperture ultralight diffractive optical elements, Dániel Apai [58], Tom D. Milster [59], Dae Wook Kim [60], Alex Bixel [61], Glenn Schneider [62], Benjamin V. Rackham [63], Rongguang Liang [64], Jonathan Arenberg [65], Proceedings Volume 11116, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems II; [66] 1111608 (2019). https://doi.org/10.1117/12.2529428 [67]

Z8.09 Small Spacecraft Transfer Stage Development

Lead Center: ARC

Participating Center(s): AFRC, GRC

Scope Title:

Small Spacecraft Transfer Stage Development

Scope Description:

NASA and industry represent prospective customers for sending small-spacecraft payloads in the near term to the cislunar environment, with longer term potential for farther destinations such as near-Earth objects, Mars, or Venus. The lunar destinations in this case include the lunar surface, with specific interest in the South Pole, low lunar and frozen lunar orbits, and cislunar space, including Earth-Moon LaGrange points (e.g., E-M L3) and the lunar Near Rectilinear Halo Orbit (NRHO) intended for Gateway. In future missions, NASA may transport small spacecraft to Venus for scientific discovery, to Mars to serve as precursors and infrastructure for human (and scientific) exploration, and on small-spacecraft missions to near-Earth objects for science measurements needed to understand prospective threats to Earth, and perhaps even for resource extraction and return to Earth. The ultimate goal is to exploit the advantages of low-cost and rapidly produced CubeSats and small spacecraft, defined as total mass less than 180 kg fueled, by enabling them to reach these locations. Due to the current limits of SmallSat propulsion capabilities and the constraints of rideshare opportunities, NASA has an interest in the development of a low-cost transfer stage to guide and propel small spacecraft on trajectories to the vicinity of the Moon, then enable their insertion into the above-referenced orbits with the transfer stage or within sufficient proximity to achieve and maintain final orbit under their own power. These same capabilities and others will later need to be extended for small spacecraft to explore nearby planets.

Transfer stage architectures and designs shall be compatible with U.S. small launch vehicles that are currently flying or will be launching imminently. Proposals shall identify one or more relevant small launch vehicles, describe how their designs fit within the constraints of those vehicles, and define the transfer capability of the proposed system (i.e., from low Earth orbit (LEO), geosynchronous transfer orbit (GTO), etc., to low lunar orbit (LLO), NHRO, E-M L3, etc.). Transfer stage designs shall contain all requisite systems for navigation, propulsion, and communication in order to complete the mission. Any and all propulsion chemistries and methods may be considered, including electric propulsion, as long as the design closes within the reference mission constraints. Transfer stages shall also include method(s) to deploy one or more SmallSat payloads into the target trajectory or
orbit. Innovations such as novel dual-mode systems that enable new science missions or offer improvements to the efficiency, accuracy, and safety of lunar missions are of interest. Concepts that can demonstrate improvements in cost and reliability and those that reduce requirements (thermal, power, etc.) on the payload are also highly desired.

This subtopic is targeting transfer stages for launch vehicles that have a capability range similar to that sought by the NASA Venture Class Launch Services. Rideshare applications that involve medium- or heavy-lift launch vehicles (e.g., Falcon 9, Atlas V) or deployment via the International Space Station (ISS) airlock are not part of this topic.

Lunar design reference mission:

- Launch on a small launch vehicle (ground or air launch).
- Payload (deployable spacecraft) mass: at least 25 kg.
- Provide sufficient delta V and guidance to enter into Trans Lunar Injection (TLI) orbit after separation from small launch vehicle. An example mission is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)/NRHO Pathfinder 12U (25 kg) CubeSat that requires a TLI orbit with a C3 of $-0.6 \text{ km}^2/\text{s}^2$.
- (Alternative) Provide sufficient delta V and guidance to place a 25- to 50-kg spacecraft directly into lunar NHRO or E-M L3 orbit.
- Deploy spacecraft from transfer stage.
- Safe and disposal of transfer stage.

A stretch goal is extensibility of the design for planetary design reference missions: Similar to the above, for Venus, Mars, or near-Earth object destinations.

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

**Primary Technology Taxonomy:**
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.1 Chemical Space Propulsion

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

- Prototype
- Hardware
- Software
- Analysis

**Desired Deliverables Description:**

A Phase I effort should provide evidence in the feasibility of key elements of cost, assembly, integration, and operations through fabrication or testing demonstrations. A prototype system should reach a "near CDR" level during Phase I with a mapping of key performance parameters (mass, power, cost, etc.) from the prototype to the flight design, along with potential opportunities for technology demonstration and commercialization.

It is highly desired that the Phase II deliverable include demonstration test of the prototype system along with detailed metrics (mass, power, cost, etc.) traceable to a flight design for the reference mission. Efforts leading to Phase II delivery of integrated prototype systems that could either be ground- or flight-tested as part of a post-Phase II effort are of particular interest.

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

Many CubeSat/SmallSat propulsion units are designed for low delta-V maneuvers such as orbit maintenance,
stationkeeping, or reaction control. Larger delta-V systems are employed for larger satellites and science/exploration missions, but are often costly and integrated as part of the satellite design. Systems typically range from cold-gas to bipropellant storables with electric systems also viable for very small systems. Rocket Lab has recently introduced an upgraded version of their monopropellant kick stage, which includes a bipropellant engine, advanced attitude control, and power subsystems. This system will be used for the first time for NASA's CAPSTONE mission and is suggested to have capability for orbits beyond the lunar environment. At the component level, Aerojet Rocketdyne and Moog, Inc. are prominent suppliers of state-of-the-art (SOA) thrusters, including commonly used variants of the R-4D engine, while companies like Blue Canyon Technologies offer spacecraft bus solutions absent dedicated propulsion elements. Advanced manufacturing, electric pumps and actuators, nontoxic propellants, and electrospray throttles all offer potential improvements in the flight capabilities of small propulsion systems. System concepts that enable improved spacecraft performance and control, such as dual-mode systems, provide potential advancements to the current SOA, especially those that enable new science missions and those that offer potential improvements to the efficiency, accuracy, and safety of future lunar manned missions. While many of these component technologies are reasonably mature, no integrated system capability has been developed and implemented specifically as a rapid, low-cost solution for translunar or cislunar mission designs.

Relevance / Science Traceability:

This subtopic extends the capabilities of the Flight Opportunities Program and Launch Services Program by seeding potential providers to establish lunar/cislunar transfer capabilities. The Small Spacecraft Technology Program (SSTP) also seeks demonstrations of technical developments and capabilities of small spacecraft to serve as precursor missions (such as landing site investigation or in situ resource utilization (ISRU) prospecting) for human exploration, and as communications and navigation infrastructure for follow-on cislunar missions. SSTP CAPSTONE is an example mission.

Many technologies appropriate for this topic area are also relevant to NASA's lunar exploration goals. Small stages developed in this topic area would also be potential flight testbeds for cryogenic management systems, wireless avionics, or advance guidance systems and sensors. Sound rocket capabilities are being improved with options financed through this topic.

Small launch vehicles provide direct access for a small spacecraft to the destination or orbit of interest at a time of the small spacecraft mission’s choosing. In support of exploration, science, and technology demonstration missions, further expansion of these vehicle’s reach beyond LEO is needed. To expand the risk-tolerant small spacecraft approach to deep space missions, frequent and low-cost access to destinations of interest beyond Earth is required.

In the longer term, technical capabilities of small spacecraft at Venus, Mars, or NEO destinations will be demonstrated by SSTP, and ultimately new kinds of transfer vehicles derived from these capabilities may be needed to propel them there.

References:

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Z8.10 Wireless Communication for Avionics and Sensors for Space Applications

Lead Center: ARC

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

Scope Title:

Modular and Flexible Wireless Avionics Architectures and Wireless Sensing and Integrated Avionics for Space Applications

Scope Description:

The Wireless Communication for Avionics and Sensors for Space Applications subtopic solicits proposals to develop enabling concepts, components, and subsystems based on innovative avionics architectures for small spacecraft. Of interest are wireless systems that demonstrate reliable data transfer across avionics components, subsystems, and interfaces to simplify system integration, reconfiguration, and testing. These can range from developmental and flight instrumentation systems used for qualification and diagnostics on large spacecraft to full-up wireless avionics for small spacecraft. Solutions that enable new avionic architectures and provide capabilities that expand mission performance while decreasing the size, weight, and power consumption (SWaP) and cost of the resulting spacecraft are highly desirable. The goal of this effort is to mature wireless avionics technology that facilitates the reuse of components, subsystems, and software across multiple spacecraft and missions while reducing production and operating costs.

Modularity is defined as utilizing a set of standardized parts or independent units to form a full avionics system, and flexibility allows adapting modular components across different configurations, missions, and design stages. For example, wireless subnets improve modularity by eliminating the physical data connections from each component, simplifying physical integration. The scope is intended to range from simple wireless sensors to complete avionics systems, including software incorporating functions compatible with common spacecraft components. This means being able to integrate a given component or entire subsystem into flight hardware and software using object-oriented frameworks, allowing components or functions to be added to a new or existing spacecraft design without requiring significant changes to the other nonrelated components or subsystems.

This subtopic also solicits proposals to develop techniques, components, and systems that reduce or eliminate the dependency on wires, connectors, and penetrations for sensing and for the transmission of data and power across avionics subsystems, interfaces, and structures. Of interest are techniques that enable new applications through the use of innovative methods such as the use of flexible materials and additive manufacturing. For example, the use of additive manufacturing and 3D printing to embed avionics components such as antennas, sensors, transmission lines, and interface functions into a spacecraft structure during the design and manufacturing process can increase efficiency while maintaining structural integrity. Similarly, the use of thin and flexible materials to construct passive wireless sensors enables sensing systems for structures such as parachutes and inflatable spacecraft without breaching the pressure interface. Systems that are applicable to small spacecraft (typically 6U/12U/24U CubeSats, including ESPA-class (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter)) but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include cislunar, lunar orbiting, lunar landed, and exploration precursor missions; low Earth orbit (LEO) “swarms” for Earth science and heliophysics; and disaggregated cooperative ensembles and sustained infrastructure for human exploration. New applications might include manned spacecraft inspection, repair, communications support, and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.
The subtopic solicits developments in wireless avionics and wireless sensing for small spacecraft and may include technologies that:

1. Improve the reliability and applicability of wireless avionics for small spacecraft with significant improvements in subsystem size, mass, and volume, particularly if the technology can simplify the spacecraft fabrication, test, and integration process.
2. Allow innovative architectures for wireless avionics featuring plug-and-play software supporting modular subsystems that can be easily incorporated into specific small-satellite missions.
3. Improve fault detection aboard spacecraft using wireless sensor systems to augment current wired sensors and which include the capability of adding sensors to address developmental and flight instrumentation use.
4. Use innovative techniques for embedding sensors and other avionics components into a spacecraft to reduce or eliminate large and heavy cables and connectors, or that enable data transfer inside and across rotating mechanisms and pressure interfaces or into remote locations where it is difficult or unfeasible to run cables or where cables are at risk of failure.
5. Use additive manufacturing of wireless components such as antennas, sensors, and processing elements to create new components that may be smaller and lighter than current products. These new components could possibly be embedded into materials and structures that enable in situ structural health management, contributing to the development of smart structures and materials.
6. Include sensors and actuators that can be distributed among cooperative spacecraft to enable automated inspection of space assets or resource detection at the surface of the Moon, Mars, or other celestial bodies.

Key performance parameters (KPPs) would include improvements of at least a factor of 2 over existing technology in size, mass, and power consumption for sensors and associated components for a wireless instrumentation system. Improvements of sensor network throughput greater than 5x the current 2-Mbps performance is desired, along with reduction of latency and incorporation of timing information.

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

**Primary Technology Taxonomy:**
- Level 1: TX 02 Flight Computing and Avionics
- Level 2: TX 02.2 Avionics Systems and Subsystems

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

- Hardware
- Prototype
- Software
- Research
- Analysis

**Desired Deliverables Description:**

Possible deliverables include benchtop hardware systems that demonstrate reliable wireless interconnectivity of two or more modules with a host flight central processing unit (CPU), or payload/developmental flight instrumentation (DFI) processor, inside a CubeSat or small-satellite form-factor bus. This system need not be flight ready, but it should be in a path to a flight demonstration that would serve as technology maturation and risk reduction activity for larger NASA missions such as Gateway and other Artemis projects.

**Specific Phase I deliverables include:**

- Methods of improving reliability of wireless avionics technology.
- Redundancy methods to broaden mission applicability.
• Improvements in tolerance to extreme environments including radiation.
• Novel avionics architecture definition and demonstration.
• Software support for redundant modular avionics.
• Plug-and-play methods for handling dynamic changes to avionics configuration.
• Fault detection and recovery for wireless avionics.
• Improvements in spacecraft production.
• Improvements in spacecraft integration and test.
• Technologies that use additive manufacturing technology for embedded avionics systems that reduce cables, connectors, and penetrations and show a path to a full solution.
• Sensors and sensor systems based on current technology needs to develop point solutions that are applicable to NASA missions in near- to mid-range time frames.

Phase II deliverables should build upon the work completed in Phase I to demonstrate the new technology at a higher Technology Readiness Level (TRL) with alignment to NASA mission needs:

• Demonstration showing the key innovations of the developed technology.
• Demonstration of specific new mission capabilities.
• Delivery of prototype hardware for NASA evaluation.

State of the Art and Critical Gaps:

Development of small satellites missions benefit from a growing number of users worldwide. This means there may be a large pool of COTS components available for a specific mission (depending on the type and class of mission). A variety of command and data handling (C&DH) developments for CubeSats have resulted from in-house development, from new companies that specialize in CubeSat avionics, and from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the onboard computer, memory, electrical power system (EPS), and the ability to support a variety of input and output (I/O) for the CubeSat class of small spacecraft.

Wireless networks have been incorporated as crew support aboard the International Space Station (ISS). Wireless sensor networks have been flown as demonstrations. Dynamic self-configuring wireless networks have been evaluated in the lab. AIAA has defined the Space Plug-and-Play (SPA) standard, and flight demonstrations are planned.

The maturation of additive manufacturing and 3D-printing technology are making embedded wireless sensors and avionics a possibility. Embedding transmission lines, antennas, connectors, and sensors onto a spacecraft structure turns that structure into a multifunctional system that reduces or eliminates bulky cables and connectors. Embedded passive wireless sensors can greatly increase sensing and telemetry capabilities, including providing low-cost techniques for vehicle health management in future missions. Moreover, flexible embedded passive sensors created with conductive and functional fabrics are enabling new opportunities for sensing in surfaces and systems where sensing has been traditionally absent, such as parachutes and inflatable structures.

Relevance / Science Traceability:

NASA and other space agencies are exploring the application of SmallSats for deep space missions. The availability of modular wireless data connectivity alleviates complexity in testing and integration of systems. Modular components allow easier reconfiguration and late additions to any design. This is a benefit conferred on any spacecraft of any size, with the larger systems benefiting from savings in mass due to a larger reduction in cable harnesses and connectors.

References:

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Z8.11 Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control

Lead Center: ARC

Participating Center(s): GSFC, JPL

Scope Title:

Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control

Scope Description:

Constellations of small spacecraft currently provide unprecedented persistent coverage of the Earth’s surface, but the use of distributed missions for exploration infrastructure and multipoint scientific measurements beyond Earth will require new approaches to operational efficiency. Current commercial constellations use ground-based semiautonomous scheduling and orbital maintenance to decrease the need for spacecraft-by-spacecraft human-in-the-loop decision making. However, each spacecraft is still individually commanded by the ground-based system. For missions operating beyond Earth, the spacecraft will need to be operated as a single unit. Enabling command and control capabilities within the flight element of the distributed mission will allow control of an otherwise impractical number of small spacecraft as well as decreased operational costs for missions with fewer spacecraft.

NASA intends to expand the exploitation of small spacecraft swarms (or potentially constellations) in support of exploration and science missions. Multiple numbers of SmallSats, working in concert, offer unique capabilities and benefits to space researchers and satellite operators. For instance, some of these advantages embedded in fractionalized architectures, such as fault-tolerance and continuous repair and upgrades enabling dynamic, agile, adaptable mission plans, are better able to deal with the unplanned and unexpected. However, as the number of spacecraft grows, and destinations of interest move farther away from traditional low Earth orbit (LEO) orbits, operational challenges created by managing large numbers of agents along with significant space-to-ground communication latencies and bandwidth issues require alternative architectures that are able to make time-critical
decisions and operate within the maneuvering limitations of each swarm member. Innovative technologies such as AI/ML can contribute significantly to the success of these deep space, multi-spacecraft missions by providing local control less reliant on the ground, as well as optimal use of propulsion.

Small spacecraft operating in formation, in close proximity to other objects, or beyond the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously. These sensor-driven operations will be enabling for safe proximity operations with spacecraft or small bodies as well as the detection and reaction to transient events for observation.

This subtopic is interested in software agents and architectures that enable relative stationkeeping, multi-spacecraft orbit determination and prediction, autonomous reactive operations, and interspacecraft timing and communications to enable the above. Proposals should address software applications and/or network applications that enable:

- Efficient information exchange between individual spacecraft.
- Minimal reliance on ground commanding.
- Efficient use of space-qualified computing architectures.
- High-precision swarm navigation and control.
- Asymmetric use of ground assets (emphasizing space side over ground side).

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.2 Reasoning and Acting
Desired Deliverables of Phase I and Phase II:

- Software
- Prototype

Desired Deliverables Description:

Phase I Deliverables:

1. Software architecture design, including figures of merit (FOMs) for performance.
2. Test-bed environment for software development and testing (identify requirements or develop/describe test bed).
3. Plan to continue through Phase II.
4. Phase I report.

Phase II Deliverables:

1. Software suitable for testing on test-bed environment.
2. Software description/documentation.
3. Final report, including test results.

State of the Art and Critical Gaps:

Currently, the operation of each small spacecraft is individually planned, scheduled, and commanded. Signals from each individual small spacecraft are acquired by ground stations individually. Volumes of unprocessed raw data demand high bandwidth, and this becomes even less practical for greater numbers of cooperative small spacecraft operating at farther distances. As SmallSats are deployed to the Moon, Mars, near-Earth objects (NEOs), and other
distant locations, it is costly—in terms of antenna time and human labor—and impractical due to time-of-flight delays at long distance and the fast dynamics of formation flight and cooperative operations to command and control each spacecraft individually, to react to dynamic situations at very remote destinations, and to change the focus of observations, data acquisition, and sample manipulation as areas of interest are discovered at the target. Very little has been done with true swarms of SmallSats, especially in deep space or even lunar locales. Flight processors are becoming more capable, but advanced software, autonomous processes, and adaptive systems that take advantage of increased processing power for SmallSats lag behind. Intelligent, adaptive behaviors and autonomous decision making in reaction to changing conditions at the target, with minimal dependence on Earthbound operators, is needed.

Relevance / Science Traceability:

The Small Spacecraft Technology Program is very interested in developing and demonstrating this technology for a broad list of crosscutting applications within the Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD). Examples include:

- Fault-tolerant swarms composed of individual assets capable of reassigning their function to compensate for loss of an individual spacecraft.
- Spacecraft capable of decisions and tactical adaptation for acquiring, preprocessing, and transmitting scientific information (rather than raw data) at distant science or exploration destinations.
- Cooperative groups of spacecraft capable of disaggregated inspection, repair, resource resupply, and other functions autonomously and cooperatively at cislunar or more remote destinations.

Small spacecraft conducting science will need to make observations, process dynamic conditions, make decisions, and adapt their performance without manual intervention (for example, sampling the eruption of a plume at Enceladus).

Suggested use cases:

- Investigation of near-Earth asteroids (NEAs) – Orbit determination and maneuvering around an asteroid.
- Coordinated sensor operations (remote sensing, etc.) between multiple spacecraft at planetary destinations.
- Coordinated observation of distant objects (stars, planets) using multiple sensor platforms.
- Autonomous formation flying and inspection of other space assets.

References:

Achieving Science with CubeSats: Thinking Inside the Box. Committee on Achieving Science Goals with CubeSats; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine, 2016. Committee Chair: Thomas Zurbuchen. ([https://doi.org/10.17226/23503](https://doi.org/10.17226/23503))


Z8.12 Modular and Batch-Prodicable Small Spacecraft

Lead Center: ARC

Participating Center(s): MSFC
Scope Title:

Modular Open Systems Architectures for Small-Spacecraft Platforms

Scope Description:

This supertopic requests advances within modular open systems architectures for small spacecraft. As the most accessible spacecraft platform logistically and financially, small spacecraft benefit from a heritage based on rapid deployment and cost-effective missions. To further the state of the art (SOA) of both of these considerations, further cost savings may be found by standardizing the system architectures that drive the subsystems for these platforms. Such a realization would enable modular, hot-swappable spacecraft subsystems to accommodate the ever-increasing need for a wider definition of what small spacecraft are capable of and utilized for.

The development of standardized, hot-swappable interfaces should be compliant with and cognizant of NASA spacecraft standards. Of particular interest are designs acquiescent to the Agency standards existing between grounding, thermal, software, and data transfer interfaces.

The adaptability introduced by an open and modular, interchangeable commercial-off-the-shelf (COTS) architecture furthers the ability to tailor current spacecraft designs for novel applications without requiring significant modifications to existing platforms. Also of interest are advances in modules that minimize complexity in spacecraft manufacturing (such as detering geometrical modifications by virtue of manufacturing). Advances in additive manufacturing may enable critical enhancements to the performance of small-spacecraft systems by embedding otherwise impractical internal features (such as through holes and cavities for electronics integration).

Systems that are applicable to small spacecraft (CubeSats up to Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class), but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include:

- Cislunar, lunar orbiting, lunar landed, and exploration precursor.
- Low Earth orbit (LEO) “swarms” for Earth science and heliophysics.
- Disaggregated cooperative ensembles and sustained infrastructure for human exploration.

New applications might include manned spacecraft inspection, repair, communications support, and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in open modular architectures for small spacecraft and may include technologies that:

1. Provide interchangeable hardware and software with standardized interfaces.
2. Enable spacecraft to be built up from “plug and play” components.
3. Improve the state of the art of open interfacing platforms suitable for small spacecraft, leveraging COTS wherever possible.
4. Leverage novel manufacturing-in-the-loop considerations for small-spacecraft design standardization.
5. Increase the reliability and durability of small-spacecraft hardware and software by integrating subsystem considerations directly into the design process at the architectural level.
6. Demonstrate expanded adaptivity for small spacecraft, allowing for platforms to be rapidly varied with respect to altering objectives and variable risk postures.

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

**Primary Technology Taxonomy:**

Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

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

Promising platform architectures that enable the standardization of COTS hardware and software could be demonstrated through benchtop setups validating numerous protocols and compliance with existing NASA design standards for small spacecraft. A demonstration of ease of hot-swapping would be ideal, demonstrating how rapidly such a system could be adapted for altered requirements with new instrumentation and subsystems.

The deliverables should address improvements for ease of integration of varied hardware and software, plug-and-play integration of small-spacecraft subsystems, increased assembly speed of small spacecraft, utilization of advanced manufacturing for ease of integration, automated error assessment for targeted repairability of subsystems, reduced small-spacecraft design complexity, and reduction of small-spacecraft development cost through standardized COTS.

Phase I Deliverable:

Trade study for and demonstration of how NASA small-spacecraft standards, such as thermal, grounding, and software/data normalizations, could be implemented into hot-swappable, modular architecture.

These architectures must be cognizant of:

- NASA thermal interface standards to demonstrate necessary conductivity and respective thermal isolation.
- NASA grounding interface standards to mitigate unwanted currents through single- or multiple-point grounding framework.
- NASA software and data interfacing standards, complying with Unified S-Band (USB) or Consultative Committee for Space Data Systems (CCSDS) standards.

Phase II Deliverable:

A benchtop hardware demonstration of open and modular architectures at work, exhibiting the standards within Phase I being conserved. The components should take advantage of supply-chain-compliant, heritage-relevant COTS whenever possible.

State of the Art and Critical Gaps:

The current SOA leverages COTS and compiled standards for integrating small spacecraft into a functional system meeting varied mission requirements. A number of in-house developments within NASA have complemented progress in academia and private industry to develop the infrastructure required to expand and normalize the definition of small-spacecraft-compliant subsystems and instrumentation. An issue arises with the software and hardware architecture regulating the agreement of these subsystems with NASA standards. Commercial vendors offering plug-and-play components are often only compliant with a limited number of subsystems, and consequently there exists a need to address this with an open modular architecture to enable more rapid, compliant, and consequently cost-effective small spacecraft that meet NASA's standards. Notable standardization gaps exist within communication gaps (such as wireless systems) and interconnectivity protocols, including but not limited to sustainable (and commonly grounded) power and data transfer with respect to manufacturability considerations.

Relevance / Science Traceability:

NASA and other space agencies are exploring the application of SmallSats for deep space missions. Modular architectures would enable a hot-swap adaptivity to altering mission requirements and serve as low-cost, rapid solutions for emerging destinations as they arise. Modular components allow easier reconfiguration and late additions to any design. Small-spacecraft modularity can be analogous for larger systems as well by virtue of
defining and standardizing interconnectivity of universal COTS systems, enabling new objectives to be realized with a wide variety of instrumentation with a wide scope of requirements.

References:


Scope Title:

Batch-Producible Small Spacecraft

Scope Description:

The Batch-Producible Small Spacecraft subtopic requests proposals to address the need for industry collaboration to manufacture 30 to 100 small spacecraft for a wide variety of missions, addressing objectives ranging from heliophysics to constellation demonstrations and sensor web applications. The ability to fabricate relatively large "batches" of spacecraft will play an important role with regard to the throughput required for addressing the needs of the mission objectives listed above. As an advent in tandem with small-spacecraft swarms, batch-producible spacecraft are an increasing need as larger spacecraft are replaced with many smaller spacecraft, distributing sensing and collaboratively accomplishing objectives enabled novelty by variable topologies and network-based considerations.

Advances in batch producibility are in tandem with standardization of rapid manufacturing of small spacecraft by private industry and will likely take advantage of advances in throughput-favorable fabrication methods. The manufacturability of batch-producible small spacecraft would need to consider the required throughput of manufacturing as a factor intrinsic to the small-spacecraft design itself. These systems must still remain compliant with existing NASA small-spacecraft protocols for thermal, electrical, communications, and redundancy considerations. However, batch-producible spacecraft should leverage design methodologies that would decrease the cost and increase the compatibility of these standardized requisites by virtue of the manufacturing process itself, exhibiting design-for-standardization through the engineering process.

Such a batch-producible set of small spacecraft should leverage supply chain considerations wherever possible and should integrate commercial-off-the-shelf (COTS) components and instrumentation into the design of spacecraft architecture. The end result of rapidly manufacturable batches of spacecraft should demonstrate a significant reduction in manufacturing costs for 30 to 100 buses, with quicker turnaround times than otherwise possible over a range of NASA-relevant projects.

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

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverable
An overview and technical description of methods for batch producibility of small spacecraft within the range of 30 to 100 buses, demonstrating the integration of COTS as part of the framework. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- A standardized high-throughput manufacturing method to enable the fabrication of small spacecraft in batches of 30 to 100 buses (within the scope of CubeSats, up to and including ESPA-class spacecraft).
- A systematic decision tree that addresses fabrication turnaround-time considerations as a factor of spacecraft complexity.
- Demonstrated cost decreases for spacecraft batches with respect to the current state of the art (SOA).
- The integration and normalization of COTS relevant for batch production of small spacecraft as a function of supply chain availability and vendor capabilities.

Phase II Deliverable

Integrating small-spacecraft standards into batch production and demonstrating an infrastructure that is batch-compliant. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- The integration of common NASA small-spacecraft standards (such as thermal, grounding, communications) directly into batch producibility.
- A method for rapid assembly of batch-produced small spacecraft that accounts for manufacturability directly into the architecture of common subsystems (such as power, communications, etc.).

State of the Art and Critical Gaps:

The current SOA of batch-produced small spacecraft relies heavily on the industry-demonstrated heritage of COTS for small-satellites. These systems have limited throughput considerations and are currently inappropriate for meeting future mission requisites pertaining to small spacecraft requiring the fabrication and integration of 30 to 100 spacecraft at a time (such as those relevant to heliophysics missions, network demonstrations, and swarm considerations).

Relevance / Science Traceability:

Partnership with industry on batch production of spacecraft will be required for distributed missions including synthetic apertures, disaggregated science observations, rapidly established planetary communications architectures, constellations, and sensor web applications; planned heliophysics missions call for 30 to 100 spacecraft. Technology development missions would also benefit from low-cost and shorter lead-time standardized bus platforms.

References:

- [https://www.nasa.gov/sites/default/files/atoms/files/nac_march2017_bibl_ida_sstp_tagged.pdf](https://www.nasa.gov/sites/default/files/atoms/files/nac_march2017_bibl_ida_sstp_tagged.pdf) [90]
- [http://msfc.atl.calpoly.edu/~workshop/archive/2018/Spring/Day%201/Session%201/JimCockrell.pdf](http://msfc.atl.calpoly.edu/~workshop/archive/2018/Spring/Day%201/Session%201/JimCockrell.pdf) [91]
Z10.01 Cryogenic Fluid Management

Lead Center: GRC

Participating Center(s): JSC, MSFC

Scope Title:

Cryogenic Fluid Management (CFM)

Scope Description:

This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, methane) storage and transfer to support NASA’s space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include, but are not limited to, upper stages, ascent and descent stages, refueling elements or aggregation stages, nuclear thermal propulsion, and in situ resource utilization (ISRU). Anticipated outcome of Phase I proposals is expected to deliver proof of the proposed concept with some sort of basic testing or physical demonstration. Proposals shall include plans for a prototype and demonstration in a defined relevant environment (with relevant fluids) at the conclusion of Phase II.

- Integrated refrigeration cycles for a combination of hydrogen and oxygen liquefaction on the lunar surface. Cycles should be initially sized for at least 11.7 metric tons per year (3.3 kg/hr of oxygen and 0.4 kg/hr of hydrogen). It is desired to minimize the mass and power of the system. Proposals should compare total input power and mass to liquefaction of fluids separately. The main contaminant is water; while the final contamination level is not known, some sensitivity should be explored in the 10s of ppm range in each stream. For Phase I, the main product should be cycle analysis and configuration, including the key sensitivities of the cycle. Phase II should include some level of buildup and test/demonstration of system.

- Subgrid computational fluid dynamics (CFD) of the film condensation process for 1g and low-gravity (lunar or martian) to be implemented into commercial industry standard CFD codes. The subgrid model should capture the formation and growth of the liquid layer as well as its movement along a wall boundary. The condensation subgrid model should be validated against experimental data (with a target accuracy of 25%), with emphasis on cryogenic fluid-based condensation data. The subgrid model and implementation scheme should be a deliverable. Phase I should be focused on simplified geometries (vertical plates/walls), while Phase II should be focused on complicated geometries (full propellant cylindrical).

- Integrated cryogenic propellant gas generation system for lander vehicles and supporting architecture: Design and develop concepts to enable integrated cryogenic propellant gas generation for lander vehicle reactor coolant system (RCS) gas accumulators. Proposers shall consider vehicle designs that use either liquid hydrogen/liquid oxygen or liquid methane/liquid oxygen main propellant combinations. Designs shall be capable of outputting a minimum 3,000-psia storage press at 300-K storage temperature and meeting the following minimum mass gasification rates: 0.1 g/sec hydrogen, 0.3 g/sec methane, and/or 0.5 g/sec oxygen. The gas generation system shall demonstrate novel integration into alternate vehicle heat sources such as thermal control systems, active CFM cooling systems, fuel cells, internal combustion (I/C) engines, electrical power systems, pumps, etc. Proposed gas generation system shall not couple to vehicle main engines or RCS thruster during firing operations. Proposers should consider integration into vehicle system architectures, mass efficiency, and minimization of propellant waste. Phase I effort should include vehicle integration concept design, design of autogenous pressurization hardware, and test demonstration of autogenous pressurization hardware using liquid cryogens. Phase II should focus on system refinement and a scale test demonstration using liquid propellants.

- Develop cryogenic mass flow meters applicable to liquid oxygen and methane, having a volumetric flow measurement capacity of 1 to 20 L/min (fluid line size of approximately ½ in.), of rugged design that is able to withstand launch-load vibrations (e.g., 20g rms), with remote powered electronics (not attached to the flowmeter), able to function accurately in microgravity and vacuum environment, and having measurement error less than +/- 0.5% of the mass flow rate reading. Ability to measure bidirectional flow, compatibility
with liquid hydrogen, and ability to measure mass flow rate during two-phase flows is also desired. Designs that can tolerate gas flow without damage to the flowmeter are also desired. Goal is proof of concept end of Phase I, working flowmeter end of Phase II.

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

**Primary Technology Taxonomy:**
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.1 Cryogenic Systems

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

- Hardware
- Software

**Desired Deliverables Description:**

Phase I proposals should at minimum deliver proof of the concept, including some sort of testing or physical demonstration, not just a paper study. Phase II proposals should provide component validation in a laboratory environment, preferably with hardware deliverable to NASA.

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

CFM is a crosscutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU-produced propellants. The Space Technology Mission Directorate (STMD) has identified that CFM technologies are vital to NASA’s exploration plans for multiple architectures, whether it is hydrogen/oxygen or methane/oxygen systems, including chemical propulsion and nuclear thermal propulsion. Several recent Phase IIs have resulted from CFM subtopics, most notably for advanced insulation, cryocoolers, and liquid acquisition devices.

**Relevance / Science Traceability:**

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; CFM is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Artemis as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g., depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, oxygen will have to be produced, liquefied, and stored, the latter two of which are CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that has to be landed.

**References:**


**Z10.03 Space Nuclear Propulsion**

Lead Center: GRC

Participating Center(s): GRC, SSC
Scope Title:

Reactor and Fuel System for Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP)

Scope Description:

The focus is on highly stable materials for nuclear fuels and nonfuel reactor components (insulator, moderator, etc.) that can heat the working fluid to high temperatures, be compatible with the working fluid, minimize dimensional deformation during operation, and be easy to manufacture to meet the design requirements.

NEP relies on reactor systems capable of achieving 5-yr life with a working fluid exit temperature of at least 927 °C and a thermal power of at least 5 MW. Innovative concepts for enhancing reactor reliability, fabricability, and testability while still enabling an acceptable power system specific mass (typically <15 kg/kWe) are sought. Projected use for human missions to Mars will require continuous run times ~2 yr.

NTP uses hydrogen as the working fluid (propellant). Fuel temperatures required to achieve a specific impulse (Isp) of 900 sec can exceed 2,600 °C. Projected use for human missions to Mars will require cumulative run times ~3.5 hr and 5 to 6 restarts. Current technology hurdles with ceramic and carbide fuels include embedding nitride or carbide kernels with coatings in a carbide matrix with potential for total fission product containment and high fuel burnup, and simple modern manufacturing of complex geometries with high uniform density.

Specific technologies being sought include:

- Innovative ultrahigh-temperature material property testing and performance evaluation above 2,000 °C in a vacuum and hot hydrogen environment. The materials used in the reactor core will reach temperatures up to 2,700 °C. No current material property data and performance characteristics above 2,000 °C exist, and the subtopic wishes to solicit innovations in this area to start filling those data gaps, thus reducing technical risk of material choices within the reactor, and begin optimization of material choices. The key materials to be evaluated are the fuel element matrix materials, such as refractory ceramics. These materials are highly sensitive to oxygen and must be tested in a vacuum, inert atmosphere, or reducing (hydrogen) atmosphere. Some of the key parameters to gather at 2,000+ °C temperatures include (but are not limited to) static modulus, modulus of rupture, tension and compression flow curves, tension and compression creep, fatigue and hardness with measurement absolute accuracies ±0.5%. In addition to those key parameters, contact and noncontact strain measurement techniques with absolute accuracies of ±0.5% at these ultrahigh temperatures are also sought.

- Innovative fuel element designs and propellant flow configurations that facilitate achieving propellant exit temperatures in excess of 2,500 °C.

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

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research

Desired Deliverables Description:

Desired deliverables for this technology would include research that can be conducted to determine technical feasibility of the proposed concept during Phase I and show a path toward a Phase II hardware demonstration. Testing the technology in a simulated (as close as possible) NTP environment as part of Phase II is preferred. Delivery of a prototype test unit at the completion of Phase II allows for followup testing by NASA.

Phase I Deliverables: Feasibility analysis and/or small-scale experiments proving the proposed technology to
develop a given product (Technology Readiness Level (TRL) 2 to 3). The final report includes a Phase II plan to raise the TRL. The Phase II plan includes a verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables: A full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 3 to 5). Also delivered is a prototype of the proposed technology for NASA to do further testing if Phase II results show promise for NTP application. Opportunities and plans should also be identified and summarized for potential commercialization of the proposed technology. Unique government facilities can be used as part of Phase II.

State of the Art and Critical Gaps:

The state of the art is reactor fuel developed for the Rover/NERVA program in the 1960s and early 1970s. The fuel was carbon based and had what is known as "midband" corrosion, which affected the fuel endurance. Switching over to cermet (metal and ceramics) or advance carbide fuels shows promise but has fabrication challenges. Limited property data for most materials at ultrahigh temperatures considered makes the material performance analysis to meet the engine operating requirements riskier.

Focus is on a range of modern technologies associated with NTP using solid-core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~25,000 lbf with an Isp goal of 900 sec (using hydrogen) and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple startups (>5) with cumulative run time >200 min in a single mission, which can be no more than 2-yr round trip, according to a recent NASA study. The Rover/NERVA program ground tested a variety of engine sizes for a variety of burn durations and startups.

Relevance / Science Traceability:

By closing these ultrahigh-temperature data gaps, the Space Nuclear Propulsion (SNP) project intends to infuse the results into design considerations/optimizations for risk reduction. In addition to directly benefiting SNP by closing the current material data gaps, the technology improvements in high-temperature materials would also benefit the following:

- Department of Defense (DOD) Defense Advanced Research Projects Agency (DARPA) NTP program.
- Wing leading-edge systems, due to their use of refractory alloy base structures to 2,000 °C.
- Fission surface power, due to the use of materials in long-term high-temperature environments.
- Refractory reaction control systems (RCSs) that reach up to 2,000 °C temperatures.
- Refractory rocket nozzles for upper stages and landers that reach ~2,200+ °C.

STMD (Space Technology Mission Directorate) is supporting the SNP project.

Future mission applications:

- Human missions to Mars.
- Science missions to the outer planets.
- Planetary defense.

Some technologies may have applications for fission surface power systems.

References:

Solid-core NTP has been identified as an advanced propulsion concept that could provide the fastest trip times for human missions to Mars over a variety of mission years. NTP had major technical work done between 1955 and 1973 as part of the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A few other NTP programs followed, including the Space Nuclear Thermal Propulsion (SNTP) program in the early 1990s. The NTP concept is like a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber and exposes the engine components and surrounding structures to a radiation environment.
Z10.04 Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters

Lead Center: GRC

Scope Title:

Structurally Robust Magnetic Circuit Materials for Hall-Effect Thrusters

Scope Description:

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. Critical NASA electric propulsion needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

To shape the magnetic fields needed for operations, Hall-effect thrusters utilize a magnetic circuit that also forms the thruster structure. The magnetic circuit components direct magnetic flux (typically produced by electromagnetic coils) and may experience operational temperatures in excess of 500 °C due to coil self-heating and the close proximity of plasma-wetted surfaces. Both low-carbon magnetic iron and cobalt-iron (Co-Fe) soft ferromagnetic alloys have been traditionally used in the role; low-carbon magnetic iron is typically cheaper with larger billet size availability, whereas Co-Fe soft ferromagnetic alloys are attractive due to high magnetic saturation and Curie temperature properties. As Hall-effect thrusters become larger to support future high-power applications, thruster components also experience and must survive increased inertial launch loads. To address this issue, prospective magnetic circuit materials are desired with improved structural strength compared to SOA options while retaining comparable or better magnetic and thermal properties. Prospective materials capable of being produced in machinable, large-diameter (i.e., >400 mm) solid billets—or that can be additively manufactured to achieve comparable sizes—are of particular interest. This
solicitation seeks such prospective magnetic circuit materials suitable for Hall-effect thruster applications with the following properties:

- **Mechanical:** Meets or exceeds yield stress properties in Table X2.4 of ASTM Standard A801-14.
- **Magnetic:** Meets or exceeds properties in Appendix X1 of ASTM Standard A848-17.
- **Thermal:** Meets or exceeds Curie temperature of 770 °C.

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

**Primary Technology Taxonomy:**
- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.2 Electric Space Propulsion

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

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**

**Phase I:**

1. Virtual kickoff meeting with the NASA Technical Monitor and potential stakeholders within the first month of the period of performance.
2. A final report containing test data characterizing key material properties as well as an assessment of material size scalability for future production.
3. Material samples that can be utilized for independent verification of claimed improvements over SOA materials.

**Phase II:**

1. Kickoff meeting with NASA Contracting Officer Representative (COR) and potential stakeholders within the first month of the period of performance.
2. A final report with test data either characterizing key material properties for produced large billets or demonstrating the functionality of one or more thruster components integrated with operating thruster hardware (in which partnering with electric propulsion developers may be necessary).

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

SOA magnetic circuit materials used for Hall-effect thrusters are typically in two families: low-carbon magnetic iron or cobalt-iron (Co-Fe) soft ferromagnetic alloys (e.g., Hiperco®). While Co-Fe alloys are frequently preferred because of their magnetic and thermal properties, their available billet sizes do not readily accommodate larger thruster components needed for future high-power (i.e., >50 kW) electric propulsion applications.
Low-carbon magnetic iron does come in large billet sizes, but past NASA high-power thruster development efforts (e.g., NASA-457Mv2 thruster) have identified potential risks regarding the survivability of components when subjected to launch loads. A magnetic circuit material that retains or exceeds the magnetic and thermal properties of SOA options while providing improved structural strength and scalability to large billet sizes is highly desirable to mitigate the risk.

Relevance / Science Traceability:

Both NASA’s Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys [92]). For HEOMD, higher-power electric propulsion is a key element in supporting sustained human exploration of cislunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy, with archival information contained in the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

References:

- Decadal surveys for each of the SMD divisions, https://science.nasa.gov/about-us/science-strategy/decadal-surveys [92]

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High-Efficiency Hollow Cathodes

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. Critical NASA electric propulsion needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Hollow cathodes in electric propulsion systems are utilized for generating discharge plasma and effecting plume neutralization in gridded-ion and Hall-effect thrusters. In SOA hollow cathodes, operating temperatures can range from 1,000 to 1,700 °C, and the cathode assembly may need to survive in excess of 10,000 operational hours and 10,000 thermal on-off cycles without failure. Critical NASA needs for hollow cathodes are:

1. High-current hollow cathodes with reduced power consumption. While SOA hollow cathodes can provide up to 25-A direct current necessary for electric propulsion applications, future interest in 100-kW electric propulsion systems will require a substantial increase in cathode current output to the range of 100 to 200 ADC. Scaling of current cathode architectures using various emitter technologies have achieved cathodes operating at >100-ADC emission current; however, these results typically require substantial increases in electrical power needed to drive plasma generation in the cathode and/or in an associated heating element for impregnate-based emission sources. Size increases for emitter and cathode, including heating elements, can also be significant to maintain the necessary thermal conditions for stable cathode life; the resultant larger sized cathodes can stress heater elements and limit their cyclic life—a concern facing cathodes utilizing LaB6 emitters. This solicitation seeks stable-performance, long-life cathode architectures that reduce power consumption (i.e., improve electrical efficiency) for >100-ADC emission current via improved heater design and operation, emitter material selection and configuration, lower plasma generation costs, reduced cathode thermal losses via conduction or radiation, etc.

2. Reduced-flow hollow cathodes in Hall-effect thrusters. Hollow cathodes used in Hall-effect thrusters are frequently operated with a fixed flow fraction relative to the anode flow; this approach is commonly utilized to reduce the cost and complexity of the propellant feed system. To promote efficient discharge plasma generation, these cathodes are typically operated with a higher than necessary propellant flow, which reduces specific impulse and may have negative impacts on cathode lifetime due to pressure-driven emission behavior. Past efforts to bifurcate the cathode flow between the cathode and an external (i.e., keeper or downstream region) contribution have demonstrated some success in providing stable and efficient cathode operation while reducing the total cathode (i.e., non-anode) flow fraction to less than 7% to 10% of the anode flow rate typically used in thruster operations. Being able to sustain thruster operations at such low total cathode flow fractions can result in significant propellant savings, particularly for high-power Hall-
effect thrusters. This solicitation seeks readily adaptable methods to reduce cathode propellant flow needs (i.e., improve propellant utilization) without adversely affecting cathode and Hall-effect thruster stability and life.

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

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

1. Virtual kickoff meeting with the NASA Technical Monitor and potential stakeholders within the first month of the period of performance.
2. A final report containing quantitative analysis, modeling, or proof-of-concept test data addressing key risk factors associated with the technical approach and comparisons to SOA cathodes.
3. A cathode subsystem design that is compatible with high-power Hall-effect thruster concepts.

Phase II:

1. Kickoff meeting with the NASA Contracting Officer Representative (COR) and potential stakeholders within the first month of the period of performance.
3. Cathode assembly hardware that can be utilized for independent verification of claimed improvements over SOA cathode assemblies.

State of the Art and Critical Gaps:

Future interest in 100-kW electric propulsion systems will require cathode current outputs in the range of 100 to 200 ADC. Experience to date with scaling current cathode architectures has resulted in cathodes that consume several kilowatts of power during operations. Such cathodes pose significant thermal management challenges for the thruster and concerns about the cathode’s cyclic lifetime. Alternative cathode architectures that can significantly reduce power consumption are highly desirable to reduce risk for high-power electric propulsion applications.

Typical Hall-effect thrusters utilize a cathode flow fraction between 7% and 10% of the anode flow, with past studies of 50-kW-class thrusters at times requiring >10% cathode flow fraction to promote thruster stability at
certain throttle points. For high-power electric propulsion systems utilizing Hall-effect thrusters, reducing cathode propellant flow needs can result in significant propellant savings on the order of hundreds of kilograms for typical NASA mission lifetimes. Past efforts to bifurcate the cathode flow between the cathode and an external (i.e., keeper or downstream region) contribution have demonstrated some success in providing stable and efficient cathode and thruster operations while achieving <7% total cathode flow fraction. Approaches for reducing cathode flow needs that can be readily adapted to SOA thruster architectures are highly desirable to improve system efficiency and lifetime.

Relevance / Science Traceability:

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions ([https://science.nasa.gov/about-us/science-strategy/decadal-surveys](https://science.nasa.gov/about-us/science-strategy/decadal-surveys) [92]). For HEOMD, higher-power electric propulsion is a key element in supporting sustained human exploration of cislunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy, with archival information contained in the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

References:

- M.A. Mantenieks and R.M. Myers, “Preliminary Test Results of a Hollow Cathode MPD Thruster,” IEPC 91-076.
- Decadal surveys for each of the SMD divisions, [https://science.nasa.gov/about-us/science-strategy/decadal-surveys](https://science.nasa.gov/about-us/science-strategy/decadal-surveys) [92]
- 2020 NASA Technology Taxonomy, [https://www.nasa.gov/offices/oct/taxonomy/index.html](https://www.nasa.gov/offices/oct/taxonomy/index.html) [94]
Z12.01 Extraction of Oxygen and Water from Lunar Regolith

Lead Center: JSC

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

Scope Title:

Solar Concentrator Technologies for Oxygen Extraction and In Situ Construction

Scope Description:

Solar concentrators have been used to successfully demonstrate multiple in situ resource utilization (ISRU) technologies, including hydrogen and carbothermal reduction, sintering of regolith to produce launch/landing pads, and production of blocks for construction. Terrestrial state-of-the-art solar concentrators are heavy, not designed for easy packaging/shipping and assembly/installation, and can be maintained and cleaned on a periodic basis to maintain performance. For ISRU space applications, NASA is interested in solar concentrators that are able to be packaged into small volumes, are lightweight, easily deployed and set up, can autonomously track the Sun, and can perform self-cleaning operations to remove accumulated dust. Materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface in temperatures of up to 110 °C (230 °F) during sunlit periods and as low as -170 °C (-274 °F) during periods of darkness. Systems must also be able to operate for at least 1 year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that regolith mining operations will be tens of meters away from the solar concentrators, but that regolith processing systems and solar concentrators will be co-located on a single lander. Phase I efforts can be demonstrated at any scale; Phase II efforts must be scalable up to 11.1 kW of delivered solar energy, assuming an incoming solar flux of ~1,350 W/m² while also considering volumetric constraints for launch and landing. Each of the following specific areas of technology interest may be developed as a standalone technology.

- **Lightweight mirrors/lenses:** Proposals must clearly state the estimated W/kg for the proposed technology. Phase II deliverables must be deployed and supported in Earth 1g (without wind loads) but should include design recommendations for mass reductions for lunar gravity (1/6g) deployment. Proposals should address the following attributes: high reflectivity, low coefficient of thermal expansion, strength, mass, reliability, and cost.
- **Efficient transmission of energy for oxygen/metal extraction:** While the solar concentrator will need to move to track the Sun, reactors requiring direct thermal energy for oxygen extraction will be in a fixed position and orientation. Concentrated sunlight must be directed to a single or multiple spots to effectively heat or melt the regolith. Proposals must define the expected transition losses from collection to delivery and should capture any assumptions made regarding the distance from collection to delivery.
- **Sintering end effector:** Solar concentrators have been used to demonstrate the fabrication of 3D printed components using regolith as the only feedstock. Proposals responding to this specific technology area must produce and maintain a focal point temperature between 1,000 and 1,100 °C for the purpose of sintering lunar regolith. Proposals should assume that the focal point can move along the regolith at a speed between 1 and 10 mm/sec.

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization
Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I deliverables may be a conceptual design with analysis to show feasibility at relevant scales and/or a small demonstration of the concept. Phase II deliverables should be hardware demonstrations at a relevant scale. See Scope Description for additional information on Phase I and Phase II deliverables.

State of the Art and Critical Gaps:

The 2011 paper “Thermal Energy for Lunar In Situ Resource Utilization: Technical Challenges and Technology Opportunities” [Ref. 1] summarized the work performed in this area and recommends future efforts focus on lightweight mirrors (possibly using composite materials) and dust mitigation techniques (dust mitigation is addressed in another subtopic).

The last solar concentrator system developed for ISRU had an overall efficiency of ~33%. The performance of the system is captured in the 2011 paper "Solar Thermal System for Lunar ISRU Applications: Development and Field Operation at Mauna Kea, HI" [Ref. 6].

Relevance / Science Traceability:

NASA Strategic Knowledge Gap (SKG) 1-F, "Determine the likely efficiency of ISRU processes using lunar simulants in relevant environments," as well as NASA SKG 1-G, "Measure the actual efficiency of ISRU processes in the lunar environment," are both important for the development of future ISRU systems. There are multiple ISRU processes that involve the use of solar concentrators, and determining their efficiency through technology development efforts may address NASA SKGs.

References:

https://ntrs.nasa.gov/citations/20110006938 [98]


Scope Title:
Novel Oxygen Extraction Concepts

Scope Description:

Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from silicates using various techniques. The target production rates are 1,000 kg of O\textsubscript{2} per year for a lunar pilot plant, and 10,000 kg of O\textsubscript{2} per year for a lunar full-scale plant. Each of the following specific areas of technology interest may be proposed as individual efforts to support existing oxygen extraction development projects.

- **Contaminant Removal:** Proposed concepts should be capable of removing 0.36 g of HCl, 0.68 g of HF, and 0.1 g of H\textsubscript{2}S per kg of processed regolith from a mixed gas stream of CO, CO\textsubscript{2}, and H\textsubscript{2} in a way that minimizes the use of consumables. Phase I efforts should provide an estimated mass/power as a function of contaminant quantities. Phase II efforts should demonstrate the technology using actual gases.

- **Regolith Inlet/Outlet Valves:** Proposed concepts should be capable of passing abrasive granular material through the valve for at least 1,000 cycles and should be actuated with a type of motor that has flight heritage (e.g., brushless direct current (BLDC) motors or stepper motors). Phase I efforts should provide an estimated mass and power for the concept through analysis and/or demonstration. Phase II efforts should demonstrate the technology using lunar regolith simulant and collect data to predict leak rates for up to 10,000 cycles.

- **Contamination-Tolerant Vacuum Pump:** Some in situ resource utilization (ISRU) processes may require a pressurized volume to be evacuated in order to prevent the loss of products and consumables to the vacuum of space when regolith either enters or exits the volume. The pump may be exposed to corrosive substances such as HCl, HF, and H\textsubscript{2}S. Proposed concepts should be capable of evacuating a volume of 50 L with an initial pressure of 5 psia down to a pressure of <5 torr at the pump inlet in <2 min while compressing the gases to 1 atm at the pump outlet. Phase I efforts should provide an estimated mass, power, and life for the concept. Phase II efforts should demonstrate the technology using actual gases.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems  
Level 2: TX 07.1 In-Situ Resource Utilization  

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

- Research  
- Analysis  
- Prototype  
- Hardware

**Desired Deliverables Description:**

See Scope Description for definitions of Phase I and II deliverables for each technology.

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

The carbothermal reduction process was demonstrated at a relevant scale using an automated reactor in 2010. Multiple efforts are underway to bring carbothermal reduction technology to TRL6. Other techniques that use ionic liquids, molten salts, and molten regolith electrolysis have been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Many of these processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

**Relevance / Science Traceability:**

The Space Technology Mission Directorate (STMD) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to begin mining it at a useful scale. A lunar water prospecting mission is required to properly assess the utilization potential of water on the lunar surface. Until water prospecting data becomes available, NASA recognizes the need to make progress on the technology needed to extract oxygen from dry lunar regolith.

**References:**

1. Fox, E. T. (2019). Ionic Liquid and In Situ Resource Utilization. [https://ntrs.nasa.gov/citations/20190027398](https://ntrs.nasa.gov/citations/20190027398) [100]
Regolith using Ionic Liquids. [102]


Scope Title:

Lunar Ice Mining

Scope Description:

We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in permanently shadowed regions (PSRs), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. One challenge with extracting the water is that desorption and sublimation can occur at temperatures as low as 150 K. The inverse challenge exists with water collection. Unless the water vapor is under pressure, extremely cold temperatures will be necessary to capture it. NASA is seeking methods to acquire lunar water ice from PSRs. Proposals must describe a method for extracting and/or collecting lunar water ice that exists at temperatures between 40 and 100 K and 10-9 torr vacuum.

- Phase I demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 2.78 kg H₂O/hr (15 metric tons of water in 225 days).
- Phase II demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 2.78 kg H₂O/hr.
- Proposals should state expected energy requirements (both electrical and thermal).
- Proposers should assume a mobile platform is considered to be available, but should not be necessary for technology demonstration.
- Proposers should state their assumptions about water ice concentration.
- Proposals should describe a tolerance for a trace amount of organics or volatiles that may accumulate on collection surfaces.
- Proposers should estimate Wh/kg H₂O for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address the ability of a concept to be able to operate for at least 1 year, with a goal of 5 years without substantial maintenance.

Estimates for mass and volume of the final expected hardware should be specified.

In addition, each of the following specific areas of technology interest may be proposed to support existing efforts related to lunar ice mining.

- Regolith/Ice Excavation: Proposed concepts should be able to excavate frozen regolith simulant with a water ice content of at least 5% by mass while minimizing a temperature increase in the excavated material. Phase I efforts should provide an estimated mass/power for the excavation concept as well as an estimate for any temperature increase in the frozen regolith caused by the excavation technique. Phase II efforts should demonstrate the technique with lunar simulant at...
a target production rate of 0.28 kg H$_2$O/hr and collect data to predict the estimated wear over time.

- **Regolith/Ice Crushing:** Proposed concepts should be able to crush frozen regolith simulant with a water ice content of at least 5% by mass while minimizing a temperature increase in the excavated material. Phase I efforts should provide an estimated mass/power for the crusher concept as well as an estimate for any temperature increase in the frozen regolith caused by the crushing technique. Phase II efforts should demonstrate the technique with lunar simulant mixed with ice having an initial unconfined compressive strength of 10 MPa at a target production rate of 0.28 kg H$_2$O/hr and collect data to predict the estimated wear over time.

- **Subsurface Volatile Extraction:** Proposed concepts should be able to release volatiles at a depth of 50 cm below the surface with a water ice content of at least 5% by mass. Phase I efforts should provide an estimated mass/power for the concept. Phase II efforts should demonstrate the technique with lunar simulant at a target production rate of 0.28 kg H$_2$O/hr and collect data to predict the estimated wear over time if applicable.

**Expected TRL or TRL Range at completion of the Project:** 4 to 5

**Primary Technology Taxonomy:**
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

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

- Prototype
- Analysis
- Hardware

**Desired Deliverables Description:**

See Scope Description for definitions of Phase I and II deliverables for each technology.

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

Scoops and bucket-wheel excavators have been demonstrated for the collection of unconsolidated material but may not be effective at excavating consolidated regolith-ice composites. The Planetary Volatiles Extractor (PVEx) developed by Honeybee Robotics is the state of the art for heated core drills, but life testing is required to determine the rate of wear due to repeated excavation. Multiple groups have investigated the use of thermal mining methods to separate water from regolith, but the depth of water removed is relatively shallow. Very little work has been performed on the ability to capture water in a lunar environment after it has been released from the surface.

**Relevance / Science Traceability:**

The current NASA Administrator has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. STMD has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

**References:**


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**Z13.01 Active and Passive Dust Mitigation Surfaces**

Lead Center: JSC

Participating Center(s): JSC, LaRC

**Scope Title:**

Advanced Technologies for Active Dust Mitigation

**Scope Description:**

Proposals are sought that use unique methods that may require power, gases, mechanisms, vibrations, or other means to keep vital surfaces clean under space conditions. Self-cleaning surfaces that require minimal effort by astronauts are highly desired. Proposers are expected to show an in-depth understanding of the current state of the art (SOA) and quantitatively describe improvements over relevant SOA technologies that substantiate investment in the new technology. Proposers must also quantitatively explain the operational benefit of the new technology from the perspective of improving or enabling mission potential. Some examples of active dust mitigation technologies include but are not limited to:

- **Brushing:** A self-cleaning brush to mechanically remove dust from surfaces. The brush can be mechanically operated using power, or temperature activated, such as shape memory alloys.
- **Electrostatic removal:** Methods to use direct-current (DC) electric fields to remove dust from surfaces, either internal to the surface (embedded) or external using a removed high-voltage source.
- **Liquid removal:** A jet of liquid is applied to the surface that traps particles and
removes them from the surface.

- Vacuum: Methods to remove particles from surfaces using suction of gases.
- Jets: High-velocity gas jet that blows dust particles from surfaces.
- Spinning surfaces: Surface rotates in a manner that does not allow collection of dust on it.
- Vibrational surfaces: Vibrating surface bounces the particles off of the surface.
- Electrodynamic removal: The surface contains embedded electrodes with varying high-voltage signals applied to lift and transport dust off of the surface.

Proposals are highly sought in which the active dust mitigation strategy could be combined with the SOA of passive dust mitigation technologies. For example, passive dust mitigation strategies include:

- Electrostatic discharge (ESD) coatings and films: Statically dissipative coatings are less likely to accumulate charge, and hence dust, in dry environments.
- Superhydrophobic coatings: Materials with a very high contact angle can lower the adhesion of water-based contaminants, not allowing the capillary forces to take hold.
- EVA and robotic-compatible dustproof electrical, fluid, and gas connectors.
- Dustproof bearings and mechanical spacesuit connectors.
- Dust-tolerant or dust-resistant hatches.
- Docking systems, including suitport docking systems and pressurized rover and habitat docking systems.
- Lotus leaf coating: Microscopic nanostructures used to limit the van der Waals force of adhesion.
- Peel-away coating: Removable surface coatings.

Strong proposals are those that identify the active dust removal strategy in coordination with other dust prevention and removal methods as listed above. Strong proposals will also include a brief description of an infusion plan to support a potential flight demonstration after completion of the Phase II effort and how the prototype(s) developed under the Phase II effort could support that goal.

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

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.3 Mechanical Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype

Desired Deliverables Description:

A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The
technology must be a device showing the desired method working in a laboratory environment, removing and/or keeping dust from adhering to a surface. The "dust" utilized in these experiments must be an appropriate simulant with justification for the source and size distribution related to the intended application and lunar location. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. Phase I deliverables shall consist of a final report. Samples or prototypes can also be delivered if available. Phase II deliverables shall consist of a final report and a prototype demonstrating surface dust mitigation.

State of the Art and Critical Gaps:

All new technologies for Active Dust Mitigation must include a full knowledge base of the SOA, and proposals that advance the current SOA are encouraged. For example, NASA has developed the Electrodynamic Dust Shield (EDS), which lifts and transports dust off of surfaces with embedded electrodes within a dielectric. A brief but not complete introduction to the technology can be found in the references.

The EDS can be incorporated into a variety of configurations addressing many of NASA’s needs. However, several potential improvements and technologies that can further the development of the EDS technology are also highly sought within this call. Some potential advances include:

- Miniaturized high-voltage three-phase power supply: The current SOA for the EDS power supply is approximately 10 × 5 × 3 cm. It is highly desired to have smaller power supplies both in size and power to drive the EDS waveform for a variety of applications.
- High dielectric breakdown strength for both glues/epoxies and the coating material: The efficiency of dust removal for the EDS is limited to amount of voltage that can be applied to the electrodes. The electrical breakdown occurs across the 2D surface because of the dielectric strength limitation of the adhering material as well as the coating material.
- Flexible transparent surfaces with high current capabilities: The optically transparent version of the EDS uses indium tin oxide (ITO) as the main conductive medium for its electrode. Although the EDS is not a high-current DC device, the displacement current (I dV/dt) can be quite high. Transparent electrode materials are sought that can replace ITO as the conductive medium that have higher current capabilities and lower overall resistivities. Another shortcoming of ITO is its range of flexibility. Many ITO coatings cannot be bent past a certain degree and are not compatible with numerous folds and bends.
- The EDS technology also works on fabrics. However, high-voltage flexible wires that can be used as threads are unavailable. The electrodes would need to be low profile and sufficient to withstand up to +10 kV DC before breakdown. A unique feature of the EDS on fabrics is that it needs to be a multilayer system, as most space fabrics are. One layer would have to support electrical grounding to protect the astronaut, but intermediate layers would have withstand high-voltage breakdown. The top layer would house the high-voltage wire system composed of the EDS requirements.
- Electrical attachment: Most EDS systems have issues with the electrical connections between the high-voltage power supply (HVPS) and the electrodes. Any possibility of arcing and/or sparking as a result of slight differences between the wiring from one material configuration to another is exacerbated when powered with EDS waveforms. Proposals are highly sought that address this key
issue for attaching high-voltage wires to electrodes embedded in an EDS circuit. EDS circuit electrodes are made using a variety of materials such as copper (wires or vapor deposited), ITO, silver paint wires, carbon nanotube (CNT), and graphene, to name a few. Likewise, these and other electrodes are usually resting on or embedded into a substrate such as glass, polyimide (Kapton), clothing fibers, polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), nylon, acrylic, Lucite, and other surfaces.

- Minimizing electromagnetic interference (EMI): Most EDS designs can generate electrical noise that would be disadvantageous if it were to be incorporated into a system. Methods to reduce electrical noise and EMI would be highly sought.
- Safety: With all EDS systems, the use of high voltage requires safety measures for the astronaut and the equipment. Methods to improve the safety and reliability of the EDS in the case of arcing is highly sought.
- Smart EDS technology: As with all dust mitigation technologies, methods to include adaptive techniques are highly sought. The system should be able to check its environment to see if dust clearing is necessary, and if it is, apply power to the system until the cleanliness requirements are met for reliability and power minimization.

Other active systems also require maturation. Critical gaps in these areas include:

- Effective and scratch-resistant brushing techniques. Apollo astronauts used brushes that are largely ineffective for large surface areas and tended to scratch sensitive equipment, such as astronaut visors.
- Gaseous removal of dust on the lunar surface may contaminate other sensitive equipment. A better approach to gaseous or fluidized removal of dust is needed.
- Simple mechanical or vibrational dust mitigation implementations are required. As particles move, they also become highly electrostatically charged, further causing dust adhesion.

Relevance / Science Traceability:

This subtopic's focus on adhesion of granular materials and technologies that address mitigation of this adhesion will advance the state of knowledge of this difficult research subject. The interplay between the surface’s energy, chemistry, and mechanical properties and the particle’s surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, on the Apollo missions, every mechanical seal was compromised over the course of 3 days due to the exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will improve our survival on dusty surfaces in space.

References:


**Scope Title:**

**Advanced Technologies for Passive Dust Mitigation**

**Scope Description:**

This call seeks unique research proposals focused on passive approaches (i.e., those that do not require external stimuli) that will minimize the potential impact lunar dust will have on future exploration missions. These approaches may include novel materials and surfaces as well as technologies that require no external input (a self-activating system). Novel materials may include high-performance plastics, metals, ceramics, etc. Surfaces may be homogeneous or heterogeneous, and rough or smooth, with topography imparted by any number of approaches, including (but not limited to) lithography, embossing, roll-to-roll processing, etc. However, spacesuit garment-related technologies should refer to the Lunar Dust Mitigation Technology for Spacesuits SBIR subtopic. Surfaces can incorporate strategies for mitigation of adhesion contributions from van der Waals interactions, electrostatic forces, and/or chemically reactive or mechanical interactions. Both the material and surface modification approach must be demonstrated to be scalable and must exhibit a dramatic reduction (>90% relative to a reference material...
surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for microparticles, specifically those described as lunar dust simulant. The simulant utilized in these experiments must be an appropriate material with justification for the source and size distribution related to the intended application and lunar location.

Strong proposals will seek to demonstrate the efficacy of lunar dust adhesion mitigation and the durability to retain these properties in a simulated environment. Strong proposals will also include a brief description of an infusion plan to support a potential flight demonstration after completion of the Phase II effort and how the prototype(s) developed under the Phase II effort could support that goal.

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

**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:**

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**

At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and should exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm. At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II is awarded, further development of the technology shall be required, including a prototype delivered to NASA at the end of the 2-year project with a goal of achieving Technology Readiness Level (TRL) 6. A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be demonstrated to remove adhered dust or prevent dust adhesion in a laboratory environment simulating some aspects of lunar environmental conditions. Durability of the material surface toward lunar dust abrasion, thermal cycling, and other environmental considerations should also be addressed. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. A well-developed infusion plan resulting in a flight demonstration must also be provided.

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

Although a myriad of materials and technologies exist for mitigation of surface contamination for a variety of terrestrial applications, requirements for mitigation of lunar dust adhesion indicate diminished efficacy of many materials. As an example, silicones are used ubiquitously to reduce adhesive interactions and can be effective for contamination prevention across a range of contaminants, but these relatively soft materials would exhibit deleterious properties in a traditional manifestation arising from particulate embedding due to the sharp edges and hardness of the lunar dust. Likewise, hard traditional ceramic materials have been shown to be beneficial for terrestrial applications. Triboelectrification of an insulating material, however, would increase adhesion interactions with lunar dust. Beyond these specific lunar dust properties, magnetic interactions, chemical activity, and the velocity of the lunar dust, especially at the lunar terminator, all contribute to adhesion and therefore must be addressed for a material to be expected to perform well in this environment. Refer to the Advanced Technologies for Active Dust Mitigation scope for a description of several state-of-the-art active dust mitigation technologies.
Relevance / Science Traceability:

This subtopic's focus on adhesion of granular materials and technologies that address mitigation of this adhesion will advance the state of knowledge of this difficult research subject. The interplay between the surface's energy, chemistry, and mechanical properties and the particle's surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, on the Apollo missions, every mechanical seal was compromised over the course of 3 days due to exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will improve our survival on dusty surfaces in space.

References:


Wagner, S. An assessment of dust effects on planetary surface systems to support exploration requirements. 2004.


Z13.02 Dust-Tolerant Mechanisms

Lead Center: JSC
Participating Center(s): GRC, JSC, LaRC

Scope Title:

Dust-Tolerant Joints

Scope Description:

A return to the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth’s economic sphere will require investment in developing new technologies and capabilities to achieve affordable and sustainable human exploration. From the operational experience gained and lessons learned during the Apollo missions, conducting long-term operations in the lunar environment will be a particular challenge given the difficulties presented by the unique physical properties and other characteristics of lunar regolith, including dust. The Apollo missions and other lunar exploration have identified significant lunar dust-related problems that will challenge future mission success. Lunar dust is composed of regolith particles ranging in size from tens of nanometers to microns, and lunar dust concerns are a manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical, and gravitational effects.

Mechanical systems will need to operate on the dusty surface of the Moon for months to years. These systems will be exposed to the harsh regolith dust and will have little to no maintenance. This scope seeks technologies that will protect from or tolerate dust intrusion in the following areas:

- Rotary joints (steering, suspension, hinges, bearings, etc.).
- Linear joints (latches, shafts, restraint systems, landing gear, etc.).
- Static joints (quick disconnects, covers, airlocks, sample tools, etc.).

Successful solutions will enable operation in a lunar environment for 10 to 100 months with limited or no maintenance.

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

Primary Technology Taxonomy:

Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, with delivery of a demonstration package for NASA testing in operational test environments at the completion of the Phase II contract.

Phase I Deliverables: Research, identify, and evaluate candidate technologies or concepts for dust-tolerant mechanisms. Simulations or laboratory-level demonstrations are desirable. Deliverables must include a report to document findings.
Phase II Deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions (regolith, thermal, vacuum). Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results, and other associated documentation. Deliverable of a functional prototype is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a Technology Readiness Level (TRL) of 6 or higher.

State of the Art and Critical Gaps:

Previous solutions used in the Apollo program did not address the current need of long-term usage. Terrestrial solutions often employ materials or methods that are incompatible with the lunar environment.

Critical Gaps:

- Rotary joints.
  - Seals: Rotary joints are very common for actuation in dusty environments because of the widespread availability of rotary seals. Most of these seals, however, use elastomers that would off-gas and become brittle in a lunar environment. Solutions are needed that employ materials or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).
  - Bearings: Regolith getting past the protective seals of rotary joint bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.
  - Successful technologies will have operational lifetimes on the order of millions of cycles in a relevant lunar environment.

- Linear joints.
  - Seals: Linear joints are less common in dusty environments because of the challenge of sealing the sliding joints. Similar to rotary seals, linear joint seals are often made from elastomers and would need to be modified to operate in a lunar environment. Solutions are needed that employ materials or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).
  - Bearings: Regolith getting past the protective seals of linear joint bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.
  - Successful technologies will have operational lifetimes on the order of hundreds of thousands of cycles in a relevant lunar environment.

- Static joints.
  - Operations on the lunar surface will include assembly, construction, and extravehicular activity (EVA) tasks. These tasks will involve the mating/demating of various structural, electrical, and fluid connections. Dust on the surface of these joints will impede their proper function and lead to failures. Solutions are needed to protect these joints from dust contamination.
  - Successful technologies will have operational lifetimes on the order of thousands of cycles in a relevant lunar environment.

Relevance / Science Traceability:

Dust will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.” Gene Cernan, Apollo 17 Technical Debrief.

References:
Z13.03 Lunar Dust Mitigation Technology for Spacesuits

Lead Center: JSC

Scope Title:

Garment Protection

Scope Description:

The multilayered fabric system (layup) that protects the structure of the suit from the extremes of the space environment is called the Exploration Extravehicular Mobility Unit (xEMU) environmental protection garment (EPG). The EPG, especially the environment-facing EPG shell fabric, is the suit's first line of defense against the extreme environment of the lunar surface. The EPG system must not only survive the environment but must perform per requirements and offer a level of protection to the underlying pressure garment system (PGS), portable life support system (PLSS), and informatics system.

The EPG is subjected to the following extreme environments:

1. Thermal

   - Extreme hot (260 °F, 127 °C).
   - Extreme cold (-280 °F, -173 °C).
   - Possible exposure to permanently shadowed regions (PSRs) (-373 °F, -225 °C).

2. Lunar regolith/dust

   - Highly abrasive.
     - Durability in the dust environment is a key requirement. The spacesuit must operate over prolonged exposure to and operation in the dusty regolith environment. This includes kneeling on the ground, thousands of walking cycles, and cleaning before ingressing the vehicle.
   - Electrostatically charged.
     - The suit is also required to severely limit the amount of dust brought into the vehicle. Therefore, materials that are easily cleaned and/or dissipative so that dust does not adhere to the suit are sought.

3. Radiation

   - The material must be able to be durable over hundreds of hours of ultraviolet (UV) radiation exposure. It is primarily only the environment-facing layer (outmost layer) of the EPG that must be resistant to degradation from the UV environment.
   - To prevent damage from discharges, NASA is considering materials that support an EPG that is dissipative.

4. Enriched oxygen atmosphere of the lunar lander in the Artemis program
The lunar lander in the Artemis program will have an atmosphere of 34±2% oxygen at a pressure of 8.2 psi (56.5 kPa). During the period the astronauts reside in the lander, they will need nonflammable materials for the outer layer of their lunar spacesuits.

5. Suit penetration protection

- Lunar secondary ejecta.
- Microgravity impact.
- Low Earth orbit (LEO) micrometeoroids.

6. Plasma

- Charged environment in contact with the suit.

In addition to the extreme environments, other requirements include the following:

1. Optical properties

- The EPG shall have an average ratio of solar absorptivity to infrared emissivity ($\alpha/\epsilon$) of 0.21 (TBR).
- The EPG shall have an average solar absorption of 0.18 (TBR).

2. Mass

- Using the current fabric layers, as a component the EPG weighs on the order of 16 lb. EMU layup mass (with seven layers aluminized Mylar) = 30.84 oz/yd$^2$ (1.92 lb/yd$^2$). Orthofabric = 14.0 oz/yd$^2$ + 1.0 - 0.5. Aluminized Mylar = 1.12 oz/yd$^2$ maximum. Neoprene-coated nylon = 9.0 oz/yd$^2$ maximum. NASA has a goal of a 25% weight reduction.

3. Mobility impacts

- While it is understood that the layered materials of the EPG will increase torque in the spacesuit joint by a small amount, the EPG cannot significantly affect mobility of the suit. This requires that the individual materials and the combination of the fabric layers of the EPG allow for joint mobility, such as bending of the elbow. The fabrics themselves must be flexible, and they must be flexible during exposure to the other environmental extremes, such as extreme low temperature and vacuum.
- Within the environment listed above, the EPG must be flexible and low mass while meeting all other architectural, functional, interface, structural, and design and construction requirements imposed on the xEMU and EPG system.

Past program solutions do not meet the requirements of the Artemis program sustaining missions.

Beta fabric, the glass fiber fabric used in the Apollo spacesuit, addressed only the high flammability risk in the Apollo Lunar Module (LM) atmosphere of 100% oxygen at 4.8 psi (33 kPa). The three extravehicular activities (EVAs) in the last Apollo mission, with an average combined duration of 22 hr, resulted in damage to the outer fabric of the Apollo spacesuits, and the suits could not have endured more EVAs. The glass fiber developed for NASA was the first-ever textile microfiber (3.8-µm fiber diameter) that would not burn in a 100% oxygen atmosphere, but it did not have the mechanical properties to withstand abrasion from the lunar regolith.

In the EMU program for the Space Shuttle and International Space Station, the shell fabric was designed for LEO, a significantly different environment from the lunar South Pole. The most notable difference is the absence of abrasives in LEO—no lunar dust. Orthofabric, the three-fiber shell fabric developed for the Space Shuttle suit outer layer, was designed for the Shuttle airlock oxygen concentration of 30% at 10.2 psi (70.3 kPa) and for durability.
While the Orthofabric does not support combustion in an exploration environment of 36% oxygen atmosphere at 8.2 psi, it is a woven fabric. The interstices of the weave (gaps between yarns) allow for some amount of lunar dust to penetrate, and therefore it is a poor barrier to dust. In addition, the GORE-TEX expanded polytetrafluoroethylene (ePTFE) film is easily abraded by the dust. Although GORE-TEX is a PTFE (Teflon) and inert, it can accumulate a charge.

In short, NASA is without adequate softgoods/textile solutions for the outermost layer of the EPG system that covers the xEMU suit system. NASA is looking for innovative materials solutions, likely requiring a layup of materials, to address all of the requirements listed above.

**Expected TRL or TRL Range at completion of the Project:** 3 to 4  
**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:**

- Analysis  
- Prototype  
- Hardware

**Desired Deliverables Description:**

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and 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, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. 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:**

Good environment-mitigation technologies and strategies are nonexistent for the spacesuit.

**Relevance / Science Traceability:**

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit Project (xEMU), which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

**References:**

No specific reference is available at this time. Under a Phase I contract, a Technical Monitor who is a subject matter expert will be assigned to the project and will be available for consultation upon award. Also, for the purpose of this solicitation, offerors may consider lunar dust simulants such as OB-1A and NU-LHT 2M for planning purposes.

**Scope Title:**

Venting Portable Life Support System (PLSS) Covers

**Scope Description:**
For spacesuits, challenges presented by lunar dust include damage from abrasion, the effects of dust’s electrostatic charge on the suit system, and dust intrusion to the suit system. Regarding the effects of dust intrusion, there is a need to provide the capability to mate and demate connectors and suit components as well as enabling venting to the environment for certain components. This will require the development of specialized dust covers for a variety of connections.

There are several spacesuit components that require access to the environment for gas flow, both in nominal and off-nominal operations. These components require specialized covers that prevent dust intrusion while at the same time allowing for sufficient gas flow. These components are:

1. **PLSS Shell Vent Ports**: The PLSS shell has two ports to allow evaporated water from the Spacesuit Water Membrane Evaporator (SWME) and its backup, the Mini-Membrane Evaporator (Mini-ME), to escape. The operation of these components is dependent on a low back pressure, and each of the vent ports must have a flow-through area of at least 7 in² to maintain the appropriate pressure for evaporation within the PLSS shell. The vents need to accommodate a water-vapor mass flow of at least 2.6 lb/hr. The total area available for the vent ports is approximately 10 by 2.5 in. on either side.

2. **PLSS Rapid Cycle Amine (RCA) System Vent Quick Disconnect (QD)**: The RCA system for water vapor and carbon dioxide (CO₂) removal requires vacuum access for the desorption of these constituents. This is accomplished via a QD on the PLSS backplate. For efficient desorption, the pressure in the vacuum access line needs to decrease quickly and allow the flow of 0.65 L of ullage gas to the environment. The ullage gas can be assumed to be 100% oxygen (O₂) at 2.15 psi. Without a specialized cover, this gas dissipates within about 2 sec. After the ullage gas has dissipated, the desorbed gas consists of CO₂ and water (H₂O) with a mass flow of 325 to 360 g/min depending on the bed loading and metabolic rate of the crew member. Between 210 to 230 g/min of that flow is CO₂. The rapid decompression of the vacuum line is essential for efficient operation of the RCA, as is the following diffusion of desorbed gas away from the absorber beds, both of which must not be impeded by the specialized dust cover.

3. **Suit Purge Valve (SPV) and Low-Flow Purge Valve (LFPV)**: The SPV is located on top of the display and control unit and is used during nitrogen purge operations in the airlock. The LFPV is used during off-nominal operations to ensure sufficient CO₂ washout in the helmet and to provide some gas flow through the pressure garment. While similar in design, both valves require different flow rates. The SPV requires 3.15 to 3.38 lb/hr and the LFPV requires 1.55 to 1.69 lb/hr of O₂ flow rate at 3.5 psi. Both valves are exposed on the outside of the spacesuit to enable crew member access and thus need specialized covers in order to tolerate large amounts of dust exposure.

4. **Positive and Negative Pressure Relief Valves (PPRV and NPRV)**: The PPRV and NPRV are located on the hard upper torso (HUT) and exposed to vacuum and dust. The full-open flow rate requirement for the PPRV is 7.49 lb/hr of dry O₂ at 70 °F with suit internal pressure of 10.1 psia and vacuum as the external reference. The requirement for the NPRV is 60.4 lb/hr of dry air at 70 °F, with the airlock pressure at 4.15 psia and a suit pressure at 3.65 psia. Specialized covers are needed in order to tolerate dust exposure.

**Expected TRL or TRL Range at completion of the Project**: 3 to 4

**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**:

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**:

**Phase I Deliverables**: Reports demonstrating proof of concept, test data from proof-of-concept studies, and 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, subsystems, or
treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. 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:

Good dust-mitigation technologies and strategies are nonexistent for the spacesuit.

Relevance / Science Traceability:

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References:

Note to offeror:

- PLSS schematics and hardware drawings shall be provided if offeror is selected for award.
- Dust simulant characteristics shall be provided if offeror is selected for award.


Scope Title:

Nonventing Portable Life Support System (PLSS) Covers

Scope Description:

For spacesuits, challenges presented by lunar dust include damage from abrasion, the effects of dust's electrostatic charge on the suit system, and dust intrusion to the suit system. Regarding the effects of dust intrusion, there is a need to provide the capability to mate and demate connectors and suit components as well as enabling venting to the environment for certain components. This will require the development of specialized dust covers for a variety of connections.

Two other connectors are on the exterior of the suit that do not need vacuum access and are nominally covered during an extravehicular activity (EVA). However, they need to be accessed at the conclusion of an EVA, at which point they may be covered in dust. Specialized covers for these connectors are needed to protect the connectors from dust intrusion during the EVA as well as during the removal of the covers. The connectors are as follows:

1. An 85-pin receptacle that serves as the battery charge connector and is located on the bottom corner of the PLSS.
2. The spacesuit common connector (SCC) contains high-pressure oxygen lines, water lines, an electrical connector, and mechanical mounting features. The SCC is located on the front of the spacesuit and is integrated with the display and control unit (DCU). The connector is flat and has a surface area of approximately 2.5 by 4 in.

Expected TRL or TRL Range at completion of the Project: 3 to 4

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:
Analysis
Prototype
Hardware

Desired Deliverables Description:

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof of concept studies, and 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, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. 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:

Good dust-mitigation technologies and strategies are nonexistent for the spacesuit.

Relevance / Science Traceability:

This scope is included under Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References:

Note to offeror:

- PLSS schematics and hardware drawings shall be provided if offeror is selected for award.
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