NASA STTR 2020 Phase I Solicitation

Small Business Technology Transfer

T2.04 Advanced in-space propulsion
Lead Center: GRC
Participating Center(s): GRC

Technology Area: TA15 Aeronautics
This subtopic is seeking small business - non-profit research institution partnerships to advance subsystem elements of three important, next generation in-space propulsion technologies: the Electrostatic Solar Sail, Freeform additive fabrication for propulsion elements, and Nuclear Thermal Propulsion low cost fuel testing.

Scope Title
Electrostatic Solar Sail (E-Sail) Advancement

Scope Description
The E-Sail is a propellant-less in-space propulsion system that utilizes electrostatic repulsion of solar wind (off of an electrically biased tether) to generate thrust. Preliminary studies indicate several advantages of this technology, including enabling access to interstellar space with transit times significantly faster than state-of-the-art (SOA) technologies. For this year's E-Sail investments, concepts to advance the Technology Readiness Level (TRL) of the E-sail guidance, navigation, and control system and/or robust models for spacecraft dynamics both during deployment as well as during operation are solicited. Marshall Space Flight Center (MSFC) is currently conceptualizing a 6-12U, ~10km total tether length E-Sail demonstration. Neither a specific architecture nor specific requirements have yet been detailed, however, responders should focus efforts in their proposed work towards this size spacecraft while keeping eventual scaling to as much as a 10x larger spacecraft in mind.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II
Prototype, Analysis, Hardware, Software, and/or Research

Desired Deliverables Description
Phase I proof of concept and/or preliminary guidance, navigation & control (GN&C) designs and/or models that will lead to Phase II medium to high fidelity prototypes ready for system infusion (in case of hardware), system analysis (in case of models), and/or advanced TRL testing (space environments testing) to support a MSFC led technology demonstration mission. Beyond Phase II, infusion into the planned E-Sail Technology Demonstration Missions (TDM) via a Phase III, IIE, directed work, etc. or additional development/test via an Announcement of Collaborative Opportunity (ACO) may be potential opportunities.

State of the Art and Critical Gaps
The E-Sail concept has potential to enable practical access to interstellar space and fast travel beyond our solar system. The E-Sail has several open technology gaps. NASA is systematically reducing known risks of full system implementation prior to a flight demonstration. State of the Art GN&C systems and modeling have limitations due to the complex and changing dynamics of an E-Sail system. A critical gap is robust and high fidelity GN&C modeling and/or concepts for control of the E-Sail vehicle.

Relevance / Science Traceability

An Electrostatic Sail E-Sail is a propellant-less advanced propulsion system that harnesses solar wind by electrostatic repulsion. Note, this contrasts Solar Sails, which utilize optical reflection of solar photons. E-Sail is comprised of thin tethers, which are electrically biased to form large electric fields. These fields create a virtual sail that repels solar ions and generates thrust. A key advantage is this mechanism better maintains thrust as it moves away from the sun – falling off at only 1/distance, substantially better than the solar sail 1/d^2. E-Sail will rapidly improve transit time within and to the edge of the solar system as well as enable out of plan maneuvers not currently possible.

References


Scope Title

Large Scale Freeform Additive Fabrication using GRCop-42 and Gradient Alloys

Scope Description

NASA is interested in soliciting proposals to develop a process for large scale freeform fabrication using additive manufacturing of GRCop-42 and functional gradient materials. Components such as rocket nozzles and heat exchangers are actively-cooled with internal channel features and require high performance materials in the extreme environment. Typically these components are made from a monolithic alloy, although various alloys and functional gradient materials could increase performance and optimize the overall system. The objective of this solicitation is to complete process development (i.e., directed energy deposition, coldspray, etc.) to fabricate a freeform component that incorporates thin-wall integral channels into a structure. This process should focus on GRCop-42 (Cu-Cr-Nb) and transition to an alternate material using a functional gradient process. The proposer should provide a technique and approach to axially transition from the GRCop-42 to alternate alloy (Superalloy, Stainless, High Entropy Alloys) providing a compatible functional gradient joint to minimize stresses. A thorough development approach would include process development, initial characterization and testing of the GRCop-42 and functional gradient alloys, process demonstration of manufacturing technology demonstrators (MTD), and trade study and/or planning to increase the scale to several feet in diameter.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, and/or Research

Desired Deliverables Description

Phase I: Develop a process for fabricating (using directed energy deposition, coldspray, etc.) a freeform structure that incorporates thin-wall integral channels targeting a heat exchanger, combustion chamber, rocket nozzle, channel-cooled structure and provide a trade on combination of compatible materials, with NASA inputs.

Leading to Phase II: Complete fabrication of process development samples using GRCop-42 and functional gradient alloys (Superalloy, High Entropy Alloys) to change the material axially along the component; and complete process characterization, mechanical testing, materials evaluation to provide first order design data. Fabricate manufacturing demonstrator components with integral channels with materials selected. Provide components that
NASA could perform benchtop, flow, and/or hot-fire testing. Demonstrate a manufacturing technology component with integral channels and that is larger than 16” diameter with the GRCop-42 and functionally gradient alloys. Provide scale-up to >40” diameter.

**State of the Art and Critical Gaps**

NASA has been developing various additive manufacturing technologies in GRCop-42 using laser powder bed fusion (L-PBF) and currently working to mature large-scale (>3 ft dia) blown powder directed energy deposition (DED) process using NASA HR-1 and JBK-75. These technologies have been limited to monolithic materials though. Additional development has included bimetallic cladding (radial deposition) to provide superalloy jackets on copper-alloy combustion chambers under the Low Cost Upper Stage Propulsion (LCUSP) project, however this technology is not easily accessible at service companies. While the technology exist to fabricate components at sizes <16” diameter using laser powder bed fusion (L-PBF) using GRCop-42, this is limited to a monolithic material in the axial direction. There are also no current additive techniques to rapidly fabricate GRCop-42 structures larger than this scale.

There are also additional challenges in this approach with a binary transition from one alloy to another. Optimized structures for heat exchanges and combustion devices would include the ability to fabricate large structures with complex internal features and vary-transition alloys along the axial length of a component (not just radial). This would allow for a more compliant bond between a copper-alloy and alternate material instead of a drastic change in alloys. This would reduce risk of joints. A further gap is the ability to produce copper-alloys, such as GRCop-42, in scales larger than 16” diameter. This provides new solutions for designers of large engines and structures providing higher thermal margins on the walls with the use of copper. The copper technology using additive manufacturing does not exist using directed energy deposition (DED) or other technologies at this scale.

**Relevance / Science Traceability**

Applications to: Propulsion and energy, Liquid rocket engines, Small thrusters, Additive Manufacturing, and Advanced Manufacturing.

**References**


**Scope Title**

Nuclear Thermal Propulsion (NTP) Advancement fuel testing

**Scope Description**

The NTP concept is similar to 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. NTP thrust is ~25,000 lbf with ~29 lbs/sec flow of hydrogen through the fuel elements. Current fuel element designs are based on cermet (ceramic metal) or carbon with low enriched uranium.
The scope is open to university/Small Business Concern (SBC) partners to propose key innovation on how to best test NTP fuel pieces in the university nuclear reactors that come close to meeting the following test goals:

- Neutron/gamma radiation fluence approximating NTP operation.
- Heat NTP fuel test piece up to 2700K.
- Power density of 5 MW/L.
- Test piece exposed to hydrogen (if possible).
- Maintain steady state up to 15 minutes (or fluence equivalent).

**Expected TRL or TRL range at completion of the project:** 3 to 6

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, and Research

**Desired Deliverables Description**

The STTR team provides the following for Phase I and II:

- Irradiation capsule design and thermal analysis predictions to handle a variety of fuel test pieces in the university reactor.
- Instrumentation required to determine how best the fuel performed and validate analysis predictions.
- Development plan for Phase II including a description of the reactor test arrangement and fuel pieces to be irradiated. Start-off with irradiating a surrogate test piece during phase II. Conclude phase II with irradiating a fuel test piece with High Assay Low Enriched Uranium. Include a description of post-test examinations to be performed.

**State of the Art and Critical Gaps**

Testing various fuel concepts in the same environment as an NTP engine at low cost is not easy. Many current irradiation test facilities can test sample pieces to only a few of the NTP environment conditions.

**Relevance / Science Traceability**

Research could have a significant positive impact on the design and development of NTP systems. NTP potentially useful for both science and exploration missions.

**References**

Multiple publicly available references, see for example:


**T2.05 Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage**

Lead Center: GRC

Participating Center(s): JSC

Technology Area: TA15 Aeronautics

Scope Description
This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, methane) production, storage, transfer, and usage to support NASA's in-situ resource utilization (ISRU) goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions to the Moon and Mars. Anticipated outcome of Phase I proposals are 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. Solicited topics are as follows:

- Subgrid Computational Fluid Dynamics (CFD) model that would model spray transport heat transfer and wall interactions during spray heat transfer during cryogenic propellant tank chilldown and fill in microgravity. Three submodels should be developed, including a (1) droplet transport and heat and mass transfer model, (2) fluid-to-wall boiling model covering all pertinent regimes (flash evaporation, film boiling, transition boiling, nucleate boiling, condensation), and (3) model that is used to capture bulk phases (e.g., volume of fluid). There should be seamless coupling between all three submodels. Emphasis should be on cryogenic fluids such as liquid hydrogen, oxygen, methane, and nitrogen. Phase I should have an emphasis on 1-g while Phase II should include microgravity applications. Models must be anchored to experimental cryogenic data.

- Develop and demonstrate methodologies for recovering propellant from lunar and Martian descent stages that have low fill levels (< 5%) of liquid oxygen, hydrogen, and/or methane mixed with helium. Methodologies can assume liquid extraction (for a short amount of time) or vapor extraction. Possible uses of the fluids could include fuel cells, life support/breathing air, or other applications. Methodologies should focus on the amount of propellant that might be extractable at different purities (prop/helium). Phase I should focus on defining and refining the methodologies for scavenging, as well as defining what should be done to the landers to enable or facilitate later access for scavenging. Phase II should include some sort of demonstration, perhaps using simulant or similar fluids.

- Develop and defend a proposed relaxed propellant grade specification for liquid oxygen, liquid methane, and/or liquid hydrogen, allowing higher amounts of water contaminants in the oxygen and hydrogen, and higher amounts of water, hydrogen, and carbon monoxide/dioxide in the methane. Starting with assessment of potential impurities coming out of the ISRU production plant, analysis should evaluate the effects on the liquefaction system, pump and pressure-fed propellant feed system, and engine performance, especially potential stability effects. Phase I should conclude with a proposed relaxed propellant specification for at least one propellant (oxygen or methane priority over hydrogen), with identification of the propulsion component (liquefaction, feed system, injectors, etc.) that has the most sensitivity to the impurities and will therefore drive the limits on the specification. Phase II should include a hardware demonstration of the critical element at a minimum to validate the accuracy of the analytical predictions.

- Advance non-liquid electrolyte technologies for chemical flow cells (e.g., fuel cells, electrolyzers, flow batteries, etc.) that generate electrical power from a chemical reaction or reconstitute a reaction byproduct into fuels and oxidizer for such a chemical flow cell. These electrolytes are required to be cycled through very low temperatures (< 150 K) during storage to survive a lunar night or cis-lunar travel and recover completely (>98%) mechanical, electrical, and chemical performance. Ideally, these electrolytes would be able to process propellants (hydrogen, oxygen, methane, kerosene, etc.) and either tolerate or recover from exposure to standard propellant contaminants with minimal/no performance loss. Due to the potential for high fluid pressures and vibration loads, any proposal will illustrate how the electrolyte could be mechanically supported to operate hermetically under these conditions. To demonstrate that the electrolyte exceeds the State of Art, the deliverable test article will support an electrical current density of at least 300 mA/cm² for at least 500 hours, support transient currents > 750 mA/cm² for at least 30 seconds, and support flow rates > 50 A/cm²/s. Providing test data for the electrolyte performance degradation rate when operated as intended is required with test times >5,000 hours significantly strengthening the proposal. It would be beneficial if the electrolyte operated reversibly with equal efficiency. Liquid electrolytes, loose or contained within a support structure, are excluded from this Scope due to the complications that liquid electrolytes pose for an eventual system during launch.

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 [5]. 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.

References


4. NASA Technology roadmap (https://gameon.nasa.gov/about/space-technology-roadmap/ [7]), §TA03.2.2.1.2. Chemical Power Generation and §TA03.2.2.2.3. Regenerative Fuel Cell Energy Storage (NOTE: This may be a dated link as this Roadmap still references ETDP/ETDD)


Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, 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 (or model subroutines) deliverable to NASA.

Electrolyte technologies for chemical cell product deliverables would be an operational electrochemical test article demonstrating the capability of the electrolyte to support the listed current density by processing the intended propellants when packaged as a flow cell. This test article will have an active area of at least 50 cm2 and would ideally contain multiple cells to demonstrate extensibility to existing stack designs. It would be favorable to include empirical electrochemical performance data of the electrolyte over as much of the pressure range from 5 psia to 3015 psia as possible to illustrate the potential viability range for Lunar applications.

State of the Art and Critical Gaps

Cryogenic Fluid Management is a cross-cutting 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. Space Technology Mission Directorate (STMD) has identified that Cryogenic Fluid Management (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. For spray transport and film condensation, there are significant gaps in modeling. For scavenging, only small scale tests have been conducted to remove residual helium from a liquid oxygen tank.

There is currently no standard on propellant grade specification for an ISRU plant.

Existing electrolytes for space applications are limited to a polymeric membrane based on perfluorinated teflon and
ceramic electrolyte. While it has the necessary electrochemical and mechanical properties, the polymeric membrane has very tight thermal constraints due to a high moisture content which complicates thermal system designs for lunar systems during transit. It is also very sensitive to chemical contamination. The ceramic electrolyte has significant mechanical and slew rate limitations, but is more resilient to chemical contamination and has a much larger thermal range which allows storage in very cold environments. Once operational and at temperature, either existing electrolyte technology operates in cold lunar regions. Should an off-nominal event occur during the lunar night that results in a cold-soak, neither existing electrolyte technology has a meaningful chance of recovering from the exposure to the low temperatures.

Relevance / Science Traceability

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; cryogenic fluid management is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Human Exploration and Operations Mission Directorate (HEOMD) 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, cryogens 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 on the Moon or Mars.

NASA already has proton exchange-membrane (PEM) based electrochemical hardware in the International Space Station (ISS) Oxygen Generator Assembly and is developing electrochemical systems for space applications through the Evolved Regenerative Fuel Cell. These system designs could be readily adapted to a solid electrolyte with capabilities beyond the existing State of Art for specific applications such as In Situ Resource Utilization, lunar fuel cell power systems, or regenerative fuel cell energy storage systems. As Commercial Lunar Payload Services (CLPS) companies have identified primary fuel cell power systems as a required technology, it would be helpful to ensure that there are options available that could survive the lunar night when off-line without active thermal control. This would enable a longer period between missions to re-fuel and recover the electrochemical system.

T4.01 Information Technologies for Intelligent and Adaptive Space Robotics

Lead Center: JPL

Participating Center(s): JSC

Technology Area: TA15 Aeronautics

Scope Title

Develop Information Technologies to Improve Space Robots.

Scope Description

Extensive and pervasive use of robots can significantly enhance space exploration and space science, particularly for missions that are progressively longer, complex, and distant. The performance of these robots is directly linked to the quality and capability of the information technologies used to build and operate them. With few exceptions, however, current information technology used for state-of-the-art robotics is designed only to meet the needs of terrestrial applications and environments.

The objective of this subtopic, therefore, is to encourage the adaptation, maturation, and retargeting of terrestrial information technologies for space robotics. Proposals should address at least one of the following research areas:

1. **Perception systems for autonomous robot operations** in man-made environments (inside spacecraft or habitats) and unstructured, natural environments (Earth, Moon, Mars). The primary objective is to significantly increase the performance and robustness of perception capabilities such as object/hazard
identification, localization, mapping, etc. through new avionics (including Commercial Off-The-Shelf [COTS] processors for use in space), sensors and/or software. Proposals for small size, weight, and power (SWAP) systems or technology that can operate on existing rad-hard processors are particularly encouraged.

2. **Robot user interfaces** that facilitate distributed human-robot teams, geospatial data visualization, summarization and notification, performance monitoring, etc. The primary objective is to enable more effective and efficient interaction with robots remotely operated with discrete commands or supervisory control. User interface technology that helps optimize operator workload or improve human understanding of autonomous robot actions are particularly encouraged. Note: proposals to develop user interfaces for direct teleoperation (manual control), augmented/virtual reality, or telepresence are not solicited and will be considered non-responsive.

3. **Robot Operating System v2 (ROS 2) for space robots.** The primary objective is reduce the risk of deploying, integrating, and verifying and validating the open-source ROS 2 for future space missions. Proposals that develop software technology that can facilitate integration of ROS 2 with common flight software (Core Flight Software, Integrated Test and Operations System [ITOS], etc.) and standards (Consultative Committee for Space Data Systems [CCSDS], etc.), methods to improve the suitability of ROS 2 for use with current flight computing, or tools / process to make ROS 2 (or a subset) ready for near-term flight missions are particularly encouraged.

Proposals are particularly encouraged to develop technologies applicable to robots of similar archetypes and capabilities to current NASA robots, such as Astrobe, Curiosity, or Robonaut 2.

**References**

[9]: https://www.nasa.gov/astrobee

[10]: https://robonaut.jsc.nasa.gov


**Expected TRL or TRL range at completion of the project:** 4 to 6

**Desired Deliverables (Phase I)**

Proposers should develop technologies that can be demonstrated with, or integrated to existing NASA research robots or projects to maximize relevance and infusion potential.

1. Identify scenarios, use cases, and requirements.
2. Define specifications.
3. Develop preliminary design.

**Desired Deliverables (Phase II)**

1. Develop prototypes (hardware and/or software).
2. Demonstrate and evaluate prototypes in real-world settings.
3. Deliver prototypes to NASA.

**State of the Art and Critical Gaps**
Future exploration and science missions will require robots to operate in more difficult environments, carry out more complex tasks, and handle more dynamic and varying operational constraints than the current state of the art, which relies on low-performance, rad-hard computing and execution of pre-planned command sequences. To achieve these capabilities, numerous new information technologies need to be developed, including high performance space computing, autonomy algorithms, and advanced robot software systems (on-board and off-board).

For example, in contrast to the International Space Station, which is continuously manned, the Gateway is expected to only be intermittently occupied – perhaps as little as 8% of the time. Consequently, there is a significant need for the facility to be robotically tended, in order to maintain and repair systems in the absence of human crew. These robots will perform a wide range of caretaking work including inspection, monitoring, routine maintenance, and contingency handling. To do this, significant advances will need to be made in autonomous perception and robot user interfaces, particularly to handle mission-critical and safety-critical operations.

As another example, a mission to explore and map interior oceans beneath the ice on Europa will require a robot to penetrate an unknown thickness of ice, autonomously carry out a complex set of activities, and navigate back to the surface in order to transmit data back to Earth. The robot will need to perform these tasks with minimal human involvement and while operating in an extremely harsh and dynamic environment. To do this, significant advances will need to be made in autonomous perception and on-board software, particularly to compensate for poor (bandwidth-limited, high-latency, intermittent) communications and the need for high performance autonomy.

Relevance / Science Traceability

The development of information technology for intelligent and adaptive space robotics is well aligned with NASA goals for robotics. In particular, this development directly addresses multiple areas (TA4, TA7, TA11) of the 2015 NASA technology roadmap. Additionally, this development is directly aligned with multiple portions of the NASA Autonomous Systems SCLT (Systems Capability Leadership Team) technology taxonomy. Moreover, this development directly addresses a core technology area (robotics and autonomous systems) of the NASA Strategic Space Technology Investment Plan. Finally, the technology is directly aligned with the needs of numerous projects and programs in Aeronautics Research Mission Directorate (ARMD), Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD).

- ARMD: The technology can be applied to a broad range of unmanned aerial systems (UAS), including both small-scale drones and Predator / Global Hawk type systems. The technology can also be potentially infused into other flight systems that include autonomous capabilities, such as Urban Air Mobility vehicles.
- HEOMD: The technology is directly relevant to “caretaker” robots, which are needed to monitor and maintain human spacecraft (such as the Gateway) during dormant/uncrewed periods. The technology can also be used by precursor lunar robots to perform required exploration work prior to the arrival of humans on the Moon.
- SMD: The technology is required for future missions in Earth Science, Heliophysics, and Planetary Science (including the Moon, icy moons and ocean worlds) that require higher performance and autonomy than currently possible. In particular, missions that must operate in dynamic environments, or measure varying phenomena, will require the technology developed by this subtopic.
- STMD: The technology is directly applicable to numerous current mid-TRL (Game Changing Development program) and high-TRL (Technology Demonstration Mission program) Research and Development (R&D) activities, including Astrobeef, In-space Robotic Manufacturing and Assembly, etc.

T4.03 Coordination and Control of Swarms of Space Vehicles

Lead Center: JPL

Participating Center(s): LaRC

Technology Area: TA15 Aeronautics
Scope Title

Enabling Technologies for Swarm of Space Vehicles

Scope Description

This subtopic is focused on developing and demonstrating technologies that enable cooperative operation of swarms of space vehicles in a dynamic environment. Primary interest is in technologies appropriate for low-cardinality (4-15 vehicle) swarms of small spacecraft, as well as planetary rovers and flyers (e.g., Mars helicopter). Large swarms and other platforms are of interest if well motivated in connection to NASA’s strategic plan and needs identified in decadal surveys.

The proposed technology should be motivated by a well-defined design reference mission presented in the proposal.

Possible areas of interest include but are not limited to:

- High precision relative localization and time synchronization in orbit and on planet surface.
- Coordinated task planning, operation, and execution with realistic communication limitations.
- Fast, real-time, coordinated motion planning in areas densely crowded by other agents and obstacles.
- Operations concepts and tools that provide situational awareness and commanding capability for a team of spacecraft or swarm of robots on another planet.
- Communication-less coordination by observing and estimating the actions of other agents in the multi-agent system.
- Cooperative manipulation and in-space construction
- Cooperative information gathering and estimation for exploration and inspection of a target object (large space structure or small asteroid).

Phase I awards will be expected to develop theoretical frameworks, algorithms, software simulation and demonstrate feasibility (TRL 2-3). Phase II awards will be expected to demonstrate capability on a hardware testbed (TRL 4-6).

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](https://www.nasa.gov/content/commercial-lunar-payload-services).

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.

References


Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Software, Hardware, Research

Desired Deliverables Description

- Algorithms and research results clearly depicting metrics and performance of the developed technology in comparison to state of the art (SOA).
- Software implementation of the developed solution along with simulation platform.
- Prototype of the sensor or similar if proposal is to develop such subsystem.

State of the Art and Critical Gaps

Technologies developed under this subtopic enable and are critical for multi-robot missions (rovers and flying vehicles such as Mars helicopter) for collaborative planetary exploration, e.g., a team of small pop-up rovers (PUFFERS) that can collaboratively create a mesh network and explore high risk and hard to reach areas such as lava tubes, etc.

These technologies also enable successful formation flying spacecraft for multi-spacecraft synthetic aperture radar and interferometry (distributed space telescope) purposes, a team of smallsats forming a convoy which the lead triggers detailed measurements on the following spacecraft of a phenomena identified by the lead, or a team of smallsats collaboratively manipulating a defunct spacecraft or small asteroid.

Relevance / Science Traceability

Subtopic technology directly supports NASA Space Technology Roadmap TA4 (4.5.4 Multi-Agent Coordination, 4.2.7 Collaborative Mobility, 4.3.5 Collaborative Manipulation) and Strategic Space Technology Investment Plan (Robotic and Autonomous Systems: Relative GNC and Supervisory control of an S/C team), and is relevant to the following concepts:

- Multi-robot follow-on to the Mars 2020 and Mars Helicopter programs are likely to necessitate close collaboration among flying robots as advance scouts and rovers.
- Pop-Up Flat-Folding Explorer Robots (PUFFERS) are being developed at Jet Propulsion Laboratory (JPL)
and promise a low-cost swarm of networked robots that can collaboratively explore lava-tubes and other hard to reach areas on planet surfaces.

- A convoy of spacecraft is being considered, in which the lead spacecraft triggers detailed measurement of a very dynamic event by the following spacecraft.

Multiple concepts for distributed space telescopes and distributed synthetic apertures are proposed that rely heavily on coordination and control technologies developed under this subtopic.

T4.04 Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway

Lead Center: JPL

Participating Center(s): JSC, KSC, SSC

Technology Area: TA15 Aeronautics

Scope Title

Artificial Intelligence for the Lunar Orbital Platform-Gateway

Scope Description

The Gateway is a planned lunar-orbit spacecraft that will have a power and propulsion system, a small habitat for the crew, a docking capability, an airlock and logistics modules. The Gateway is expected to serve as an intermediate way station between the Orion crew capsule and lunar landers as well as a platform for both crewed and un-crewed experiments. The Gateway is also intended to test technologies and operational procedures for suitability on long-duration space missions such as a mission to Mars. As such, it will require new technologies such as autonomous systems to run scientific experiments onboard, including biological experiments; perform system health management, including caution and warning; autonomous data management and other functions. In contrast to the International Space Station, Gateway is much more representative of lunar and deep-space missions—e.g., for example, the radiation environment.

This subtopic solicits autonomy, artificial intelligence and machine learning technologies to manage and operate engineered systems to facilitate long-duration space missions, with the goal of testing proposed technologies on Gateway. The current concept of operations for Gateway anticipates un-crewed (dormant) periods of up to nine months. Technologies need to be capable of or enable long-term, mostly unsupervised, autonomous operation. While crew are present, technologies need to augment the crew’s abilities and allow more autonomy from Earth-based Mission Control. Additionally, the technologies may need to allow for coordination with the Orion crew capsule, lunar landers, Earth and their various systems and subsystems.

Examples of needs include but are not limited to:

1. Autonomous operations and tending of science payloads including environmental monitoring and support for live biological samples, and in-situ automated analysis of science experiments.
2. Prioritizing data for transmission from the Gateway. Given communications limitations, it may be necessary to determine what data can be stored for transmission when greater bandwidth is available, and what data can be eliminated as it will turn out to be useless, based on criteria relevant to the conduct of science and/or maintenance of the physical assets. Alternatively, it may be useful to adaptively compress data for transmission from the Gateway, which could include scientific experiment data and status, voice communications, scientific experiment data and status, and/or systems health management data.
3. Autonomous operations and health management of the Gateway. When Gateway is unoccupied, unexpected events or faults may require immediate autonomous detection and response, demonstrating this capability in the absence of support from Mission Control (which is enabling for future Mars missions and time-critical responses in lunar environment as well). Efforts to develop smart habitats will allow long-term human presence on the moon and Mars, such as the Space Technology Research Institutes (https://www.nasa.gov/press-release/nasa-selects-two-new-space-tech-research-institutes-for-smart-
habits [16]) are relevant.

References

Basic Moon to Mars Background: https://www.nasa.gov/topics/moon-to-mars/lunar-outpost [17]

Basic Gateway Background: https://www.nasa.gov/topics/moon-to-mars/lunar-gateway [18]


Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Hardware, Research

Desired Deliverables Description

The deliverables range from research results to prototypes demonstrating various ways that autonomy and artificial intelligence (e.g., automated reasoning, machine learning, and discrete control) can be applied to aspects of Gateway operations and health management individually and/or jointly. As one example, for autonomous biological science experiments, the prototype could include hardware to host live samples for a minimum of 30 days that provide monitoring and environmental maintenance, as well as software to autonomously remedy issues with live science experiments. As another example, software that monitors the gateway habitat while un-crewed, automatically notifies of any off-nominal conditions, and then, when crew arrive, transitions the gateway from quiescent status to a status capable of providing the crew with life support. As another example, machine learning from the data stream of Gateway sensors to determine anomalous vs. nominal conditions and prioritize and compress data communications to Earth.

Phase 1 deliverables minimally include a detailed concept for autonomy technology to support Gateway operations such as experiments. Prototypes of software and/or hardware are strongly encouraged. Phase 2 deliverables will be full technology prototypes that could be subsequently matured for deployment on Gateway. Coordination with related efforts, such as the Space Technology Research Institutes (https://www.nasa.gov/press-release/nasa-selects-two-new-space-tech-research-institutes-for-smart-habitats [16]) is expected to eliminate redundancy of effort and allow appropriate interactions between Gateway and smart habitats.

State of the Art and Critical Gaps

The current state-of-the-art in human spaceflight allows for autonomous operations of systems of relatively limited scope, involving only a fixed level of autonomy (e.g., amount of human involvement needed), and learning at most one type of function (e.g., navigation). The Gateway will require all operations and health management to be autonomous at different levels (almost fully autonomous when no astronauts are on board vs. limited autonomy when astronauts are present), will require the autonomy to learn from human operations, and will require autonomy across all functions. The autonomy will also need to adapt to new missions and new technologies.

As NASA continues to expand with the eventual goal of Mars missions, the need for autonomous tending of science payloads will grow substantially. In order to address the primary health concerns for crew on these
missions, it is necessary to conduct science in the most relevant environment. Acquisition of this type of data will be challenging while the gateway and Artemis missions are being performed due to limited crewed missions and limited crew time.

Relevance / Science Traceability

Gateway and other space station-like assets in the future will need: The ability to learn autonomous operations from human operations which will be critical as the assets are expected to operate increasingly autonomously due to increasing duration space missions such as missions to Mars.

T5.03 Electric Field Mapping and Prediction Methods within Spacecraft Enclosures

Lead Center: KSC

Participating Center(s): GSFC, JPL, JSC, MSFC

Technology Area: TA15 Aeronautics

Scope Title

Expected Electric Field Prediction Methods in Fairing/Aircraft and Spacecraft Enclosures

Scope Description

NASA Launch Services program is responsible for ensuring the safety of NASA payloads on commercial rockets. NASA has also undertaken Gateway. This includes prediction and mitigation of hazardous electric fields created within the payload enclosure and similar areas of the rocket. NASA and industry have commonly used approximation methods to determine the average fields in enclosures. In the last decade the Launch Services Program (LSP) has funded studies to support quantification of electromagnetic field characterization in fairing cavities due to internal and external sources. By accurately predicting these fields, acoustic and thermal blanketing can be optimized for Radio Frequency (RF) attenuation and design changes can be quickly evaluated reducing schedule impacts. Cost savings can also be realized by reducing stringent radiated susceptibility requirements, and reliability improved by accurately predicting signal transmission/reception environments within enclosures. This methodology can also improve human exposure safety limits evaluations for manned vehicle enclosures with transmitting systems.

Initially, studies focused on computational methods using the recent advances in computing power and the improved efficiency of matrix based solutions provided by Graphics Processing Unit (GPU) computing. Results indicate solution of an integrated fairing is deterministic, but sensitive to small variation in structures, materials. As of yet, only the empty or sparse cavity can be reliably solved with 3D computational tools, even with large computing systems and the use of non-linear basis functions. Results also indicate that computational approximation methods such as physical optics and multilevel fast multipole are not reliable prediction methods within enclosures of this scale because of the underlying assumption sets that are inconsistent with enclosure boundaries. More recently, LSP has concentrated on statistically formulating a compilation of test/computational results to produce a maximum expected environment. Preliminary results are promising in the area of statistical bounding of the desired solution. The researched methodology should offer the following advantages over 3D computational and standard volume based approximation methods:

- Predict both statistical mean and maximum expected E field and/or common mode current.
- Consider the over-moded (electrically large conductive cavities) and under-moded (electrically smaller damped enclosures).
- Consider complex materials with multiple joined enclosures.
- Applications of this prediction methodology are far reaching and include shielding effectiveness and prediction of fields within a cavity enclosure due to internal transmitters and operating avionics.

To enable bounded solutions in electromagnetic environment prediction, proposals are solicited to develop
technology that does the following:

- Bounds the expected peak electric field environment inside enclosures such as rocket fairings, and spacecraft enclosures. The method should include the technology required, the technique, as well as the necessary verification efforts.
- Develops a numerical or statistically based methodology for characterizing shielding effectiveness of enclosures with associated applicable apertures.
- Develops methods field enhancement/reduction based on thermal/acoustic blanketing and metal/composite components such as avionics and Payload Attached Fitting (PAF) structures.
- Develops preliminary user friendly modeling software that can be easily customized to support NASA-specific applications.

References


Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Phase I Deliverables: Research, identify and evaluate candidate algorithms or concepts for electromagnetic field mapping of typical spacecraft and rocket enclosures. Demonstrate the technical feasibility, and show a path towards a computer model development. It should identify improvements over the current state of the art for both time/resource savings and systems development and the feasibility of the approach in a varied-enclosure environment. Lab-level demonstrations are required. Deliverables must include a report documenting findings.

Phase II Deliverables: Emphasis should be placed on developing usable computer model and demonstrating the technology with under and over-moded conditions with testing. Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, verification test results, computer model with user’s and other associated documentation. Deliverable of a functional computer model with associated software is expected at the completion of the Phase II contract.
State of the Art and Critical Gaps

Reliability of communications systems is critical for all spacecraft. Determining RF exposure limits in cavity environments is also critical. Given this criticality it is often desired to transmit and receive before separation from the launch vehicle where there is precise tracking information to improve the probability of signal capture. When the transmission or reception is in the launch vehicle fairing whether for pre-flight checks or during launch, the presence of the cavity surrounding the antennas causes significant uncertainties in the desired signal. In addition, there is a significant increase in the RF environment in which the spacecraft and launch vehicle hardware are exposed. Since hardware qualification testing is based on free space environments the higher fields in the cavity can lead to an increase mission risk of failure due to susceptible hardware. Prediction of fields within rectangular highly conductive over-moded chambers is well studied in the reverberation testing community; however, launch vehicle fairings are sometimes composite and always covered with acoustic damping materials that have unknown RF damping characteristics. There are also thermal materials surrounding launch vehicle and spacecraft avionics and instruments leading to further complications in defining the communication path losses and RF environment exposure and cavity mode underdamping characteristics where more research is needed especially in the layered wall covering case.

Determining the RF environment in the fairing cavity is a significant problem that affects every launched mission; even if transmission with the fairing is not planned, it has historically happened inadvertently and the effects of failed inhibits are required to be provided. Shielding effectiveness to external range and launch vehicle transmitters are also significantly affected by not only the material conductive properties, but also the characteristics of the penetrated cavity.

3D computational electromagnetic tools are limited by the size of the matrix required to solve the typical transmit frequency of at least 2GHz in a cavity with 5 meter diameters and over 10 meter length. The size of just modeling the fairing alone is daunting using method of moments (limited also by non-uniqueness for external radiators) and unachievable with finite difference frequency domain. When internal spacecraft and blanketing structures are added, the computational limits are quickly surpassed. Approximation techniques such as physical optics and multilevel fast multipole methods are limited by underlying assumptions that do not hold in cavity environments. Time domain techniques are not clearly fitted for frequency specific applications and have shown similar size/complexity limitations.

Substantially, new methods are needed to predict path loss, shielding effectiveness and RF environment in launch vehicle fairings and spacecraft cavities.

Relevance / Science Traceability

This subtopic is intended for STTR, but all NASA payloads, particularly those with hardware sensitive to electric fields, will benefit from launch and ascent risk reduction.

T5.04 Quantum Communications

Lead Center: KSC

Participating Center(s): GSFC, JPL

Technology Area: TA15 Aeronautics

Scope Description

NASA seeks to develop quantum networks to support the transmission of quantum information for aerospace applications. This distribution of quantum information could potentially be utilized in secure communication, sensor arrays and quantum computer networks. Quantum communication may provide new ways to improve communication link security and availability through techniques such as quantum cryptographic key distribution. Another area of benefit is the entanglement of distributed sensor networks to provide extreme sensitivity for applications such as astrophysics, planetary science and earth science. Also of interest are ideas or concepts to support the communication of quantum information between quantum computers over significant free space.
distances (greater than 10km up to GEO) for space applications. Technologies that are needed include quantum memory, quantum entanglement sources, quantum repeaters, high efficiency detectors, quantum processors, quantum sensors that make use of quantum communication for distributed arrays and integrated systems that bring several of these aspects together using Integrated Quantum Photonics. A key need for all of these are technologies with low size, weight and power that can be utilized in aerospace applications. Some examples of requested innovation include:

- High brightness, efficient and tunable sources of entangled photon pairs.
- Photonic waveguide interferometric circuits for quantum information processing and manipulation of entangled quantum states; requires phase stability, low propagation loss, i.e. < 0.1 dB/cm, and efficient fiber coupling, i.e. coupling loss < 1.5 dB
- Waveguide-integrated single photon detectors for > 100 MHz incidence rate, 1-sigma time resolution of < 25 ps, dark count rate < 100 Hz, and single-photon detection efficiency > 50% at highest incidence rate
- Integrated sensors that support arrays of distributed sensors, such as an entangled interferometric imaging array
- Integrated photonic circuit quantum memory
- Integrated photonic circuits and detectors for balanced homodyne detection
- Quantum entanglement verifying system

Quantum sensor focused proposals that do not include an aspect of quantum communication should propose to the Quantum Sensing and Measurement subtopic as individual quantum sensors are not covered by this subtopic.

References


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I research should (highly encouraged) be conducted to demonstrate technical feasibility with preliminary hardware (i.e. beyond architecture approach/theory; a proof-of-concept) being delivered for NASA testing, as well as show a plan toward Phase II integration. Phase II new technology development efforts shall deliver components at the TRL 4-6 level with mature hardware and preliminary integration and testing in an operational environment. Deliverables are desired that substantiate the quantum communication technology utility for positively impacting the NASA mission. The quantum communication technology should impact one of three key areas: information security, sensor networks, and networks of quantum computers. Deliverables that substantiate technology efficacy
include reports of key experimental demonstrations that show significant capabilities, but in general it is desired that the deliverable include some hardware that shows the demonstrated capability.

**State of the Art and Critical Gaps**

There is a critical gap between the United States and other countries, such as Japan, Singapore, Austria and China in quantum communications in space. Quantum communications is called for in the 2018 National Quantum Initiative (NQI) Act, which directs National Institute of Standards and Technology (NIST), National Science Foundation (NSF) and Department of Energy (DOE) to pursue research, development and education activities related to Quantum Information Science. Applications in quantum communication, networking and sensing, all proposed in this subtopic, are the contributions being pursued by NASA to integrate the advancements being made through the NQI.

**Relevance / Science Traceability**

This technology would benefit NASA communications infrastructure as well as enable new capabilities that support its core missions. For instance, advances in quantum communication would provide capabilities for added information security for spacecraft assets as well as provide a capability for linking quantum computers on the ground and in orbit. In terms of quantum sensing arrays, there are a number of sensing applications that could be supported through the use of quantum sensing arrays for dramatically improved sensitivity.

**T6.05 Testing of COTS Systems in Space Radiation Environments**

**Lead Center:** KSC

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

**Technology Area:** TA15 Aeronautics

**Scope Description**

The use of commercial off-the-shelf (COTS) parts in space for electronics is a potential significant enabler for many capabilities during a mission. This subtopic is seeking a better understanding of the feasibility of COTS electronics in space environments. It seeks strategies based on a complete system analysis that include, but not limited only to, failure modes to mitigate radiation induced impacts to systems in the space radiation environment.

As background, spacecraft experience exposure to damaging radiation and that amount of exposure from various sources, (e.g., sun and galactic cosmic radiation sources) increases notably as the spacecraft ventures further away from the Earth’s magnetic field, since the magnetic field offers some level of protection. As spacecraft, and their electronic systems, proceed again to the moon and further into deep space, considerable work has and continues to be done to evaluate and determine how to appropriately protect the astronauts and to shield or otherwise protect various spacecraft, habitats, and their electronic systems, depending upon the needs of the missions.

Many of the most protective physical shielding approaches known result in infrastructure which is too heavy for what is considered acceptable for many missions’ intended launch and spaceflight conditions. Therefore, typically lighter infrastructure shielding is presently being used when and where possible. Spacecraft faring deeper into space for fly-by missions (e.g., New Horizons), orbiters (e.g., Mars Orbiter), or landers (e.g., Mars Rover) are examples of such relatively lightly shielded systems. The lighter shielding sacrifices some radiation protection and therefore results in some limitations in what their electronic systems could do. There are already ongoing projects to upgrade current radiation hardened parts, but these are not COTS items and are expensive to manufacture and to buy. For critical systems that must be operational continuously and which may also have more lightly shielded systems, there is no other option at this time. This subtopic does not seek work of that nature.

Unlike the lightly shielded space environments discussed above, space environments which are highly shielded from radiation, such as is inherently the case for the interiors of manned missions and for habitats where humans live and work, high level radiation hardened systems may not be as necessary even in deeper space beyond most
of the present day low earth orbit (LEO) situations. Instead, a less expensive COTS solution may be acceptable for a number of non-critical tasks that are not harmed by power interruptions, hardware failures, radiation upsets, etc. in those environments over what may have been thought likely. In order to assess the feasibility of a COTS solution for those types of highly shielded space environments, this subtopic is seeking proposals.

Successful Small Business Concern/Research Institution teams would be able to do space radiation modeling and a complete analysis of the COTS (e.g., modelling for an appropriate space relevant environment; statistical modeling of the electronic parts themselves and their connections in a system; destructive testing and analysis; and testing in an appropriate space relevant environment [e.g., in particle beams]). Further, since all parts in these systems cannot be individually tested, an understanding of what parts are susceptible to radiation damage is crucial so as to create the list of potential test candidates.

Phase I proposers are expected to develop a plan or strategy that explains and details how they would approach solving the problem that helps NASA mitigate radiation induced failures in the system/components, identify COTS equipment that are likely candidates based on environmentally relevant testing, as well as modeling of interior environment and data analysis of similarly known/used approaches like the Orion vehicle testing (EM-1 when released). They should highlight the innovation in the suggested approach and explain why it would be a better solution over what may presently be used. Additionally, they should also indicate how the proposed strategies could be used commercially if developed. Phase I concept studies are expected raise the TRL to at least a 3/4 when completed. Phase II proposals would use that innovative approach to refine and conduct further relevant interior environmental modeling and conduct the space radiation relevant testing and analysis on the selected COTS parts/systems which could lead toward creating prototypes of the potential commercial items that come from the analysis. The deliverables from a successful Phase II is expected to raise the TRL to 5/6.

References

There are many references on each individual aspect of the work involved, but very few references on the entire process wanted. For a tool that can model the radiation environment inside a spacecraft:


A reference to help understand the radiation testing of powered COTS parts, see:


Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Hardware, Research

Desired Deliverables Description

Either a prototype or flyable hardware to perform the proposed task. Either software or software reports that show theoretically, the hardware will withstand the space environment with any predictions of failure rates or potential upset rates and mitigation.

State of the Art and Critical Gaps

Many systems have never been subjected to replacement with COTS part based systems, either off the shelf systems or specially designed systems with COTS parts. The list is long and not appropriate for NASA to designate a list. It is up to the proposer to identify what has been done in the past to mitigate COTS parts in a system, if anything.

Relevance / Science Traceability
This work would benefit all entities flying specialty systems in space. If reduced cost, more reliable and capable systems are needed, then COTS is a pathway to this. It just needs to be confirmed that the system can survive in the space environment.

**T6.06 Spacecraft Water Sustainability through Nanotechnology**

Lead Center: KSC

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

**Technology Area:** TA15 Aeronautics

**Scope Title**

Nanotechnology Innovations for Spacecraft Water Management Applications

**Scope Description**

Water recovery from wastewater sources is key to long duration human exploration missions. Without substantial water recovery, life support system launch weights are prohibitively large. Regenerative systems are utilized on the International Space Station (ISS) to recycle water from humidity condensate and urine. The Water Processor Assembly (WPA) accepts distillate from the Urine Processor Assembly (UPA) and humidity condensate from condensing heat exchanges. The WPA contains multi-filtration beds to remove inorganic and non-volatile organic contaminants, followed by a catalytic oxidation reactor where low molecular weight organics not removed by the adsorption process are oxidized in the presence of oxygen, elevated temperature, and a catalyst. To stabilize urine and protect components from biofouling and precipitation, a toxic pretreatment formula is added to collected urine. Simple measurements of water composition are made during flight, including conductivity, total organic carbon and iodine concentration. For determination of ionic or organic species in water and wastewater, samples must be returned to earth.

This subtopic solicits for technologies to fill specific gaps in NASA’s water management systems for human spaceflight. Proposals must address needs in one of the three target areas specified. These areas of scope are aligned with the three specific thrusts described within the white paper of the Nanotechnology Signature Initiative (NSI) “Water Sustainability through Nanotechnology”. Please see references for additional information, including water quality requirements and guidelines.

**Increasing Water Availability Using Nanotechnology: Removal of Problematic Contaminants from Processed Wastewater**

Two problematic organic compounds are recalcitrant to WPA processing on the ISS. Dimethylsilanediol (DMSD) is a silicon-containing degradation byproduct from siloxane based compounds. DMSD can violate ISS potable water quality standards over time, requiring premature multfiltration (MF) bed replacement. Dimethyl sulfone (DMSO2) is a sulfur-containing metabolic byproduct that has historically been consistently present in ISS potable water delivered to the Oxygen Generation Assembly (OGA) for electrolysis to O₂ and H₂. DMSO2 accumulates in the OGA water recirculation loop and is thus present in the OGA hydrogen product stream. When fed to the Sabatier reactor this contaminated H₂ has been shown to poison the Sabatier catalyst over time from sulfur exposure. The presence of DMSO2 is negatively impacting exploration design requirements and Concepts of Operation (CONOPS) for the Advanced-OGA and the Sabatier subsystems, including periodic automated flushing and trace contaminant getter devices. The development of a technology or method for physicochemical removal of these contaminants, compatible with the ISS WRS/WPA, will benefit both current manned and future exploration missions. Although technical solutions are sought that involve novel utilization of nanotechnology, proposals using more conventional or alternative approaches will also be considered.

**Improving the Efficiency of Water Delivery and Use with Nanotechnology: Management and Monitoring of Silver Biocide in Potable Water**
NASA is considering using silver as the active biocide in potable water systems for use in future spacecraft. NASA is seeking technologies for delivery, maintenance and monitoring silver in potable water.

- NASA seeks technologies to deliver and replenish silver ions in potable water, to maintain a concentration at a chosen set point within a range of 200 to 400 ug/L. The system should be capable of operating in-line, to deliver silver at a flow rate of 0.1 to 0.15 L/min potable water. Furthermore, the device should be able to operate at ambient temperature, pH ranges between 4.5 - 9.0, and system pressures up to 30 psig (200 kPa). Moreover, the device should also be small, robust, lightweight, and have minimal power and consumable mass requirements. Additionally, candidate technologies should be microgravity compatible and have no adverse effects on the potability of the drinking water system. The technology should also be capable of providing continuous, stable and autonomous operation, and be fully functional following periods of long-term system dormancy – up to 1 year.

- Silver ions may drop out of solution, depositing on fluid lines and tank surfaces, resulting in loss of silver concentration, impacting its efficacy as a residual disinfectant in potable water. Alternative methods are sought to minimize loss of silver ions in spacecraft potable water plumbing systems.

- NASA is interested in sensing technologies for the in-line measurement of ionic silver in spacecraft potable water systems. Overall, the sensing technology should offer small, robust, lightweight, low-power, compatible design solutions capable of stable, continuous, and autonomous measurements of silver for extended periods of time. Sensors of particular interest would provide: continuous in-line measurement of ionic silver at concentrations between 0 and, at least, 1000 parts per billion (ppb); a minimum detection limit of 10 ppb or less; measurement accuracy of at least 2.5% full scale (1000 ppb); stable measurements in flows up to 0.5 L/min and pipe diameters up to ¾ inch; high sampling frequency, e.g., up to 1 measurement per minute; stable calibration, greater than 3 years preferred; minimal and/or no maintenance requirements; operation at ambient temperature, system pressures up to 30 psig (200 kPa), and a solution pH between 4.5 - 9.0; and finally, a volumetric footprint less than 2000 cubic centimeters. The sensing technology should have little to no impact on the overall volume and concentration of silver being maintained within the spacecraft water system.

Enabling Next-Generation Water Monitoring Systems with Nanotechnology

NASA is seeking miniature analytical systems to measure mineral and organic constituents in potable water and wastewater. NASA is interested in sensor suites capable of simultaneous measurement of inorganic and organic species. Spacecraft applications exist for monitoring species within wastewater (potential waste streams: urine, humidity condensate, Sabatier product water, waste hygiene, and waste laundry water), regenerated potable water and in support of on-board science. Multi-species analyte measurement capability is of interest that would be competitive to standard water monitoring instruments such as ion-chromatography, inductively coupled plasma spectroscopy, and high performance liquid chromatography. Components that enable the miniaturization of these monitoring systems, such as microfluidics and small scale detectors, will be considered. Technologies should be targeted to have >3 year service life and >50% size reduction compared to current state of the art. Ideally, monitoring systems should require no hazardous reagents, have long-term calibration stability, and require very little crew time to operate and maintain.

References

NASA is a collaborating agency with the NTSC Committee on Technology Subcommittee on Nanoscale Science, Engineering and Technology’s Nanotechnology Signature Initiative (NSI): “Water Sustainability through Nanotechnology” (Water NSI). For a white paper on the NSI, see https://www.nano.gov/node/1580 [22]

A high-level overview of NASA’s spacecraft water management was presented at a webinar sponsored by the Water NSI: "Water Sustainability through Nanotechnology: A Federal Perspective, Oct. 19, 2016" https://www.nano.gov/publicwebinars [23]

A general overview of the state of the art of spacecraft water monitoring and technology needs was presented at a webinar sponsored by the Water NSI: "Water Sustainability through Nanotechnology: Enabling Next-Generation Water Monitoring Systems, Jan. 18, 2017" located at https://www.nano.gov/publicwebinars [23]

For a list of targeted contaminants and constituents for water monitoring, see "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants" located at https://www.nasa.gov/feature/exposure-guidelines-

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Advanced Exploration Systems Program, Life Support Systems Project [24]


Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II: 4 to 5

Desired Deliverables of Phase II:

Research, Analysis, Prototype, Hardware

Desired Deliverables Description

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

State of the Art and Critical Gaps
NASA has unique water needs in space that have analogous applications on Earth. NASA’s wastewater collection differs from systems used on Earth in that it is highly concentrated with respect to urine, uses minimal flush water, is separated from solid wastes, and contains highly acidic and toxic pretreatment chemicals. NASA is interested in recovery of potable water from waste water, low toxicity residual disinfection, antifouling treatments for plumbing lines and tanks, “microbial check valves” that prevent microbial cross-contamination where water treatment and potable water systems share connections, and miniaturized sensors and monitoring systems for contaminants in potable water and waste water. NASA’s goal is zero-discharge water treatment, targeting 100% water recycling and reuse. Spacecraft traveling away from Earth require the capability of a fully functional water analysis laboratory, including identification and quantification of known and unknown inorganic ions, organics, and microbes, as well as pH, conductivity, total organic carbon and other typical measurements. Spacecraft Water Exposure Guidelines (SWEGs) have been published for selected contaminants. Nanotechnology may offer solutions in all of these application areas.

**Relevance / Science Traceability**

This technology could be proven on the ISS and would be useful to long duration human exploration missions, including Gateway, Lunar surface, and Mars, including surface and transit. It is essential and enabling for water to be recycled to reduce launch costs associated with life support consumables. This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS).

This subtopic is directed at meeting NASA’s commitments as a collaborating agency in the National Nanotechnology Signature Initiative: “Water Sustainability through Nanotechnology”. This initiative was established under the NTSC Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology.

**T6.07 Space Exploration Plant Growth**

Lead Center: KSC

Participating Center(s): JSC

Technology Area: TA15 Aeronautics

**Scope Title**

Nutrient Recovery from Urine and Wastewater

**Scope Description**

Estimates for growing enough plants to support one human's food (dietary calories) suggest that 90-100 kg of fertilizer would be required per person per year. Even if plants were used only for partial life support (1/4 or 1/2 of the oxygen or food), this fertilizer mass would be substantial. NASA seeks methods and approaches for using *in situ* waste streams, such as urine and waste water to provide important nutrients and fertilizer for plants. Concepts should consider alternate approaches for how urine might be pre-treated to make it more amenable for fertilizer, and how the high levels of sodium typically found in urine might be separated or managed, since most plants are not tolerant to high levels of sodium.

**References**


Jackson, W.A., A. Morse, N. Landes and D. Low. 2010. An optimum biological reactor configuration for water
Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

Phase I proposals should at a minimum deliver proof of concept for retrieving useful plant nutrients and removal / partitioning sodium from urine or ersatz urine wastewater. By the completion of Phase II, we hope to have prototypic or engineering development unit hardware delivered to NASA for the technology. The potential for Phase III funding for spaceflight validation would then be explored.

State of the Art and Critical Gaps

Current approaches for fertilizing plants for space depend largely on time-release fertilizer pellets that are mixed in with a solid rooting media (used both in Veggie and APH). This approach is not sustainable for multiple crop cycles and requires that all the fertilizer be delivered from Earth. Hydroponic approaches have been suggested for space (e.g., AES NextSTEP AstroGarden) and will hopefully be tested soon on the International Space Station (ISS), and eventually on surface settings. In this case, fertilizer salts would be mixed with water to provide a nutrient solution for the plants. Growing plants in space would be more sustainable if the cost and amount of fertilizer salts could be reduced by using recycled wastes, including processed urine.

Relevance / Science Traceability

This technology would be relevant and science traceable to:

- Human Exploration and Operations Mission Directorate (HEOMD): Space Life and Physical Science (SLPSRA)
Scope Title

Ethylene Gas Sensor

Scope Description

Ethylene is a 2-carbon alkene gas that has growth regulating effects on plants. Plants can produce ethylene through natural metabolic processes, and this ethylene can accumulate in closed environments (such as closed plant growth chambers) and have undesirable effects on the plants. These effects can include reduced growth, impaired pollen development and/or fertilization, leaf epinasty, flower abortion, accelerated fruit ripening, and more (Abeles et al., 1992). Being hormonal in nature, ethylene can affect plants at very low concentrations, with levels as low as 25 ppb being reported to have subtle effects on some plants. More sophisticated plant growth chambers for space have included ethylene removal systems, such as KMnO₄ coated pellets, but this is a consumable material and adds resistance to air circulation in the chamber. Real time ethylene monitoring would allow more judicious use of ethylene removal for controlling plant growth, and save on consumables. NASA seeks a miniature, sensitive (25 ppb), real time or near-real time sensor to monitor ethylene in plant growth environments for space.

References


Expected TRL or TRL range at completion of the project: 4 to 7

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

Phase I proposals should at a minimum deliver proof of concept for a principle to detect ethylene real-time to a target level of 25 ppb. By the completion of Phase II, we hope to have prototypic or engineering development unit hardware delivered to NASA for the technology. The potential for Phase III funding for spaceflight validation with hardware like the Veggie or Advanced Plant Habitat chambers would then be explored.

State of the Art and Critical Gaps
Ethylene monitoring has traditionally been conducted using gas chromatography with either flame ionization or photo-ionization detection. However, gas chromatographs can be large instruments and require collection of gas samples, which are then analyzed. This limits their use in small spaces/volumes and their ability to analyze gases real-time.

Relevance / Science Traceability

This technology would be relevant and science traceable to:

- Human Exploration and Operations Mission Directorate (HEOMD): Space Life and Physical Science (SLPSRA)
- HEOMD: Advanced Exploration Systems (AES)
- HEOMD: Human Research Program (HRP)
- Space Technology Mission Directorate (STMD): Game Changing Development (GCD)

STMD: Space Technology Research Institute (STRI)

T8.04 Metamaterials and Metasurfaces Technology for Remote Sensing Applications

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

Scope Title
Research and Development Opportunities for Metamaterials

Scope Description

Metamaterials are man-made (synthesized) composite materials whose electromagnetic, acoustic, optical, etc. properties are determined by their constitutive structural materials and their configurations. Metamaterials can be precisely tailored to manipulate electromagnetic waves, including visible light, microwaves, and other parts of the spectrum, in ways that no natural materials can. The development of metamaterials continues to redefine the boundaries of materials science. In the field of electromagnetic research and beyond, these materials offer excellent design flexibility with their customized properties and their tunability under external stimuli. These properties enable Metamaterials to be a game changer for many technologies needing reduced size, weight, and power (SWaP), enhanced tunability and reconfigurability. Topics of interest for NASA's applications are listed below.

1. Beam shaping with metamaterials (at optical as well as microwave wavelengths).
2. Control of emission and absorption with metamaterials (for applications such as tunable lenses).
3. Engineering mid-infrared and optical nonlinearities with metamaterials.
4. Development of microwave and millimeter-wave metamaterials: radar scanning systems, flat panel antennas, mobile communication antennas, novel magnetic materials and high-performance absorbing and shielding materials for electromagnetic compatibility (EMC) and reduction of radio frequency interference (RFI).
5. Thin-film technology incorporated with metamaterial nanocomposites to collect light from wide angles and absorption over wide spectrum.
6. Tunable, reconfigurable metamaterials using liquid crystal medium (Applications: IR and Optical spectrometers).
7. Development of artificial ferrites and artificial dielectrics using metamaterial concepts to design electrically small, lightweight, and efficient RF components.
8. Transformation electromagnetic techniques with advances in fabricating metamaterials (Applications:
microwaves and infrared wavelength sensors).

**Expected TRL or TRL range at completion of the project:** 1 to 3

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Research

**Desired Deliverables Description**

It is expected at the end of year one for selected teams to provide a comprehensive feasibility study to address an applicable area of interest within the field of metamaterial technology. Deliverables in subsequent years could involve prototypes and demonstration of performance.

**State of the Art and Critical Gaps**

Metamaterial research is interdisciplinary and involves such fields as electrical engineering, electromagnetics, classical optics, solid state physics, microwave and antenna engineering, optoelectronics, material sciences, as well as nanoscience and semiconductor engineering.

Potential applications of metamaterials are diverse and include: optical filters, remote aerospace applications, sensor detection, radomes, and lenses for high-gain antennas. Metamaterials also offer the potential to create superlenses, which could allow imaging below the diffraction limit that is the minimum resolution that can be achieved by conventional glass lenses. Transformation optics is a technique that simplifies the modeling of optical devices by altering the coordinate system to control the trajectories of light rays. At microwave frequencies, the first, imperfect invisibility cloak was realized in 2006.

**Relevance / Science Traceability**

Metamaterial technology has the biggest potential to impact the future of space borne instrumentation by reducing size, weight, and power (SWaP) as well as the overall cost of future space missions. There is especially a need for these improved capabilities in the development of instruments for Planetary and the Earth Science missions to reduce their cost. Due to the nature of metamaterials, there are a multitude of possible applications for this technology. For example, applications of metamaterials for remote sensing include tunability, complex filtering, light channeling/trapping, superbeaming, and determination of optical angular momentum modes via metamaterials. For additional information regarding Science Mission Directorate (SMD) technology needs, please review https://science.nasa.gov/about-us/science-strategy/decadal-surveys [32].

**References**

www.centerformetamaterials.org/ [33]


T8.06 Quantum Sensing and Measurement

Lead Center: GSFC

Participating Center(s): GRC, JPL

Technology Area: TA15 Aeronautics

Scope Title
Quantum Sensing and Measurement

Scope Description
This Quantum Sensing subtopic calls for proposals using quantum systems to achieve unprecedented measurement sensitivity and performance, including quantum-enhanced methodologies that outperform their classical counterparts. Shepherded by advancements in our ability to detect and manipulate single quantum objects, the so called "Second Quantum Revolution" is upon us. The emerging quantum sensing technologies promise unrivaled sensitivities and are potentially game changing in precision measurement fields. Significant gains include technology important for a range of NASA missions such as: efficient photon detection, optical clocks, gravitational wave sensing, ranging, and interferometry. Atom Interferometry and Quantum Communication focused proposals should apply to those specific subtopics and are not covered in this Quantum Sensing and Measurement subtopic.

Specifically identified applications of interested include quantum sensing methodologies achieving the optimal collection light for photon-starved astronomical observations, quantum-enhanced ground penetrating radar, and quantum-enhanced telescope interferometry.

- Superconducting Quantum Interference Device (SQUIDs) systems for enhanced multiplexing factor reading out of arrays of cryogenic energy-resolving single-photon detectors, including the supporting resonator circuits, amplifiers, and room temperature readout electronics.
- Quantum light sources capable of efficiently and reliably producing prescribed quantum states including entangled photons, squeezed states, photon number states, and broadband correlated light pulses. Such
entangled sources are sought for the vis-IR and in the microwave entangled photons sources for quantum ranging and ground penetrating radar.

- On-demand single photon sources with narrow spectral linewidth are needed for system calibration of single photon counting detectors and energy-resolving single-photon detector arrays in the MIR, NIR, and visible. Such sources are sought for operation at cryogenic temperatures for calibration on the ground and aboard space instruments.

References

- Quantum Communication, Sensing and Measurement in Space, Team Leads: Erkmen, Shapiro, and Schwab 2012
  - [34](http://kiss.caltech.edu/final_reports/Quantum_final_report.pdf)
- National Quantum Initiative Act:
  - [35](https://www.congress.gov/congressional-report/115th-congress/house-report/950/1)
- [37](https://www.lightourfuture.org/getattachment/7ad9e04f-4d21-4d98-bd28-e1239977e262/NPI-Recommendations-to-HSC-for-National-Quantum-Initiative-062217.pdf)
- European Union Quantum Flagship Program: [https://qt.eu](https://qt.eu)
- UK National Quantum Technologies Programme [http://uknqt.epsrc.ac.uk](http://uknqt.epsrc.ac.uk)
- DLR Institute of Quantum Technologies [https://www.dlr.de/qt/en/desktopdefault.aspx/tabid-13498/23503_read-54020/]
- C. L. Degen, F. Reinhard, and P. Cappellaro, Quantum Sensing, Rev. Mod. Phys. 89, 035002 (2017).

**Expected TRL or TRL range at completion of the project:** 2 to 4

**Desired Deliverables of Phase II**

Prototype, Analysis, Research

**Desired Deliverables Description**

NASA is seeking innovative ideas and creative concepts for science sensor technologies using quantum sensing techniques. The proposals should include results from designs and models, proof-of-concept demonstrations and prototypes showing the performance of the novel quantum sensor.

**State of the Art and Critical Gaps**

Sources for entangled photons.

Quantum dot source produced entangled photons with a fidelity of 0.90, a pair generation rate of 0.59, a pair extraction efficiency of 0.62, and a photon indistinguishability of 0.90 simultaneously. (881 nm light) at 10 MHz. Wang Phys. Rev. Lett. 122, 113602 2019.

Spectral brightness of 0.41 MHz/mW/nm for multi-mode and 0.025 MHz/mW/nm for single mode coupling. Jabir Scientific Reports volume 7, Article number: 12613 (2017).

Higher brightness and multiple entanglement and heralded multiphoton entanglement and boson sampling sources. Sources that produce photon number states or Fock states are also sought for various applications including energy-resolving single photon detector applications.

For energy resolving single photon detectors current state of the art multiplexing can achieve kilopixel detector arrays which with advances in microwave SQUID mux can be increased to megapixel arrays. (Morgan Physics Today 71, 8, 28 (2018)).

**Relevance / Science Traceability**

Quantum technologies enable a new generation in sensitivities and performance. Including atomic clocks and ultra-
precise sensors with applications ranging from natural resource exploration and biomedical diagnostic to navigation.

HEOMD - Astronaut Health Monitoring.

SMD - Earth, Planetary and Astrophysics including imaging spectrometers on a chip across the electromagnetic spectrum from X-ray through the IR.

STMD - Game changing technology for small spacecraft communication and navigation (optical communication, laser ranging, gyroscopes).

STTR- Rapid increased interest.

Space Technology Roadmap - 6.2.2, 13.1.3, 13.3.7, all sensors 6.4.1, 7.1.3, 10.4.1, 13.1.3, 13.4.3, and 14.3.3.

**T11.03 Distributed Digital Ledger for Aerospace Applications**

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

Technology Area: TA15 Aeronautics

**Scope Description**

A Blockchain is a decentralized, online record keeping system, or ledger, maintained by a network of computers that verify and record transactions using established cryptographic techniques. A Blockchain is a data structure that makes it possible to create a consistent, digital ledger of data and share it among a network of independent parties. Blockchain distributed ledger technology may become a key enabler of digital transformation, enabling peer to peer transactions without requiring intermediaries or pre-established trust. Blockchain was originally developed to support digital currency transactions. Now, application of Blockchain is being explored for other financial services, software security, Internet of Things, parts tracking (supply chain), asset management, smart contracts, identify verification, and much more. NASA is seeking innovative solutions involving Blockchain that would greatly enhance operational efficiency by providing a single, immutable "source of truth", viewable by all authorized parties, and usable by automated reporting and verification systems, for the following two NASA-specific challenges.

Model Based System Engineering (MBSE): A significant challenge in MBSE is knowing that the system model being used is the current (or needed) version, since various aspects evolve through the system development and operations lifecycle. Further, because systems are becoming increasingly complex, tracking the vast number of changes that occur needs to be automated and efficient. Blockchain solutions may enable a single, real-time source of truth for system models, to eliminate several sources of error and inefficiency in MBSE.

Distributed space mission management: To accomplish complex space mission and Earth observation objectives, constellations of distributed satellites are often the most cost-effective approach. These constellations share key consolidated resources such as ground stations, a space network, communication networks, onboard processes, etc. A blockchain solution to managing distributed space missions should enable collaboration in a partially trusted environment and increase responsiveness, reliability, and availability of spacecraft and ground resources. The management functions enhance flexibility (e.g., reduce overhead for components to join and leave constellations), and enhance automation (e.g., automate resource outage alerts, facilitate localized replanning, enable a constellation level model-based diagnostics). To accomplish this, proposed solutions must overcome the slow transaction rate, large file sizes, and concurrency issues of some blockchain implementations.

**References**

Mandl; "Bitcoin, Blockchains and Efficient Distributed Spacecraft Mission Control". [1](https://sensorweb.nasa.gov/Bitcoin%20Blockchains%20and%20Distributed%20Satellite%20Management%20Control%202017v12.pdf)


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Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables

Description

The desired deliverable is a prototype system that demonstrates a scalable, Blockchain-based solution to one of the NASA challenges described.

State of the Art and Critical Gaps

Almost all successful Blockchain solutions to date are for ledgers for digital currency transactions. Use of Blockchain is being explored in a broad range of areas, but there are no known scalable solutions for the NASA challenges described. Here, scalable means that the solution works efficiently and securely for a large number of transactions and users in a relevant, distributed digital environment.

Relevance / Science Traceability

Blockchain solutions can benefit all NASA Mission Directorates and functional organizations. NASA activities could be dramatically more efficient and lower risk through Blockchain support of more automated creation, execution, and completion verification of important agreements, such as international, supply chain, or data use.

T11.04 Digital Assistants for Science and Engineering

Lead Center: MSFC

Participating Center(s): ARC

Technology Area: TA15 Aeronautics

Scope Description

NASA is seeking innovative solutions that combine modern digital technologies (e.g., natural language processing, speech recognition, machine vision, machine learning and artificial intelligence, and virtual reality and augmented reality) to create digital assistants. These digital assistants can range in capability from low-level cognitive tasks (e.g., information search, information categorization and mapping, information surveys, semantic comparisons), to expert systems, to autonomous ideation. NASA is interested in digital assistants that reduce the cognitive workload of its engineers and scientists so that they can concentrate their talents on innovation and discovery. Digital assistant solutions can target tasks characterized as research, engineering, operations, data management and analysis (of science data, ground and flight test data, or simulation data), business or administrative. Examples of potential digital assistants include:

- A digital assistant that uses the semantic, numeric, and graphical content of engineering artifacts (e.g., requirements, design, verification) to automate traces among the artifacts and to assess completeness and consistency of traced content. For example, the digital agent can use semantic comparison to determine whether the full scope of a requirement may be verified based on the description(s) of the test case(s) traced from it. Similarly, the digital assistant can identify from design artifacts any functional, performance, or non-functional attributes of the design that do not trace back to requirements. Currently, this work is performed by project system engineers, quality assurance personnel, and major milestone review teams.
- A digital assistant that can identify current or past work related to an idea by providing a list of related government documents, academic publications, and/or popular publications. This is useful in characterizing the state-of-the-art when proposing or reviewing an idea for government funding. Currently, engineers and scientists accomplish this by executing multiple searches using different combinations of keywords from the idea text, each on a variety of search engines and databases; then the engineers read dozens of documents and returns to establish relevance. This example looks for digital assistive technologies to...
reduce this workload substantially.

- A digital assistant that can highlight lessons learned, suggest reusable assets, highlight past solutions or suggest collaborators based on the content that the engineer or scientist is currently working on. This example encourages digital solutions that can parse textual and/or graphical information from an in-progress work product and search Agency knowledge bases, project repositories, asset repositories, and other in-progress work products to identify relevantly similar information or assets. The digital assistant can then notify the engineer of the relevant information and/or its author (potential collaborator).
- A digital assistant that can recommend an action in real-time to operators of a facility, vehicle, or other physical asset. Such a system could work from a corpus of system information such as design artifacts, operator manuals, maintenance manuals, and operating procedures to correctly identify the current state of a system given sensor data, telemetry, component outputs, or other real-time data. The digital assistant can then use the same information to autonomously recommend a remedial action to the operator when it detects a failure, to warn the operator when their actions will result in a hazard or loss of a mission objective, or to suggest a course of action to the operator that will achieve a new mission objective given by the operator.
- A digital assistant that can create one or more component or system designs from a concept of operations, a set of high-level requirements, or a performance specification. Such an agent may combine reinforcement learning techniques, generative-adversarial networks, and simulations to autonomously ideate solutions.
- An expert system that uses a series of questions to generate an initial system model (e.g. using Systems Modeling Language [SysML]), plans, estimates, and other systems engineering artifacts.
- Question and Answer (Q&A) Bots: A digital agent that can answer commonly asked questions on "how-to" for scientists and engineers (e.g., what resources [grounds facilities, labs, media services, IT] are available; where to get site licenses for software packages; who to contact for assistance on a topic; answers for general business procedures such as procurement, travel, time and attendance, etc.)

References

CIMON "Crew Interactive Mobile Companion"

https://www.nasa.gov/mediacast/space-to-ground-meet-cimon-07062018 [49]

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170000676.pdf [51]


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase II would conclude with a demonstration (prototype) or a deployable digital assistant with quantifiable reduction in time or cost of an activity typically performed by NASA scientists, engineers, or operators.

State of the Art and Critical Gaps
Digitally assistive technologies currently permeate the consumer market with products like the Amazon Echo, Apple devices with Siri, Google devices with Google Assistant, and Microsoft devices with Cortana. Though Apple, Google, and Microsoft are also moving their assistive technologies into the enterprise space, these developments are largely focused on reducing information technology costs. Some cities and college campuses have also acted as early adopters of smart city or smart campus technologies that include digital assistants. However, application of these assistive technologies to engineering and science has largely been limited to university research. Moreover, most assistive technologies exercise no more cognition than a Q&A bot or executing simple commands. The emergence of improved natural language processing brings the possibility of digital assistants that can perform low-level cognitive tasks. This subtopic aims not only to bring commercially available assistive technologies to the engineering environment, but elevate their cognitive capabilities so that engineers and scientists can spend more time innovating and less time on low-level cognitive work that is laborious or repetitive.

Relevance / Science Traceability

This subtopic is related to technology investments in the NASA Technology Roadmap, Technical Area 11 Modeling, Simulation, Information Technology, and Processing under sections 11.1.2.6 Cognitive Computer, 11.4.1.4 Onboard Data Capture and Triage Methodologies, and 11.4.1.5 Real-time Data Triage and Data Reduction Methodologies. This subtopic is seeking similar improvements in computer cognition, but more generally applied to the activities performed by engineers and scientists and made more easily accessible through technologies like speech recognition.

T12.01 Thin-Ply Composite Technology and Applications

Lead Center: JPL

Participating Center(s): GRC

Technology Area: TA15 Aeronautics

Scope Description

The use of thin-ply composites is one area of composites technology that has not yet been fully explored or exploited. Thin-ply composites are those with cured ply thicknesses below 0.0025 in., and commercially available prepregs are now available with ply thicknesses as thin as 0.00075 in. By comparison, a standard-ply-thickness composite would have a cured ply thickness of approximately 0.0055 in. or greater. Thin-ply composites hold the potential for reducing structural mass and increasing performance due to their unique structural characteristics, which include (when compared to standard-ply-thickness composites):

- Improved damage tolerance.
- Resistance to microcracking (including cryogenic-effects).
- Improved aging and fatigue resistance.
- Reduced minimum-gage thickness.
- Thinner sections capable of sustaining large deformations without damage.
- Increased scalability of structures.

The particular capabilities requested for potential Phase I proposals in this subtopic in line with the critical gaps between the state of the art and the technology needed are:

- New processing methods for making repeatable, consistent, high quality thin-ply carbon-fiber prepreg materials, (i.e., greater than 55% fiber density with low degree of fiber twisting, misalignment and damage, low thickness non-uniformity and minimal gaps in the material across the width) using currently used and commercially available fiber/matrix combinations. The intent of this requirement is to provide thin-ply prepreg material with the same quality as the standard-ply material of the same material system in order to facilitate substitution of thin-ply into structural concepts, and while continuous fiber forms are sought, this does not preclude development of new and novel prepreg material forms. Prepreg product forms of interest
have area weights below 60 g/m² for unidirectional tape with tape widths between 6 and 300 mm wide, and below 120 g/m² for woven/braided prepreg materials. Matrices of interest include both toughened epoxy resins for aeronautics applications, and resins qualified for use in space.

- Development of novel low creep and low stress relaxation polymer thin-ply composites for inflatable and rollable/foldable space structures. Amongst others, approaches of interest are: designing new molecular structures showing high restriction of distortion of atomic bond angle under stress; controlling cross-linking density by reactive functional groups of molecular chains to keep a good balance between restriction of molecular rearrangement and material brittleness; restricting large scale rearrangements of polymer molecules by second phase of components; and securing strong interfaces between reinforcing fibers and polymer matrix by chemical bonding or fiber sizing improvements to prevent fibers and polymer molecules slippage under load. The temperature dependent viscoelastic-plastic properties of the developed thin-ply material shall be characterized to predict the long-term behavior of the system under continuous loading.

- Fabrication of large, thin-gauge structures, such as deployable/rollable thin-shell booms or wing skins, are often limited in size by autoclave constraints. Innovative out-of-autoclave processing methods for thin-gauge structures are sought to facilitate the production of large structures. Additionally, the innovative method shall guarantee the curing process variables (temperature, pressure, etc.) are uniform over the long parts to achieve better final products with less process-related defects and part-to-part variability.

- Cure-induced deformation of thin composite structures such as the spring-in effect is a known phenomenon that affects part accuracy during fabrication. Simulation software compatible with general purpose finite element environments such as ABAQUS or ANSYS for predictions of the manufacturing process-induced deformations and residual stresses are sought. These software tools should be tailored to the modeling needs of thin-ply composite structures, especially for structures with a final thickness under 1.5 mm. In addition, simulation capability of sequential multi-step processes (cure and post-bonding) as well as complex process (composite sections co-cure and/or co-bond) are of special interest. The goal is to develop recommendations for geometric tool compensation, as well as cure cycles and tooling that meets cure cycle specifications.

- Fracture mechanics models for thin-shell, thin-ply polymer composites subjected to large continuous and cyclic bending strains (>2%) for which the nonlinear and viscoelastic-plastic response of the material plays an important role on the damage initiation and progression in the foldable/rollable/deformable structural member. Multi-scale failure models for spread-tow woven/braided lamina, as well as laminates that combine these with spread-tow unidirectional plies are sought. The study of material creep rupture, thermal fatigue, mechanical fatigue and resin micro-cracking at lower strains (≤ 1%), as related to environmental ageing, durability and dimensional stability of the final thin-ply composite structure is of special interest as part of a larger goal to qualify thin-shell, flexible composite structures for space flight.

- Testing and micromechanics models capable of identifying damage initiation and growth for hybrid thin-ply composites are sought. Specifically, methods for composites comprising thin and standard unidirectional plies, and composites combining different forms, such as combining unidirectional plies with woven or braided plies of the same or dissimilar areal weights.

References

https://www.nasa.gov/aeroresearch/programs/aavp [55]

https://www.nasa.gov/aeroresearch/programs/tacp [56]

https://www.nasa.gov/directorates/spacetech/home/index.html [57]

https://gameon.nasa.gov/projects/deployable-composite-booms-dcb/ [58]

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

The Phase II deliverables will depend on the aspect addressed, but in general will be manufacturing processes, documentation of the analytical foundation and process, maturing the necessary design/analysis codes, and
validation of the approach through design, build, and test of an article representative of a component/application of interest to NASA.

**State of the Art and Critical Gaps**

Thin-ply composites are attractive for a number of applications in both aeronautics and space as they have the potential for significant weight savings over the current state-of-the-art standard-ply materials due to improved performance. For example, preliminary analyses show that the notched strength of a hybrid of thin and standard ply layers can increase the notched tensile strength of composite laminates by 30%. Thus, selective incorporation of thin plies into composite aircraft structures may significantly reduce their mass. There are numerous possibilities for space applications. The resistance to microcracking and fatigue makes thin-ply composites an excellent candidate for a deep-space habitation structure where hermeticity is critical. Since the designs of these types of pressurized structures are typically constrained by minimum gage considerations, the ability to reduce that minimum gage thickness also offers the potential for significant mass reductions. For other space applications, the reduction in thickness enables: thin-walled, deployable structural concepts only a few plies thick that can be folded/rolled under high strains for launch (and thus have high packaging efficiencies) and deployed in orbit; and, greater freedom in designing lightweight structures for satellite buses, landers, rovers, solar arrays, and antennas. For these reasons, NASA is interested in exploring the use of thin-ply composites for aeronautics applications requiring very high structural efficiency, for pressurized structures (such as habitation systems and tanks), for lightweight deep-space exploration systems, and for low-mass high stiffness deployable space structures (such as rollable booms or foldable panels, hinges or reflectors).

There are many needs in development, qualification and deployment of composite structures incorporating thin-ply materials – either alone or as a hybrid system with standard ply composite materials. In particular, there is substantial interest in proposals that address manufacturability and production of composite structures utilizing thin-ply composites that at minimum develop the process and plan for the production of one prototype in Phase 1, and demonstrate reproducibility of prototype manufacturing and key parameter validation of repeated samples in Phase 2. Available predictive manufacturing-cure-induced deformation/residual stress software uses solid finite elements to represent the composite plies and those result in high aspect ratios elements when thin-ply materials are used, which ultimately derive in computationally expensive models or loss of convergence. New ways of modeling thin-ply materials are thus needed on these specialized software, particularly for complex-shaped, thin-shell structures just a few plies thick. Another area requiring development is in fracture initiation/progression mechanism models, efficient homogenization methods for spread-tow textile fabrics and hybrid (textile and unidirectional plies) laminates that include viscoelastic-viscoplastic and thermo-mechanical response, and new large deformation testing and analysis methods adapted for thin-ply composites subjected to high bending strains (>1.5%) for foldable and/or rollable thin-shell structures. Finally, polymer matrix composites subjected to high strains for a long-period of time are particularly susceptible to stress relaxation or creep. New thin-ply polymer composites materials for space applications tailored for low relaxation/creep response under large bending deformations and high strains, such as for rollable or foldable thin-shell structures, are needed.

**Relevance / Science Traceability**

The most applicable Aeronautics Research Mission Directorate (ARMD) program is Advanced Air Vehicles Program (AAVP), and within that is Advanced Air Transport Technologies (AATT). Additional projects withing AAVP that could leverage this technology are: Commercial Supersonic Technology (CST), Hypersonic Technology (HT), and Revolutionary Vertical Lift Technologies (RVLT). Projects within Transformative Aeronautics Concepts Program (TACP) could also benefit. That is, any project in need of lightweight structures can benefit from the thin-ply technology development.

Within Space Technology Mission Directorate (STMD), projects with deployable composite booms, landing struts, foldable reflectors, and other very lightweight structures can benefit from the thin-ply technology.

**T12.05 Deposition and Curing of Thermoset Resin Mixtures for Thermal Protection**

Lead Center: JPL

Participating Center(s): ARC, GSFC, LaRC
Technology Area: TA15 Aeronautics

Scope Description

NASA has a need to significantly improve the manufacturing processes of Thermal Protection Systems (TPS) used in human-rated spacecraft with the intention of reducing cost and improving quality and system performance. The fabrication and installation of current TPS are labor intensive, cost prohibitive, and result in many seams between the segments. Future human missions to Mars will require the landing of large-mass payloads on the surface, and these large entry vehicles will require large areas of TPS to protect the structure. A sustained lunar presence will require the development of Lunar-return vehicles which will also need TPS. In order to reduce the cost and complexity of these vehicles, new TPS materials and compatible additive manufacturing techniques are being developed such that thermoset-resin based mixtures can be deposited, bonded and cured on spacecraft structures with automated systems. Typically, these thermoset resin systems are filled with fibers, microballoons, rheology modifiers and other additives. Technologies are sought to mix and feed, and then deposit and cure these highly filled thermoset resin mixtures on the flight structure. Basic requirements and goals for the material system are provided in the references.

This subtopic seeks to develop the materials and subsystems needed to design, fabricate and operate an automated production process for TPS. The technologies needing development include:

1. Compatible thermoset resin mixtures, extruder and tool-path algorithms to produce uniform printed and cured TPS material with voids/flaws less than 1/8”.
2. Printable resins yielding TPS materials with low coefficient of thermal expansion. Approaches could include additives to thermoset resin mixtures or alternate material systems potentially with imbedded and longer fibers.
3. Capability to vary the resin-mixture composition during the layer deposition to produce an insulative layer at the structure and a more robust layer on the outer surface.
4. Scalable material feed systems to transport the material to the extruder head(s). Mixing the raw materials in the feed system is desirable.
5. Cure/set the highly filled thermoset resin mixture on the flight structure without the need for large ovens. Curing can be accomplished by chemical composition and/or external energy sources, such as, but not limited to, radio frequency (RF) generators, ultraviolet (UV) lights, etc.
6. Processes and subsystems to ensure a good bond between the deposited material and high-temperature carbon-fiber composite structures.

During Phase I, the focus should be to develop and demonstrate, on a small scale, a solution to at least one of the technologies described above using a candidate thermoset resin mixture. Concepts for the other technologies should be developed during Phase I and then further developed and demonstrated in Phase II.

References


Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I deliverables should include a small scale demonstration of the resin mixture printing and curing process and also include printed and cured material samples for testing. The goal deliverables for Phase II would include...
the demonstration of a prototype system with a clear path for scale up to production of a full-size heat shield and the demonstrated capability to print, cure and bond acceptable TPS materials on a small, non-planar composite structure.

**State of the Art and Critical Gaps**

Current state of the art (SOA) for manufacturing and installing thermal protection on NASA space vehicles is too labor intensive and too costly. Furthermore, the heat shield designs are constrained by manufacturing processes that result in segmented blocks with gap fillers that create flight performance issues. To develop an automated additive manufacturing process for spacecraft heat shields that are monolithic, the development of the materials and technologies to deposit and cure the materials on the flight structures are needed.

**Relevance / Science Traceability**

Both Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) would benefit from this technology. All missions that include a spacecraft that enters a planetary atmosphere require TPS to protect the structure from the high-heating associated with hypersonic flight. Improved performance and lower cost heat shields benefit the development and operation of these spacecraft. Human missions to the moon and Mars would benefit from this technology. Commercial Space programs would also benefit from TPS materials and manufacturing processes developed by NASA.

**T12.06 Extensible Modeling of Additive Manufacturing Processes**

Lead Center: JPL

**Technology Area:** TA15 Aeronautics

**Scope Title**

Process Modeling of Additive Manufacturing

**Scope Description**

The subtopic of modeling of additive processes is highly relevant to NASA as NASA is currently on a path to implement additive processes in space flight systems with little or no ability to model the process and thereby predict the results. In order to reliably use this process with a variety of materials for space flight applications, NASA has to have a much deeper understanding of the process. NASA is currently considering these processes for the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC), ion engines and other spacecraft structural and multi-functional applications. Additive manufacturing of development and flight hardware with metallic alloys is being developed by NASA and its various partners for a variety of spacecraft applications. These components are expected to see extreme environments coupled with a need for high-reliability (e.g., manned spaceflight), which requires a deeper understanding of the manufacturing processes. Modeling of the additive processes to provide accurate dimensional designs, preferred micro-structures that are defect-free is a significant challenge that would dramatically benefit from a joint academic-industry approach. The objective would be to create process models that are compatible with current alloys systems and additive manufacturing equipment which will provide accurate prediction of outcomes from a variety of additive manufacturing process parameters and materials combinations. The primary alloys of interest to NASA at this time include: Inconel 625 & 718, stainless steels, such as 304 and 316, Al10SiMg, Ti-6Al-4V, and copper alloys (GrCop-84). It is desired that the modeling approach address a focused material system, but be readily adaptable to eventually accommodate all of these materials. Therefore, the model should incorporate modest parameter changes coupled with being easily extensible for future alloys of interest to NASA. NASA is interested in modeling of the Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Laser Engineered Net Shaping (LENS) processes.

**References**

Expected TRL or TRL range at completion of the project

Proposed technologies should mature to TRL 1 to 2 by the end of Phase II effort.

Desired Deliverables of Phase II

Software

Desired Deliverables Description

A functional process model covering the specific area by the proposer, using open source or code shared with the Agency.

State of the Art and Critical Gaps

Additive manufacturing will be used for space flight applications. NASA, and its suppliers, currently have very little knowledge of what is happening with these processes. Modeling of these additive processes is essential for NASA to be able to use these processes reliably. NASA is currently working on a specification for these processes and modeling would help that effort as well.

Relevance / Science Traceability

Process modeling of additive manufacturing is relevant to Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD), all of which have extant efforts in additive manufacturing. HEOMD is focusing heavily on the use of additive manufacturing for propulsion systems (e.g. RS-25, RL10) for SLS, SMD is using additive manufacturing on the Planetary Instrument for X-ray Lithochemistry (PIXL) on the Mars 2020 mission, the Psyche Mission, as well as various ESI initiatives through STMD.

T13.01 Intelligent Sensor Systems

Lead Center: SSC

Technology Area: TA15 Aeronautics

Scope Title

Advanced Instrumentation for Rocket Propulsion Testing

Scope Description

Rocket propulsion system development is enabled by rigorous ground testing to mitigate the propulsion system risks inherent in spaceflight. Test articles and facilities are highly instrumented to enable a comprehensive analysis of propulsion system performance. Advanced instrumentation has the potential for substantial reduction in time and cost of propulsion systems development, with substantially reduced operational costs and evolutionary improvements in ground, launch and flight system operational robustness.

Advanced instrumentation would provide a wireless, highly flexible instrumentation solution capable of measurement of heat flux, temperature, pressure, strain, and/or near-field acoustics. Temperature and pressure measurements must be acquired from within the facility mechanical systems or the rocket engine itself. These sensors would be capable of addressing multiple mission requirements for remote monitoring such as vehicle health monitoring in flight systems, autonomous vehicle operation, or instrumenting inaccessible measurement
locations, all while eliminating cabling and auxiliary power. Rocket propulsion test facilities also provide excellent test beds for testing and using the innovative technologies for possible application beyond the static propulsion testing environment.

This subtopic seeks to develop advanced wireless instrumentation capable of performing some processing, gathering sensory information and communicating with other connected nodes in the network. Sensor systems should have the ability to provide the following functionality:

- Acquisition and conversion to engineering units for quantifying heat flux, temperature, pressure, strain, and/or near-field acoustics such that it contributes to rocket engine system performance analysis within established standards for error and uncertainty.
- Capable of in-place calibrations with The National Institute of Standards and Technology (NIST) traceability.
- Collected data must be time stamped to facilitate analysis with other collected data sets.
- Transfer data in real-time to other systems for monitoring and analysis.
- Interface to flight qualified sensor systems, which could be used for multi-vehicle use.
- Determine the quality of the measurement and instrument state-of-health.
- Self-contained to collect information and relay measurements through various means by a sensor-web approach to provide a self-healing, auto-configuring method of collecting data from multiple sensors, and relaying for integration with other acquired data sets.
- Function reliably in extreme environments, including rapidly changing ranges of environmental conditions, such as those experienced in space. These ranges may be from extremely cold temperatures, such as cryogenic temperatures, to extremely high temperatures, such as those experienced near a rocket engine plume.

References

Fernando Figueroa, Randy Holland, David Coote, "NASA Stennis Space Center integrated system health management test bed and development capabilities," Proc. SPIE 6222, Sensors for Propulsion Measurement Applications, 62220K (10 May 2006);


Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software
Desired Deliverables Description

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

State of the Art and Critical Gaps

Highly modular, remote sensors are of interest to many NASA tests and missions. Real-time data from sensor networks reduces risk and provides data for future design improvements. Wireless sensors offer a highly flexible solution for scientists and engineers to collect data remotely. They can be used for thermal, structural and acoustic measurement of systems and subsystems and also provide emergency system halt instructions in the case of leaks, fire or structural failure. Other examples of potential NASA applications include 1) measuring temperature, strain, voltage and current from power storage and generation systems, 2) measuring pressure, strain and temperature in pumps and pressure vessels and 3) measuring strain in test structures, ground support equipment and vehicles, including high-risk deployables.

There are many other applications that would benefit from increased, real-time sensing in remote, hard-to-test locations. For example, sensor networks on a vehicle body can give measurement of temperature, pressure, strain and acoustics. This data is used in real time to determine safety margins and test anomalies. The data is also used post-test to correlate analytical models and optimize vehicle and test design. Because these sensors are small and low mass, they can be used for ground test and for flight. Sensor module miniaturization will further reduce size, mass and cost.

No existing wireless sensor network option meets NASA’s current needs for flexibility, size, mass and resilience to extreme environments.

Relevance / Science Traceability

This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate. Supports all test programs at Stennis Space Center (SSC) and other propulsion system development centers. Potential advocates are the Rocket Propulsion Test (RPT) Program Office and all rocket propulsion test programs at SSC.

T15.03 Electrified Aircraft Propulsion Energy Storage

Lead Center: GRC

Participating Center(s): AFRC, LaRC

Technology Area: TA15 Aeronautics

Scope Description

Proposals are sought for the development of enabling rechargeable batteries (or other types of energy storage) for Electrified Aircraft Propulsion (EAP).

Two paths to improved battery performance are sought:

1. Innovative thermal, structural, and electrical integration that reduce the mass fraction added when scaling from a battery cell to an integrated battery
2. Battery chemistry improvements that substantially enhance usable energy density, cycle life, life cycle cost, and safety

Batteries and other energy storage systems with some combination of some or all of the following performance levels at the integrated battery pack level are sought:
• Specific energy >400Whr/kg at the system level
• Cycle life >10,000 cycles
• Prime flight quality and safety
• Cost effective enough to close electric air services at a profit

Battery pack level energy density means the amount of usable energy after derating for depth of discharge, cycle life, C rate limits, thermal constraints, and any other applicable limit to energy that can be used during the mission divided by the mass of the battery package (including the structure, safety devices, battery management system, and thermal management parts that are mounted to the battery). This will typically require cell level energy densities in the range to 600-800 W-hr/kg along with an innovative combination of those cells into a battery system. Alternate electrical energy storage approaches will also be considered.

All-electric conventional and vertical takeoff research vehicles that can carry one or two people have been demonstrated. In order to achieve commercial viability, improvements in batteries are required for the aircraft to have sufficient range, safety, and operational economics for regular service. Markets needs span Urban Air Mobility (UAM), thin/short haul aviation, and commercial air transport vehicles which use electrified aircraft propulsion. Hybrid electric and all electric power generation as well as distributed propulsive power have been identified as candidate transformative aircraft configurations with reduced fuel consumption/energy use and emissions.

References

Electrified Aircraft Propulsion (EAP) is called out as a key part of Thrust 4 in the ARMD strategic plan: https://www.nasa.gov/aeroresearch/strategy [67]

NASA Urban Air Mobility (UAM): https://www.nasa.gov/aero/taking-air-travel-to-the-streets-or-just-above-them [68]


Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Deliverables most likely will include prototypes of energy storage units along with research and analysis addressing safety and cost considerations. In some cases test data for safety may be a deliverable. Ideally, proposals would identify a technology pull area (with a market size estimate), how the proposed idea addresses the needs of the technology pull area, and then deliver a combination of analysis and prototypes that substantiate the idea's merit.

Please consider SBIR subtopic A1.04 - Electrified Aircraft Propulsion if you are considering energy storage technologies appropriate for near term applications that will have a higher TRL (3-5) at completion.

State of the Art and Critical Gaps

Specific Energy: Need approximately a factor of 2 improvement. Current assessment of battery specific energy requirements for all-electric operations are in the 300-400 Wh/kg at the installed/pack level (Installed means after derating for depth of discharge limit, cycle life, battery management, packaging, and thermal environment). This assumes the ability to quickly recharge between flights. Current state of the art (SOA) is about 160-170 Wh/kg (pack level). Li-ion batteries are nearing practical maximums so new chemistry(s) or energy storage types are likely required to meet all-electric UAM mission needs, solid state appears to be the most promising. For reference, automotive needs will likely be more than met with 300-500 Wh/kg (cell level), but, with regards to NASA goals, all electric helicopters and regional passenger aircraft will likely need 600Wh/kg and 500-700Wh/kg (cell level) respectively. Note that approximately 30-40% Wh/kg is lost when cells are integrated into packs and installed; justify any improvements you expect.
Cycle Life: Need a substantial improvement. Current SOA is 1500-3000 cycles which lasts about 3 months for UAM. For reference, automotive needs 500-1000 cycles for 10 year lifespans.

Cost: Aviation is probably less sensitive to cost than automotive if the overall operations and vehicle concept can close profitably.

Prime Flight Quality: New feature that needs to be demonstrated. The expected reliability of an aviation system is probably a few orders of magnitude higher than an automotive application and safety considerations are a more significant driver – including time needed to get passengers out of danger. Justify how your concept may address these goals.

Relevance / Science Traceability

Electrified Aircraft Propulsion (EAP) is an area of strong and growing interest in ARMD. Energy Storage is an enabling technology for the UAM and Thin Haul segments of the effort. There are emerging vehicle level efforts in Urban On-Demand Mobility, the X-57 electric airplane being built to demonstrate EAP advances applicable to thin and short haul aircraft markets, and an ongoing technology development subproject to enable EAP for single aisle aircraft. Additionally, NASA is formulating a megawatt-level EAP flight demo this year.

EAP is called out as a key part of Thrust 4 in the ARMD strategic plan.

Key Outcomes NASA intends to achieve in this area are:

- Outcome for 2015-2025: Markets will begin to open for electrified small aircraft.
- Outcome for 2025-2035: Certified small aircraft fleets enabled by electrified aircraft propulsion will provide new mobility options. The decade may also see initial application of electrified aircraft propulsion on large aircraft.
- Outcome for >2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.


T15.04 Integration of Airframe with Distributed Electric Propulsion (DEP) System

Lead Center: GRC

Participating Center(s): ARC, GRC

Technology Area: TA15 Aeronautics

Scope Title
Develop Highly-Integrated Air Vehicle Technologies Using both Distributed Electric Propulsion (DEP) System and Airframe

Scope Description

NASA/Aeronautics Research Mission Directorate (ARMD) laid out Strategic Implementation Plan for aeronautical research aimed at the next 25 years and beyond. The documentation includes a set of Strategic Thrusts that are research areas which NASA will invest and guide. It encompasses a broad range of technologies to meet future needs of the aviation community, the nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation. Furthermore, the convergence of various technologies will also enable highly integrated electric air vehicles to be operated in domestic or international air space. In response to Strategic Thrust
#1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles) and #4 (Transition to Low-Carbon Propulsion), a new subtopic titled “Integration of Airframe with Distributed Electric Propulsion (DEP) System” is proposed in all areas related to the subject.

References

ARMD/Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt [70]

ARMD/Revolutionary Vertical Lift Technology (RVLT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt [71]

ARMD/Convergent Aeronautics Solutions (CAS) Project: https://www.nasa.gov/aeroresearch/programs/tacp/cas [72]

ARMD/Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt [73]

ARMD/University Innovation (UI) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ui [74]

ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy [67]

ARMD Urban Air Mobility Grand Challenge: https://www.nasa.gov/uamgc [75]

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Hardware, Research

Desired Deliverables Description

Integration of Distributed Electric Propulsion (DEP) system into an aircraft involves multidisciplinary design, analysis, and optimization (MDAO) of several disciplines in aircraft technologies. These disciplines include aerodynamics, propulsion, structures, acoustics, and/or control in traditional aeronautics related subjects. The use of light-weight high-power electric components (e.g. motors, controllers, etc.) in propulsion system are enabling new electric propulsion aircraft for fixed wing and Vertical Take-Off and Landing (VTOL) applications. Addressing ARMD’s Strategic Thrust#1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles) and #4 (Transition to Low-Carbon Propulsion), innovative approaches in designing and analyzing highly integrated DEP aircraft are needed to reduce the energy use, noise, emissions, and safety concerns. In support of these three Strategic Thrusts, the following integration research areas for DEP aircraft are to be considered under this solicitation.

1. Configure and analyze DEP-enabled highly-integrated multidisciplinary aircraft features or vehicle configuration.
2. Develop MDAO tools and methods to assess DEP-enabled highly-integrated multidisciplinary aircraft features or vehicle configuration.
3. Develop tools and methods to assess safety issues associated with DEP-enabled highly-integrated multidisciplinary aircraft features or vehicle configuration.

Expected outcome (TRL 2-3) of Phase I awards, but not limited to:

- Highly integrated multidisciplinary aircraft features with DEP system for fixed wing or VTOL application.
- Highly integrated DEP-enabled fixed wing or VTOL aircraft definition and system level assessment.
- Initial development of analytical/computational/experimental/simulation tools and methods in assessing highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.
Expected outcome (TRL 4-6) of Phase II awards, but not limited to:

- Detailed feasibility study and demonstration of the subscale hardware of highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.
- Refinement of tools and methods in assessing highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.
- Experimental (e.g., wind tunnel) results or simulation capability that assess the validity of the highly integrated multidisciplinary aircraft features or vehicle configuration with DEP system.

**State of the Art and Critical Gaps**

Design and analysis (analytical, experimental, computational, and/or system analysis) addressing highly-integrated DEP aircraft technology are critically needed.

Traditional/conventional aircraft design and development have been approached from individual discipline topics such as aerodynamics, propulsion, structure, etc. In order to improve the performance of an aircraft, multidisciplinary solutions including MDAO approach are encouraged.

**Relevance / Science Traceability**

The proposed subtopic supports ARMD’s Strategic Thrust#1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles), #4 (Transition to Low-Carbon Propulsion), and ARMD Strategic Implementation Plan 2017. Specifically, the following ARMD programs and projects are highly relevant.

**NASA/ARMD/Advanced Air Vehicles Program (AAVP):**

- Advanced Air Transport Technology (AATT) project
- Revolutionary Vertical Lift Technology (RVLT) project

**NASA/ARMD/Transformative Aeronautics Concepts Program (TACP):**

- Convergent Aeronautics Solutions (CAS) project
- Transformational Tools and Technologies (TTT) project
- University Innovation (UI) project