NASA STTR 2021 Phase I Solicitation

Small Business Technology Transfer

T5.04 Quantum Communications

Lead Center: GRC

Participating Center(s): GSFC, JPL

Scope Title:

Quantum Communications

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 sensing the entangling 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 10 km up to geosynchronous equatorial orbit (GEO)) for space applications or supporting linkages between terrestrial fiber-optic quantum networks. Technologies that are needed include quantum memory, quantum entanglement distribution systems, quantum repeaters, high-efficiency detectors, quantum processors, and 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 (not all inclusive) of requested innovation include:

- High-rate free-space quantum entanglement distribution systems.
- Photonic waveguide integrated circuits for quantum information processing and manipulation of entangled quantum states; requires phase stability, low propagation loss, that is, <0.1 dB/cm, and efficient fiber coupling, that is, 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.
- Quantum entanglement fidelity measurement capabilities.
- Scalable quantum memory.

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.

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

Primary Technology Taxonomy:
Desired Deliverables of Phase I and Phase II:

- Hardware
- Analysis
- Research
- Prototype

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 to 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 the 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.

References:

T5.05 Solar and Electric Sail Embedded Technologies for Communications, Control, or Ancillary Functions

Lead Center: MSFC

Participating Center(s): ARC, GRC, JPL

Scope Title:

Solar and Electric Sail Control Systems Modeling and/or Development

Scope Description:

One of the challenges with higher performance solar sails remains to be a highly resilient yet low-resource and low-complexity control system. Traditional solar sail options under consideration have previously considered impulsive systems (chemical and electric), mechanical systems (translation tables, guy wires, and moving masses), reflective control devices, and advanced diffractive metafilms. Further electric solar wind sail (E-sail) control systems are lower maturity and require new modeling and analysis tools for higher fidelity performance assessment. This solicitation seeks either embedded sail control technologies for traditional solar sails or the development of advanced modeling capabilities for E-sail control systems.

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

Primary Technology Taxonomy:

Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

For a traditional solar sail, the anticipated final product would be a prototype-tested control solution with potential to enable high performance for long-duration (>10-year) missions. For Phase I, the final deliverable must include very clear Key Performance Parameters (KPPs) of the control system approach based on preliminary proof-of-concept testing and/or analysis. The proposal must indicate anticipated KPPs for system-level implementation for a known design reference mission (e.g., Solar Polar Imager). The Phase II product must contain hardware development with laboratory performance testing to validate anticipated KPPs.

For an E-sail, the anticipated final product would be a high-fidelity modeling tool for performance assessment of solar sail control system performance. The Phase I product must include the identification and assessment of the key driving elements for
total control system performance and control system performance uncertainty in addition to the approach to mitigate flight system performance uncertainty in the Phase II development. The Phase II product must include the delivery of a fully functional control system modeling tool suitable for high-fidelity performance assessment applied to missions of interest (e.g., Solar Polar Imager and Interstellar Probe).

State of the Art and Critical Gaps:

State-of-the-art solar sail systems use translating masses (so-called AMT (Active Mass Translator)) and reflective control devices. Solar sail thrust, though miniscule in size, can produce large-velocity deltas over a multiyear mission. These small forces also create disturbance torques caused by misalignment in the center of mass (CM) and center of pressure (CP). NEAScout (current NASA Sail mission) estimates that the CP/CM offset is large enough to overload control systems and requires a mechanical system to adjust the CM and trim the spacecraft—the AMT. However, the scalability of the AMT to larger sail missions, such as the Interstellar Probe is currently unknown.

Attitude can also be controlled by varying solar radiation pressure directly on the sail itself. So-called reflectivity control devices (RCDs) were demonstrated on JAXA’s first solar sail mission, IKAROS, and are currently being investigated by NASA and academic partners. A typical RCD utilizes a polymer-dispersed liquid crystal whose optical properties can be adjusted via an applied electric voltage. These devices show promise, although challenges exist in yielding control in all three axes. Further, space environments survivability in extreme environments, especially the hot thermal of a high-inclination Solar Polar Imager, for example, also remains a challenge.

E-sails have low-fidelity simulations for control systems. Multitethered bodies coupled with varying plasma environments throughout the mission profiles, spacecraft charging, tether dynamics, and the like, are critical gaps.

Relevance / Science Traceability:

The resulting product should improve the performance or lower the subsystem mass for a solar-sail-based spacecraft optimized for the high-inclination Solar Polar Imager, advanced generation Solar Storm Warning systems, as well as the interstellar probe.

References:

- Overview of NEAScout Sail mission with AMT: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170012287.pdf [1]
- AMT Translation Table Development at NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160008126.pdf [2]
- SOA RCDs being evaluated by NASA: https://drum.lib.umd.edu/bitstream/handle/1903/19291/Ma_umd_0117E_17785.... [3]
- SOA RCDs at JAXA: https://www.semanticscholar.org/paper/Optimal-Design-of-Advanced-
Scope Title:

Lightweight Deployable (Solar Sail) Embedded Interplanetary Communication Solutions

Scope Description:

The Mars Cube One (MarCO) mission demonstrated the potential of SmallSat spacecraft to perform interplanetary missions. SMD is continuing to invest in technologies and interplanetary missions due to the high science value enabled by SmallSat spacecraft; several of those being solar-sail-based missions. However, MarCO was extremely limited in communication rates. Also, future interplanetary missions will be carrying science instrumentation with higher data requirements. This solicitation is seeking deployable embedded technology solutions for higher gain, enabling higher data rate communications for interplanetary spacecraft with an emphasis on applicability to solar sail missions (very low SWaP-C (Size, Weight, Power, and Cost)). The NEAScout solar sail architecture can be used as a sample design reference for the proposed technologies. However, the proposed technologies should be extensible to solar sails in general (that is, not be tied to NEAScout-specific requirements) as well as to stand-alone devices (that is, to be applicable to nonsolar sail missions).

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

Primary Technology Taxonomy:

Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis

Desired Deliverables Description:

The anticipated Phase I product of this solicitation would be a proof-of-concept demonstration of the technology with determination of the Key Performance Parameters by test and/or analyses leading to a higher fidelity prototype(s) and relevant environmental demonstrations in Phase II.

State of the Art and Critical Gaps:

The current state of the art for SmallSat/CubeSat missions is led by ISARA (Integrated Solar Array and Reflectarray Antenna) flown on MarCO. Using a combination reflectarray and patch array, it demonstrated an
8-kbps X-band downlink from Mars orbit with a 28-dB-gain design in a small form factor of <1 kg and 272 cm$^3$ at 5 W. For reference, the Mars Reconnaissance Orbiter is a large spacecraft communicating from approximately the same distance as MarCO with a 46.7-dB 3-m dish that varies from 500- to 4,000-kbps X-band downlink at 100 W.

Outside of ISARA, various arrays of 16 patch antennas or fewer are available from places like Endurosat and Clyde Space with gains from 11.5 to 16 dB. Thin-film solutions such as the Lightweight Integrated Solar Array and anTenna (LISA-T) are in development. However, the ultimate scalability (mechanically, mass, stowage volume, etc.) is limited. Thus, a critical technology gap exists in higher data rate communication solutions for SmallSats outside Earth orbit. The current NASA Small Spacecraft Strategic Technology Plan states this need in several ways including large deployable apertures. This gap is especially critical for deployable solar sail missions such as interstellar probe and potentially for second- and third-generation space weather monitoring platforms. In short, low SWaP-C, high-gain communication techniques that will push small spacecraft data rates towards their larger spacecraft brothers and sisters are needed. To enhance future solar sail missions, these concepts should be amenable if not directly embedded onto the solar sail itself.

Relevance / Science Traceability:

The SIMPLEX solicitation opportunities would benefit significantly from higher data rate communication solutions for SmallSat missions. Further specific solar sail mission such as the high-inclination Solar Polar Image mission and second- and third-generation space weather monitoring missions would be enhanced by this technology, and specific solar sail missions such as the interstellar probe would be enabled by this technology.

References:

- LISA-T: https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbmxqb2huYW50aG9ueWNhcnJ8Z3g6YzcxMGZjY2Y4MDYwMmJl [9]

T6.06 Enabling Spacecraft Water Monitoring through Nanotechnology

Lead Center: JSC

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

Scope Title:

Monitoring Systems for Inorganic and Organic Analytes in Spacecraft Water Streams

Scope Description:
This subtopic solicits for technologies that fill specific gaps in capabilities needed for spacecraft water management in the area of environmental monitoring. Its focus is on technologies that identify and quantify inorganic and organic species in water for use during long-duration human missions away from Earth. This subtopic is aligned with the thrust "Enabling Next-Generation Water Monitoring Systems with Nanotechnology," described within a white paper of the Nanotechnology Signature Initiative (NSI) "Water Sustainability through 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 or organic species. There is interest in the capability for monitoring species within wastewater, regenerated potable water, thermal control system cooling water, and samples generated from science activities and biomedical operations. Potential wastewater streams, both current and possible in the future, include urine, urine brines, humidity condensate, Sabatier and Bosch product water, wastewater from hygiene, and wastewater from laundry. Multispecies analyte measurement capability is of interest that would provide a similar capability to that available from 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 also be considered.

Technologies should be targeted to have >3-year service life and at least >50% size reduction compared to current state of the art. Ideally, monitoring systems should require no hazardous reagents, have long-term calibration stability, can be recalibrated in flight, require few consumables, and require very little crew time to operate and maintain. The proposed analytical instrument should be compact, require minimal sample preparation, be compatible with microgravity and partial gravity, and be power efficient. Sample volumes should be minimized and should be identified within the proposal.

Monitoring capability is of interest for both identification and quantification of organic and inorganic contaminants, including polyatomic ions and unknowns. Examples of species of interest and their levels for measurement are specified in Spacecraft Water Exposure Guidelines (SWEGs), released as JSC 63414 (last revised July 2017). Targeted inorganic compounds identified in the SWEGs for human exploration missions include ammonium, antimony, barium, cadmium, manganese, nickel, silver, and zinc. But there is also interest in measurement of other cations and anions including iron, copper, aluminum, chromium, calcium, magnesium, sodium, potassium, arsenic, lead, molybdenum, fluoride, bromide, boron, silicon, lithium, phosphates, sulfates, chloride, iodine, nitrate, and nitrite. Examples of organics include benzene, caprolactam, chloroform, phthalates, dichloromethane, dimethylsilanediol, glycols, aldehydes, formate, 2-mercaptobenzothiazole, alcohols, ketones, and phenol, N-phenyl-beta-naphthylamine.

Please see references for additional information, including NASA's water quality requirements and guidelines, and the current state of the art in spacecraft water.
management, including recycling wastewater.

**Expected TRL or TRL Range at completion of the Project:** 2 to 4  
**Primary Technology Taxonomy:**  
Level 1: TX 06 Human Health, Life Support, and Habitation Systems  
Level 2: TX 06.4 Environmental Monitoring, Safety, and Emergency Response  
**Desired Deliverables of Phase I and Phase II:**

- Research  
- Analysis  
- Prototype  
- Hardware

**Desired Deliverables Description:**

Phase I Deliverables—Reports demonstrating proof of concept, including test data from proof-of-concept studies, and concepts and designs for Phase II. In addition, 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, and test data and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

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

There is limited capability for water quality analysis onboard current spacecraft. Simple measurements of water composition are made on the ISS during flight, and these are limited to conductivity, total organic carbon and iodine concentration. For identification and characterization of ionic or organic species in water and wastewater, samples currently must be returned to Earth.

Water recovery from wastewater sources is considered enabling to long-duration human exploration missions away from Earth. 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, Sabatier product water, and urine into potable water (see ICES-2019-36 for more information). Several hardware failures have occurred onboard the ISS, which demonstrate the need for in situ measurement of inorganic and organic contaminants (for examples, see ICES-2018-123 and ICES-2018-87). This will be especially important for human exploration missions in deep space where return of samples to Earth for analysis on the ground will be impossible. Spacecraft water analysis capability will also benefit onboard science, biomedical, and spacecraft maintenance operations. It will be necessary to confirm that potable water systems are safe for human use following periods of
spacecraft dormancy (ICES-2017-43).

NASA has unique water needs in space that have analogous applications on Earth. NASA’s goal is zero-discharge water treatment, targeting 100% water recycling and reuse. 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 wastewater, 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 wastewater. Only the last gap, technologies to monitor contaminants in water, is requested in this subtopic. 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. SWEGs have been published for selected contaminants. Nanotechnology may offer solutions in all of these application areas.

Relevance / Science Traceability:

Technologies developed under this subtopic could be proven on the ISS and would be enabling to long-duration human exploration missions away from Earth, including Gateway and exploration of the Moon and Mars, including both surface and transit.

This subtopic is directed at needs identified by the Environmental Control and Life Support—Crew Health and Performance Systems Leadership Team (ECLS-CHP SLT) in areas of water management and environmental monitoring.

This subtopic is directed at meeting NASA's commitments as a collaborating agency with 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.

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 [10]
- 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:

- For a list of targeted contaminants and constituents for water monitoring, see "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants, JSC 63414" located at https://www.nasa.gov/feature/exposure-guidelines-smacs-swgs [12]

Several of the references may also be available at https://ntrs.nasa.gov [19]
Scope Title:
Remote Sensing Technologies for Monitoring Plants
Scope Description:
Plant (crop) systems envisioned for future space travel could provide supplemental fresh food for the human crews during early missions and increased amounts of food along with oxygen and carbon dioxide removal for future longer-term missions. This latter concept has been referred to as bioregenerative life support. To do this will require controlled environments for growing the crops, perhaps using techniques similar to recirculating hydroponics used on Earth. But this will require careful monitoring of the environment and the plants themselves to assess their health and performance. In addition, crew time will likely be limited in many space settings, so having the monitoring systems operate autonomously or with little human intervention would be beneficial.

This subtopic solicits advanced technologies for remotely sensing the status of plants in controlled environments of space. These environments are typically small in volume, often use narrow band lighting from light-emitting diodes (LEDs), and are subject to reduced gravity. Example methods might include multispectral and hyperspectral sensing of crops, use of bio-indicators in the crops themselves, or other innovative, noninvasive means. Technologies could focus on approaches for (1) monitoring the morphology and growth of plants and possibly standing biomass and/or (2) monitoring stress to the plants, including water stress, nutrient stress, and plant pathogens. Sensing of volatile compounds produced by the plants is not solicited for this subtopic.

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor
Desired Deliverables of Phase I and 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 approaches for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

- Identification of microbes of interest from literature accounts or current experimentation from existing libraries, including Veggie or the International Space Station (ISS).
  a. Obtain full genomic profiling to scan for unfavorable genomic components and triage candidates for beneficial effects.

Phase II Deliverables—Delivery of isolated microorganisms and/or microbial communities for testing on candidate crops. Preliminary assessment on the safety for use with food crops should be included. Scientific publications and presentations at relevant professional societies.
Apply to candidate crop seedlings and conduct growth evaluations.
   a. Assess growth and metabolite content of treated crops.
   b. Perform toxicity and biofilm tests for candidate microbes both in isolation and in combination. Toxicity screen will be against relevant human cell lines.

State of the Art and Critical Gaps:

NASA’s Advanced Plant Habitat (APH) growth chamber on the International Space Station (ISS) provides a controlled environment with about 0.2 m$^2$ growing area. Within the APH, environmental control includes light from LEDs, temperature, humidity, and carbon dioxide concentration, along with water delivery to a solid medium used to support root systems. The APH is used primarily for plant research on the ISS, and the environmental parameters are logged regularly. Plants in the APH chamber can be monitored with visible imagery and infrared sensing for canopy temperatures. The APH is closed atmospherically to allow condensate recovery and water recycling and to also track plant carbon dioxide uptake and evapotranspiration. Larger plant chambers used for crop production on future missions would build on these capabilities, but may or may not be atmospherically closed to the crew cabin.

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. This subtopic is directed at needs identified by the Life Support and Habitation Systems Capability Leadership Team (CLT) in areas of in situ production of fresh foods.

References:


Scope Title:

Biopriming of Plant Microbiome to Promote Crop Health and Growth

Scope Description:

This subtopic solicits advanced technologies for identifying, selecting, developing, or designing microbes that can promote plant growth in controlled environment crop production systems for space. In the terrestrial environment, the microbiome of the roots (rhizosphere) and the above ground plant (phyllosphere) act as a genetic extension of the plant. The rhizosphere consortia metabolizes precursor compounds that can be further metabolized by the plants and in turn promote growth. This consortia can also produce secondary metabolites that exhibit antimicrobial activity and further protect the plant. Currently, space-bound seeds are surface sterilized, and growth substrates are sterilized, which does away with most microbially conferred advantages—think of a human without its own healthy gut microbes. Therefore, NASA is interested in tailoring a rhizosphere for space crops and “biopriming” plant seeds with a beneficial, probiotic microbial assemblage that is amenable to containment and presents no human health risk. Approaches should consider one or a few organisms that have demonstrated beneficial effects on crops rather than whole communities. These organisms could be applied to seeds or be transferred endophytically (inside the seed or plant material). Crops for these systems would be grown hydroponically or in solid media watered with nutrient solution, or using water along with controlled-release fertilizer. As examples, microbes that confer resistance to stresses such as root zone hypoxia, root zone drought stress, and plant pathogens could be considered. Target crops should focus on leafy greens, such as lettuce, leafy Brassica species, leafy Chenopod species, or small fruiting crops such as pepper and tomato. The ability to put organisms into stasis and then reactivate them in a relevant, operational mode should be considered.

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

Primary Technology Taxonomy:

Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.3 Human Health and Performance

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

Desired Deliverables Description:

Phase I Deliverables—Reports demonstrating proof of concept, including test data from proof-of-concept studies, and concepts and approaches for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

a. Identification of microbes of interest from literature accounts or current experimentation from existing libraries, including Veggie or the International Space Station (ISS).

b. Obtain full genomic profiling to scan for unfavorable genomic components and triage candidates for beneficial effects.

Phase II Deliverables—Delivery of isolated microorganisms and/or microbial communities for testing on candidate crops. Preliminary assessment on the safety for use with food crops should be included. Scientific publications and presentations at relevant professional societies.

a. Apply to candidate crop seedlings and conduct growth evaluations.

b. Assess growth and metabolite content of treated crops.

c. Perform toxicity and biofilm tests for candidate microbes both in isolation and in combination. Toxicity screen will
be against relevant human cell lines.

State of the Art and Critical Gaps:

NASA’s Advanced Plant Habitat (APH) and Veggie plant growth chambers on the ISS provide controlled environments with about 0.2 m² growing area. Plants are grown in a solid medium (arcillite or calcined clay) that is sterilized prior to launch, and plants are typically propagated using surface sterilized seeds. But neither system is sterile in its operations and are open to the cabin environment (Veggie) or occasionally opened and accessed by the crew for horticultural operations (APH). For one Veggie study, a Fusarium fungus was noted growing on zinnia plants, likely due to a malfunction in the air circulation resulting in very high humidity. Similar environmental anomalies (environmental control failures, too little or too much water in the root zone, nutrient stress) can occur in any controlled environment, including those envisioned for future space crop production systems. Having a microbiome that can confer resistance to such perturbations and generally promote healthier growth can reduce the risk of crop failures for these systems. Biocontainment measures are not typically required for probiotic consortia in field settings, but may be an issue in confined environments of space. Introducing a tailored microbiome into a controlled environment such as Veggie aboard the ISS will undoubtedly rule out classes of microbes due to their propensity to become opportunistic pathogens. Therefore, there is a large knowledge gap when it comes to the types of strains that will be beneficial for crop production not only in space, but in closed environments. Storage and handling of these tailored microbiomes for long-duration space exploration also presents a unique challenge.

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. This subtopic is directed at needs identified by the Life Support and Habitation Systems Capability Leadership Team (CLT) in areas of in situ production of fresh foods. The research is also applicable to the rapidly expanding controlled environment agriculture (CEA) industry on Earth.

References:


Quiza, L.; St-Arnaud, M.; Yergeau, E. 2015. Harnessing phytomicrobiome signaling for rhizosphere microbiome
T7.04 Surface Construction

Lead Center: KSC

Participating Center(s): GRC, MSFC

Scope Title:

Surface Construction

Scope Description:

Surface construction technologies must be developed to support long-term sustainable human presence on the lunar and eventually Martian surfaces. To enable a sustained human presence on the Moon, multiple assets are likely to be landed proximal to each other. While the Apollo landers demonstrated that it is possible to land on an unprepared surface, landing multiple proximal assets under Artemis will pose an unacceptable risk to nearby hardware.

For this reason, launch and landing pads are a high initial priority due to significant risks associated with these operations. When a lander vehicle launches or lands on an extraterrestrial body, the rocket engine exhaust plume impinges on the surface and interacts with the regolith, and blast ejecta is created along with associated cratering of the surface. Lunar regolith blast ejecta travels at high velocities (>2,000 m/s) for long distances (kilometers) in a vacuum environment creating hazards for surrounding assets. Ejecta can also impact the bottom of the lander vehicle, risking damage to the engines, thermal insulation, and sensors. Regolith ejecta can enter cis-lunar space as debris if the ejecta is sufficiently energetic to achieve orbit. The cratering can affect the stability of the landing gear and expose subsurface hazards.

As a part of a Launch and Landing Pad (LLP) system, concepts for construction of blast ejecta barriers such as berms, walls, curtains, deflectors, or other solutions are also sought. These blast ejecta barriers will protect the lunar base in the vicinity of the LLP during routine launches and landings and will also provide protection in the event of an anomalous energy release in the lander.

Upon the completion of an LLP system, follow-on surface construction projects will reduce risk to other parts of the lunar infrastructure and are expected to include:

- Stabilized roads and pads to mitigate trafficability and operational risks.
- Radiation shielding for nuclear power plants.
- Trenching for cables and other below-grade operations.
- Site preparation including establishing grade, leveling, compaction, and rock clearing.
- Unpressurized structures for radiation, thermal, and micrometeoroid protection.
- Pressurized structures.

This subtopic is focused on applied research to enable the design, testing, and verification of civil engineering products suitable for use in lunar surface architecture. New analysis methods and specialized construction equipment will be required to meet the unique lunar environment. The desired outcome of this work is the definition
of feasible civil engineering system solutions with associated methods, analysis, structural designs, construction equipment concept prototypes, and concepts of operations.

The construction operations shall be robotically competed using indigenous lunar resources to the highest degree possible to minimize crew interaction and minimize the transportation mass from Earth to the Moon. Proposers need to consider operations and hardware designs in a Global Positioning System (GPS-) denied environment for positioning, leveling, and control. In selecting and developing procedures and materials for surface stabilization and landing pad construction, proposers should consider the ability to perform maintenance and repair for long-term operations.

For hardware, processes, and operations that require mobility, proposers should define the interface and operation requirements, but may refrain from designing specific mobility units as these may be available through other development activities. Proposers should also specify the interfaces to other lunar systems that might be required such as power, regolith size sorting, beneficiation, etc., and include the source of all feedstocks for construction materials and associated processing required.

Proposed techniques can utilize Earth-supplied consumables (such as binders, water, purge gases, etc.) but need to quantify the types and amounts needed for the proposed construction operations. Emphasis should be given to consumables that can eventually be extracted or produced from in situ resources. The proposed lunar methods, materials, and technologies shall be traceable to Mars applications to the highest degree possible. The lunar construction technologies proposed should also contain methodologies for verification of the as-built or finished construction to ensure it will perform as required.

Research institute partnering is anticipated to provide analytical, research, and engineering support to the proposers. Examples may include helping apply civil engineering principles and planning methods, identification and development of needed standards or specifications for lunar operations, or the development of analytical and verification methods for the design and prototyping of structures, hardware, and associated software.

Specific figures of merit for proposed solutions include the following for Commercial Lunar Payload Services (CLPS) and human-class landers:

- Performance of infrastructure in intended applications (e.g., under launch/landing conditions).
- Performance under lunar surface environmental conditions (e.g., thermal cycling, ultraviolet (UV), vacuum, and radiation).
- Required payload mass.
- Estimated power requirements.
- Feedstock sources and requirements.
- Construction time.
- Surface preparation/analysis requirements.
- Strategy for verification of as-built structural performance.
- Concepts of operation.
- Expected life of infrastructure.

All proposals need to identify the state-of-the-art of applicable technologies and processes. Prototypes to be delivered at the conclusion of Phase II will be required to operate under lunar equivalent vacuum, temperature, and dust conditions, so thermal management and dust mitigation strategies utilized during the operation of the proposed technology will need to be specified in the Phase I proposal. The Phase I proposals should at least result in a Technology Readiness Level (TRL) of 2 to 4.

Expected TRL or TRL Range at completion of the Project: 2 to 6
**Primary Technology Taxonomy:**
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

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

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

Phase I must include the design and test of critical attributes or high risk areas associated with the proposed surface construction technology or process used to achieve the objectives of the Phase II delivered prototype as described in a final report.

By the end of Phase II, the prototype hardware should be advanced by appropriately justified demonstration(s) to TRL 4 to 6, and be capable of further testing in more relevant environments (TRL 7 to 8) beyond Phase II.

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

The state of the art for robotic construction on the lunar surface includes regolith excavation and manipulation systems such as the Regolith Advanced Surface Systems Operations Robot (RASSOR). Sintered regolith interlocking pavers and emplacement systems were jointly developed and tested by NASA and the Pacific International Space Center for Exploration Systems (PISCES). Robotic construction of blast ejecta barriers was completed by NASA where a lunar teleoperated robotic bulldozer was able to clear and level an area of 100 by 100 m and then build a 2-m-high berm in the sand dunes of Moses Lake in Washington. Sintered basalt and ablative polymer concrete materials that have been tested at high plasma temperatures in the Arc Jet facility at NASA Ames Research Center performed well as a heat shield material. Specialized concrete formulations and emplacement systems have been developed by Marshall Space Flight Center and others.

**Relevance / Science Traceability:**

Surface construction of infrastructure directly addresses the STMD Strategic Thrust, “Land: Increase Access to Planetary Surfaces.” It also addresses the strategic thrust of “Explore: Expand Capabilities Through Robotic Exploration and Discovery.” The risks of landing on the Moon were demonstrated in the lunar Surveyor and Apollo missions. The robotic Surveyor spacecraft had difficulty landing safely, and during Apollo, five of six landings had close calls such as avoiding hazardous terrain, dust obscuration during landing, and slopes that tipped the lander as far as 11°, which happened on Apollo 15. The need for trafficability risk mitigation is highlighted by Spirit rover becoming immobilized in Martian regolith. Lunar dust and radiation mitigations are considered major risks for long-term lunar operations.

**References:**


**T8.06 Quantum Sensing and Measurement**

Lead Center: GSFC

Participating Center(s): GRC, JPL, LaRC

**Scope Title:**

Quantum Sensing and Measurement

**Scope Description:**

This Quantum Sensing and Measurement 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. Proposals focused on atomic quantum sensor and clocks and quantum communication should apply to those specific subtopics and are not covered in this Quantum Sensing and Measurement subtopic.

Specifically identified applications of interest 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 (SQUID) 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 visible infrared (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 midwave infrared (MIR), near infrared (NIR), and visible. Such sources are sought for operation at cryogenic temperatures for calibration on the ground and aboard space instruments.

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

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

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

**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.

Phase I does not need to include a physical deliverable to the government but it is best if it includes a demonstration of feasibility through measurements. This can include extensive modeling, but a stronger proposal will have measured validation of models or designs that support the viability of the planned Phase II deliverable.

Phase II should include prototype delivery to the government. (It is understood that this is a research effort and the prototype is a best effort delivery where there is no penalty for missing performance goals.) The Phase II effort should be targeting a commercial product that could be sold to the government and/or industry.

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

Quantum entangled photon sources.
Sources for generation of quantum photon number states. Such sources would utilize high detection efficiency photon energy-resolving single-photon detectors (where the energy resolution is used to detect the photon number) developed at NASA for detection. Sources that fall in the wavelength range from 20 ?m to 200 nm are of high interest. Photon number state generation anywhere within this spectral range is also highly desired including emerging photon-number quantum state methods providing advantages over existing techniques. (Stobi?skas et al., Quantum interference enables constant-time quantum information processing. Sci. Adv. 5 (2019)).

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)). Further advances are sought.

Spectral brightness of 0.41 MHz/mW/nm for multimode 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)).

Energy-resolving detectors achieving 99% detection efficiency have been demonstrated in the NIR. Even higher quantum efficiency absorber structures are sought (either over narrow bands or broadband) compatible with transition-edge sensor (TES) detectors. Such ultra-high- (near-unity-) efficiency absorbing structures are sought in the UV, vis-IR, NIR, mid-infrared, far-infrared, and microwave.

Absolute detection efficiency measurements (without reference to calibration standards) using quantum light sources have achieved detection efficiency relative uncertainties of 0.1% level. Further reduction in detection efficiency uncertainty is sought to characterize ultra-high-efficiency absorber structures. Combining calibration method with the ability to tune over a range of different wavelengths is sought to characterize cryogenic single-photon detector’s energy resolution and detection efficiency across the detection band of interest. For such applications, the natural linewidth of the source lines must be much less than the detector resolution (for NIR and higher photon energies, resolving powers $R=E/?E_{FWHM} = ?/?F_{FWHM} < 100$ are required). Quantum sources operating at cryogenic temperatures are most suitable for cryogenic detector characterization and photon number resolving detection for wavelengths of order 1.6 ?m and longer.

For quantum sensing applications that would involve a squeezed light source on an aerospace platform, investigation of low SWaP (size, weight, and power) sources of squeezed light would be beneficial. From the literature, larger footprint sources of squeezed light have demonstrated 15 dB of squeezing [1]. For a source smaller in footprint, there has been a recent demonstration of parametric downconversion in an OPO (optical
parametric oscillator) resulting in 9.3 dB of squeezing [2]. Further improvement of the state-of-the-art light squeezing capability (i.e., > 10 dB), while maintaining low-SWaP parameters, is desired.


Relevance / Science Traceability:

Quantum technologies enable a new generation in sensitivities and performance and include low baseline interferometry and ultraprecise 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 infrared.

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

References:


  ○ http://kiss.caltech.edu/final_reports/Quantum_final_report.pdf(link is external) [24]

• National Quantum Initiative Act:
  ○ https://www.lightourfuture.org/getattachment/7ad9e04f-4d21-4d98-bd28-e1239977e262/NPI-Recommendations-to-HSC-for-National-Quantum-Initiative-062217.pdf(link is external) [27]

• European Union Quantum Flagship Program: https://qt.eu(link is external) [28].

• UK National Quantum Technologies Programme: http://uknqt.epsrc.ac.uk(link is external)
• DLR Institute of Quantum Technologies:
  https://www.dlr.de/qt/en/desktopdefault.aspx/tabid-13498/23503_read-54020/[link is external] [30].


**T8.07 Photonic Integrated Circuits**

Lead Center: GSFC

Participating Center(s): GRC, LaRC

**Scope Title:**

Photonic Integrated Circuits

**Scope Description:**

Photonic integrated circuits (PICs) generally integrate multiple lithographically defined photonic and electronic components and devices (e.g., lasers, detectors, waveguides/passive structures, modulators, electronic control, and optical interconnects) on a single platform with nanometer-scale feature sizes. PICs can enable size, weight, power, and cost reductions and improve the performance of science instruments, subsystems, and components. PIC technologies are particularly critical for enabling small spacecraft platforms. Proposals are sought to develop PIC technologies including the design and fabrication of PICs that use nanometer-scale structures and optical metamaterials. On-chip generation, manipulation, and detection of light in a single-material system may not be practical or offer the best performance, so hybrid packaging of different material systems are also of interest. This subtopic solicits methods, technology, and systems for development and incorporation of active and passive circuit elements for PICs for:

- PICs for in situ and remote sensors—NASA application examples include but are not limited to lab-on-a-chip systems for landers, 3D mapping lidar, front end and back end for remote-sensing instruments including trace gas lidars, optical spectrometers, gyroscopes, and magnetometers.
- PICs for analog radiofrequency (RF) applications—NASA applications require new methods to reduce the size, weight, and power of passive and active microwave signal processing. As an example, PICs having very low insertion loss (e.g., ~1 dB) and high spurious-free dynamic range for analog and RF signal
processing and transmission that use monolithic high-Q waveguide micro-resonators or other filters with a few GHz RF passbands. These components should be suitable for designing chip-scale tunable optoelectronic RF oscillator and high-precision optical clock modules. Example applications include terahertz spectroscopy, microwave radiometry, and hyperspectral microwave sounding.

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

**Primary Technology Taxonomy:**

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.1 Remote Sensing Instruments/Sensors

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

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**

Phase I does not need to include a physical deliverable to the government but it is best if it includes a demonstration of feasibility through measurements. This can include extensive modeling but a stronger proposal will have measured validation of models or designs.

Phase II should include prototype delivery to the government. (It is understood that this is a research effort and the prototype is a best effort delivery where there is no penalty for missing performance goals.) The phase II effort should be targeting a commercial product that could be sold to the government and/or industry.

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

There is a critical gap between discrete and bulk photonic components and waveguide multifunction PICs. The development of PICs permits size, weight, power, and cost reductions for spacecraft microprocessors, communication buses, processor buses, advanced data processing, and integrated optic science instrument optical systems, subsystems, and components. This is particularly critical for small spacecraft platforms.

**Relevance / Science Traceability:**

- HEOMD—Astronaut health monitoring.
- SMD—Earth, planetary, and astrophysics compact science instrument (e.g., optical and terahertz spectrometers and magnetometers on a chip).
- STMD—Game-changing technology for small spacecraft communication and navigation (optical communication, laser ranging, and gyroscopes).
- STTR—Exponentially increasing interest and programs at universities and startups in integrated photonics.

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, 14.3.3

**References:**

1. AIM integrated photonics: [http://www.aimphotronics.com](http://www.aimphotronics.com) [32].
T9.02 Rapid Development of Advanced High-Speed Aerosciences Simulation Capability

Lead Center: ARC

Participating Center(s): JSC, LaRC

Scope Title:

Aerothermal Simulation on Advanced Computer Architectures

Scope Description:

Aerothermodynamic simulations of planetary entry vehicles such as Orion and Dragonfly are complex and time consuming. These simulations, which solve the multispecies, multitemperature Navier-Stokes equations, require detailed models of the chemical and thermal nonequilibrium processes that take place in high-temperature shock layers. Numerical solution of these models results in a large system of highly nonlinear equations that are exceptionally stiff and difficult to solve efficiently. As a result, aerothermal simulations routinely consume 20 to 50 times the compute resources required by more conventional supersonic computational fluid dynamics (CFD) analysis, limiting the number of simulations delivered in a typical engineering design cycle to only a few dozen. Moreover, entry system designs are rapidly increasing in complexity, and unsteady flow phenomena such as supersonic retropropulsion are becoming critical considerations in their design. This increases the compute resources required for aerothermal simulation by an additional one to two orders of magnitude, which precludes the delivery of such simulations in engineering-relevant timescales.

In order to deliver the aerothermal simulations required for NASA’s next generation of entry systems, access to greatly expanded compute resources is required. However, scaling up conventional central processing unit (CPU-) based supercomputers is problematic due to cost and power constraints. Many-core accelerators, such as Nvidia’s general-purpose graphical processing units (GPGPUs), offer increased compute capability with reduced cost and power requirements and are seeing rapid adoption in top-end supercomputers. As of June 2020, 144 of the top 500 fastest supercomputers leveraged accelerators or co-processors, including 6 of the top 10 [1]. All three of the U.S. Department of Energy’s upcoming exascale supercomputers will be accelerated using GPGPUs [2]. NASA has deployed Nvidia v100 GPGPUs to the Pleiades supercomputer [3]. Critically, NASA’s aerothermal simulation tools are fundamentally unable to run on many-core accelerators, and must be reengineered from the ground up to efficiently exploit such devices.

This scope seeks to revolutionize NASA’s aerothermal analysis capability by developing novel simulation tools capable of efficiently targeting the advanced computational accelerators that are rapidly becoming standard in the world’s fastest supercomputers. A successful solution within this scope would demonstrate efficient simulation of a large-scale aerothermal problem of relevance on an advanced many-core architecture, for example, the Nvidia Volta GPGPU, using a prototype software package.

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

Primary Technology Taxonomy:

Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

The desired deliverable at the conclusion of Phase I is a prototype software package capable of solving the multispecies, multitemperature, reacting Euler equations on an advanced many-core accelerator such as an Nvidia v100 GPGPU. Parallelization across multiple accelerators and across nodes is not required. The solver shall demonstrate offloading of all primary compute kernels to the accelerator, but may do so in a nonoptimal fashion, for example, using managed memory, serializing communication and computation, etc. Some noncritical kernels such as boundary condition evaluation may still be performed on a CPU. The solver shall demonstrate kernel speedups (excluding memory transfer time) when comparing a single accelerator to a modern CPU-based, dual-socket compute node. However, overall application speedup is not expected at this stage. The solver shall be demonstrated for a relevant planetary entry vehicle such as FIRE-II, Apollo, Orion, or the Mars Science Laboratory.

A successful Phase II deliverable will mature the Phase I prototype into a product ready for mission use and commercialization. Kernels for evaluating viscous fluxes shall be added, enabling computation of laminar convective heat transfer to the vehicle. Parallelization across multiple accelerators and multiple compute nodes shall be added. Good weak scaling shall be demonstrated for large 3D simulations (>10M grid cells). The implementation shall be sufficiently optimized to achieve an ~5x reduction in time-to-solution compared to NASA's Data-Parallel Line Relaxation (DPLR) aerothermal simulation code, assuming each dual-socket compute node is replaced by a single accelerator (i.e., delivered software running on eight GPGPUs shall be 5 times faster than DPLR running on eight modern, dual-socket compute nodes). Finally, the accuracy of the delivered software shall be verified by comparing to the DPLR and/or LAURA codes. The verification study shall consider flight conditions from at least two of the following planetary destinations: Earth, Mars, Titan, Venus, and Uranus/Neptune.

State of the Art and Critical Gaps:

NASA’s existing aerothermal analysis codes (LAURA, DPLR, US3D, etc.) all utilize domain-decomposition strategies to implement coarse-grained, distributed-memory parallelization across hundreds or thousands of conventional CPU cores. These codes are fundamentally unable to efficiently exploit many-core accelerators, which require the use of fine-grained, shared-memory parallelism over hundreds of thousands of compute elements. Addressing this gap requires reengineering our tools from the ground up and developing new algorithms that expose more parallelism and scale well to small grain sizes.

Many-core accelerated CFD solvers exist in academia, industry, and government. Notable examples are PyFR from Imperial College London [4], the Ansys Fluent commercial solver [5], and NASA Langley’s FUN3D code, which recently demonstrated a 30x improvement in node-level performance using Nvidia v100 GPUs [6]. However, nearly all previous work has focused on perfect gas flow models, which have different algorithmic and resource requirements compared to real gas models. The Sandia Parallel Aerodynamics and Reentry Code (SPARC) solver is the only project of note to have demonstrated efficient real-gas capability at scale using many-core accelerators [7].

Relevance / Science Traceability:

This scope is directly relevant to NASA space missions in both HEOMD and SMD with an entry, descent, and landing (EDL) segment. These missions depend on aerothermal CFD to define critical flight environments and would derive large, recurring benefits from a more responsive and scalable simulation capability. This scope also has potential cross-cutting benefits for tools used by ARMD to simulate airbreathing hypersonic vehicles. Furthermore, this scope directly supports NASA’s CFD Vision 2030 Study, which calls for sustained investment to ensure that NASA’s computational aeroscience capabilities can effectively utilize the massively parallel,
heterogeneous (i.e., GPU-accelerated) supercomputers expected to be the norm in 2030.

References:


Scope Title:

Robust Aerothermal Simulation of Complex Geometries

Scope Description:

NASA’s production aerothermodynamic flow solvers all share a common characteristic: they utilize second-order accurate finite volume schemes to spatially discretize the governing flow equations. Schemes of this type are ubiquitous in modern compressible CFD solvers. They are simple to implement, perform well on current computer architectures, and provide reasonable accuracy for a wide range of problems. Unfortunately, one area where these schemes struggle to deliver high accuracy is at hypersonic speeds when a strong shock wave forms ahead of the vehicle. In such cases, the computed surface heat flux exhibits extreme sensitivity to the design of the computational grid near the shock [1], which must be constructed from cell faces that are either parallel or perpendicular to the shock to minimize error.

This stringent requirement for shock-aligned grids precludes the use of fully unstructured tetrahedral meshes in aerothermal simulation. While this restriction is manageable for simple or idealized entry systems [2], unstructured grids have significant accuracy and efficiency benefits for complex vehicle geometries, for example, ADEPT, and flow fields, for example, Mars 2020 reaction control system (RCS) firings, where large disparities in length scales must be resolved accurately. Moreover, unstructured grids can be developed much more rapidly and with a much higher degree of automation than traditional structured grid topologies [3]. As such, they are widely used in most other CFD subdisciplines.

Fortunately, recent research has demonstrated that high-order, finite-element schemes such as the Discontinuous
Galerkin (DG) method can achieve high-quality solutions for shock-dominated flows on unstructured grids when appropriate stabilization mechanisms are employed [4][5]. This research also suggests high-order methods are largely insensitive to the choice of the upwind flux function, potentially resolving a long-standing deficiency of second-order finite volume schemes at high speeds. However, while DG methods are robust and commonly applied in subsonic regimes, their continued development for aerothermal applications is hampered by ad hoc implementations in research-level codes.

This scope seeks to revolutionize NASA’s aerothermal analysis capability by enabling rapid, robust, and highly automated analysis of complex entry systems using fully unstructured tetrahedral grids. A successful solution within this scope would demonstrate accurate simulation of a 3D capsule geometry at conditions relevant to planetary entry using DG or an equivalent numerical scheme in a prototype software package.

**Expected TRL or TRL Range at completion of the Project:** 2 to 5  
**Primary Technology Taxonomy:**  
Level 1: TX 09 Entry, Descent, and Landing  
Level 2: TX 09.1 Aeroassist and Atmospheric Entry  
**Desired Deliverables of Phase I and Phase II:**

- Software  
- Prototype

**Desired Deliverables Description:**

The desired deliverable at the conclusion of Phase I is a prototype software package capable of solving the two-dimensional, multispecies, multitemperature, reacting Euler equations on unstructured triangular grids at planetary entry velocities (>7 km/s). The software shall demonstrate robust capturing of the bow shock ahead of a simple cylinder at a variety of flight conditions without requiring adjustment of algorithm parameters, for example, artificial viscosity scale factors. The postshock flow field shall be free of the numerical noise in the entropy field, which is typical of conventional second-order finite volume schemes on triangular grids. Convergence to machine precision shall be demonstrated for all calculations.

A successful Phase II deliverable will mature the Phase I prototype into a product ready for use on mission-relevant engineering problems. Extension to the laminar, multispecies, multitemperature Navier-Stokes equations shall be implemented. Extension to three spatial dimensions using unstructured tetrahedral grids shall be implemented, with efficient multinode parallelization targeting modern high-performance computing (HPC) platforms such as the NASA Pleiades supercomputer. The software shall be demonstrated on a range of planetary entry problems that include at least two of the following destinations: Earth, Mars, Titan, Venus, and Uranus/Neptune. Surface heat flux predictions shall be verified by comparison with NASA's DPLR and/or LAURA simulation codes, and must be free of numerical noise typically observed when using second-order finite volume codes on unstructured tetrahedral grids. Computational performance, as measured by total time-to-solution for a given heat flux accuracy, shall be characterized and compared to DPLR/LAURA, but no specific performance targets are required.

**State of the Art and Critical Gaps:**
Multiple academic [4][5][6][7] and NASA [8] groups have demonstrated promising results when using high-order DG/finite element methods (FEMs) to perform steady-state aerothermodynamic analysis at conditions relevant to planetary entry. The bulk of these studies were conducted using structured grids with some degree of shock alignment (though not sufficient alignment to support a second-order finite volume scheme). However, [4] and [5] demonstrate equally accurate results on fully unstructured grids, suggesting that their technologies are capable of meeting the objectives of this scope. An additional shortcoming of current research is that all efforts examine the same 5 km/s flight condition (relatively slow for planetary entry) with simplistic, nonionized flow models. An infusion of resources is needed to mature these promising algorithms into scalable, production-ready software that can be tested across a full entry trajectory with best-practice thermochemical models.

Relevance / Science Traceability:

This scope is directly relevant to NASA space missions in both Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) with an EDL segment. These missions depend on aerothermal CFD to define critical flight environments and would see significant, sustained reductions in cost and time-to-first-solution if an effective unstructured simulation capability is deployed. This scope also has strong crosscutting benefits for tools used by ARMD to simulate airbreathing hypersonic vehicles, which have stringent accuracy requirements similar to those in aerothermodynamics. Finally, this scope aligns with NASA’s CFD Vision 2030 Study, which calls for a “much higher degree of automation in all steps of the analysis process” with the ultimate goal of making “mesh generation and adaptation less burdensome and, ultimately, invisible to the CFD process.” In order for the aerothermal community to realize these goals, we must eliminate our dependence on manually designed, carefully tailored, block structured grids. This scope is an enabling technology for that transition.

References:


Scope Title:

Efficient Grid Adaption for Unsteady, Multiscale Problems

Scope Description:

The current state of the art for production CFD simulation in EDL is the solution of steady-state problems on fixed computational grids. However, most of the current challenge problems in the discipline are unsteady. Examples include supersonic retropropulsion, where engine plumes exhibit unsteady behavior across a wide range of timescales [1]; capsule dynamic stability, where the vehicle pitch motion is amplified by the unsteady wake dynamics [2]; and single-event drag modulation, where a high-drag decelerator is separated from the main vehicle at hypersonic speeds [3]. Successful analysis of these phenomena require simulating many seconds of physical time while simultaneously resolving all features of the flow field with high accuracy. Since critical features, for example, shocks, shear layers, etc., will evolve and move through the computational domain over time, current
practice requires large, globally refined grids and stringent limitations on simulation time step. This makes these problems computationally infeasible without dedicated access to leadership-class supercomputers.

One promising method to reduce the cost of these simulations is to employ feature-based grid adaption such that the computational grid is only refined in the vicinity of critical flow features. Adaptive techniques, particularly metric-aligned anisotropic adaption [4], have been shown to dramatically reduce computational cost for a wide range of steady-state flow problems, often by as much as an order of magnitude. These techniques have been successfully used to solve large-scale, EDL-relevant problems with high Reynolds number boundary layers by incorporating prismatic near-wall layers [5]. Application of efficient adaptive techniques to unsteady problems is less established, but recent advancements have demonstrated a nearly 100x reduction in compute time required to achieve an equivalent level of space-time accuracy relative to globally refined grids [6].

This scope seeks to accelerate the infusion of cutting-edge algorithms for unsteady grid adaption that promise to radically reduce the time required to simulate unsteady fluid phenomena. A successful solution within this scope would demonstrate an order of magnitude reduction in computational cost without compromising solution accuracy for an unsteady supersonic or hypersonic flow problem relevant to EDL.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.4 Vehicle Systems
Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

The desired deliverable at the conclusion of Phase I is a prototype software package employing adaptive grid refinement algorithms for the simulation of unsteady, shocked flows in at least two spatial dimensions. An inviscid, perfect gas model is acceptable for Phase I efforts. The prototype software shall be demonstrated on a suitable challenge problem. Suggested challenge problems are prescribed motion of a cylinder relative to the computation domain subject to Mach 6+ supersonic flow or 2D axisymmetric simulation of a shock tube with an initial pressure ratio >50. Other challenge problems of similar complexity are acceptable. The prototype software is not expected to be scalable or performant at this stage.

A successful Phase II deliverable will mature the Phase I prototype into a product ready for use on mission-relevant engineering problems. The code shall be extended to solve the unsteady laminar Navier-Stokes equations in three spatial dimensions with appropriate controls to manage adaption in the boundary layer and the far field, if needed. Extension to reacting, multitemperature gas physics is desired, but not required. The software shall be parallelized to enable simulation of large-scale problems using modern HPC platforms such as the NASA Pleiades supercomputer. The software shall be demonstrated on a 3D challenge problem such as a single jet supersonic retropropulsion configuration at zero angle of attack; free-to-pitch simulation of the Orion entry capsule at supersonic free-stream conditions; or aerodynamic interaction and
separation of multiple spheres in a supersonic free stream. The software shall demonstrate a 10x speedup relative to a nonadaptive, time-marched calculation without significantly degrading simulation accuracy as measured by an appropriate solution metric (average reflectance measurement system (RMS) pressure fluctuation, final capsule pitch angle, etc.).

State of the Art and Critical Gaps:

Multiple academic, government, and commercial software packages exist that implement some form of solution-adaptive mesh refinement. NASA’s LAURA and DPLR codes offer simplistic clustering algorithms for structured grids that solve the limited problem of resolving strong bow shocks [7][8]. NASA’s FUN3D code implements an advanced metric-based, anisotropic refinement capability that has been demonstrated on large-scale aerospace calculations [7]. However, unsteady solution-adaptive algorithms have yet to be demonstrated for EDL-relevant problems outside of academic research codes. Significant investment is required to implement these algorithms into a production-quality flow solver with the performance and scaling characteristics required to address NASA’s requirements for unsteady flow simulation.

Relevance / Science Traceability:

This scope has extremely broad applicability across multiple NASA mission directorates. In particular, ARMD, HEOMD, SMD, and STMD each contend with complex, unsteady flow phenomena that could be more readily analyzed with the aid of the proposed technology: flutter analysis, parachute inflation, fluid slosh, and atmospheric modeling are just a few examples. In EDL specifically, a robust time-space adaption capability would enable simulation of supersonic retropropulsion at Mars using NASA’s existing supercomputing assets. Capsule stability could be analyzed in the preliminary design phase, allowing mission designers to utilize low-heritage capsule shapes without adding significant cost or risk to the project. Drag skirt separation could be modeled in detail to reduce risk prior to a technology demonstration mission. The potential benefits of this technology are widespread, making this a critical investment area for the Agency.

References:


T10.03 Coordination and Control of Swarms of Space Vehicles

Lead Center: ARC

Participating Center(s): LaRC

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- to 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 must be motivated by a well-defined "design reference mission" presented in the proposal with clear connection to the needs identified in decadal surveys. The proposed design reference mission is used to derive the high-level requirements for the technology development effort.

Areas of high interest are:

- Distributed estimation for exploration and inspection of a target object or phenomena by various assets with heterogenous sensors and from various vantage points.
- High-precision relative localization and time synchronization in orbit and on planet surface.
- Operations concepts and tools that provide situational awareness and commanding capability for a team of spacecraft or swarm of robots on another planet.
- Coordinated task recognition and planning, operation, and execution with realistic communication limitations.
- Communicationless coordination by observing and estimating the actions of other agents in the multiagent system.

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 [50]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

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

Primary Technology Taxonomy:

Level 1: TX 10 Autonomous Systems
Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Software
- Hardware

Desired Deliverables Description:

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

- Phase I and Phase II: 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 must be included as a deliverable.
- Phase II only: 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 for collaborative planetary exploration. Distributed task recognition, allocation, and execution, collaborative motion planning for larger science return, and distributed estimation and shared common operational picture are examples of technology needs in this area.

These technologies also enable successful formation flying spacecraft missions, robust distributed GNC, precision relative navigation, distributed tasking and execution, and distributed estimation of the swarm state as well as the science target are examples of the technology gaps in this area.

Relevance / Science Traceability:

Subtopic technology directly supports NASA Space Technology Roadmap TA4 (4.5.4 Multi-Agent Coordination, 4.2.7 Collaborative Mobility, and 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 advanced scouts and rovers.
- PUFFERs are being developed at the 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.

References:


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. 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 uncrewed experiments. 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—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 uncrewed (dormant) periods of up to 9 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, allow more autonomy from Earth-based Mission Control, and learn how to perform or improve their performance of autonomous operations by observing the crew. 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 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 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-habitats [60]) are relevant.

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 uncrewed, automatically notifies of any off-nominal conditions, and then, when crew arrive, transitions 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 versus nominal conditions and prioritize and compress data communications to Earth.

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

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

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
Desired Deliverables Description:

Phase I 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 II deliverables will be full technology prototypes that could be subsequently matured for deployment on Gateway.

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). Gateway will require all operations and health management to be autonomous at different levels (almost fully autonomous when no astronauts are on board versus limited autonomy when astronauts are present), the autonomy to learn from human operations, and the autonomy across all functions. The autonomy will also need to adapt to new missions and new technologies. Proposers should be aware of and consider potential interfaces and interactions such as those between Gateway and smart habitats. Proposers may want to be aware of pertinent related efforts such as those being conducted by the Space Technology Research Institutes.

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 execute an increasingly large number of autonomous operations over longer durations with higher degrees of complexity and less ability to have human intervention due to increasing duration space missions such as missions to Mars.

References:

- Basic Moon to Mars Background: https://www.nasa.gov/topics/moon-to-mars/lunar-outpost [61].
- Basic Gateway Background: https://www.nasa.gov/topics/moon-to-mars/lunar-gateway [62].
- Deep Space Gateway Science Opportunities: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001581.pdf [65].
- Conducting Autonomous Experiments in Space: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180004314.pdf [66].

T10.05 Integrated Data Uncertainty Management and Representation for Trustworthy and Trusted Autonomy in Space

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

Scope Title:

Integrated Data Uncertainty Management and Representation for Trustworthy and Trusted Autonomy in Space

Scope Description:

Multi-agent Cyber-Physical-Human (CPH) teams in future space missions must include machine agents with a high degree of autonomy. In the context of this subtopic, by “autonomy” we mean the capacity and authority of an agent (human or machine) for independent decision-making and execution in a specified context. We refer to machine agents with these attributes as autonomous systems (AS). In multi-agent CPH teams, humans may serve as remote mission supervisors or as immediate mission teammates, along with AS. AS may function as teammates with specified independence, but under the ultimate human direction. Alternatively, AS may exercise complete independence in decision-making and operations in pursuit of given mission goals; for instance, for control of uncrewed missions for planetary infrastructure development in preparation for human presence, or maintenance and operation of crew habitats during the crew’s absence.

In all cases, trustworthiness and trust are essential in CPH teams. The term “trustworthiness” denotes the degree to which the system performs as intended and does not perform prohibited actions in a specified context. “Trust” denotes the degree of readiness by an agent (human or machine) to accept direction or advice from another agent (human or machine), also in a specified context. In common sense terms, trust is a confidence in a system’s trustworthiness, which in turn, is the ability to perform actions with desired outcomes.

Because behind every action lies a decision-making problem, trustworthiness of a system can be viewed in terms of the soundness of decision-making by the system participants. Accurate and relevant information forms the basis of sound decision-making. In this subtopic, we focus on data that inform CPH team decision-making, both in human-machine and machine-machine interactions, from two perspectives: the quality of the data and the representation of the data in support of trusted human-machine and machine-machine interactions.

We consider data exchanges in multi-agent CPH teams that include AS. Data exchanges in multi-agent teams must be subject to the following conditions:

- Known data accuracy, noise characteristics, and resolution, as a function of the physical sensors in relevant environments.
- Known data accuracy, noise characteristics, and resolution as a function of data interpretation if the contributing sensors have a perception component or if data are delivered to an agent via another perception engine (e.g., visual recognition based on deep learning).
- Known data provenance and integrity.
- Dynamic anomaly detection in data streams during operations.
- Comprehensive uncertainty quantification (UQ) of data from a single source.
- Data fusion and combined UQ, if multiple sources of data are used for decision-making.
- If data from either a single source or fused data from multiple sources are used for decision-making by an agent (human or machine), the data and the attendant UQ must be transformed into a representation conducive to and productive for decision-making. This may include data filtering, compression, or expansion, among other approaches.
- UQ must be accompanied by a sensitivity analysis of the mission/operation/action
goals with respect to uncertainties in various data, to enable appropriate risk estimation and risk-based decision-making by relevant agents, human or machine.

- Tools for real-time, a priori, and aposteriori data analysis, with explanations relevant to participating agents. For instance, if machine learning is used for visual data perception in decision-making by humans, methods of interpretable or explainable AI (XAI) may be in order.

We note that deep learning and machine learning, in general, are not the chief focus of this subtopic. The techniques are mentioned as an example of tools that may participate in data processing. If such tools are used, the representation of the results to decision-makers (human or machine) must be suitably interpretable and equipped with UQ.

Addressing the entire set of the conditions listed above would likely be impractical in a single proposal. Therefore, proposers may offer methods and tools for addressing a subset of conditions.

Proposers should offer both a general approach to achieving a chosen subset of the listed conditions and a specific application of the general approach to appropriate data types. The future orbiting or surface stations are potential example platforms, because the environment would include a variety of autonomous systems used for habitat maintenance when the station is uninhabited, continual system health management, crew health, robotic assembly, and cyber security, among other functions. However, the proposers may choose any relevant design reference mission for demonstration of proposed approaches to integrated data uncertainty management and representation, subject to a convincing substantiation of the generalizability and scalability of the approach to relevant practical systems, missions, and environments.

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

**Primary Technology Taxonomy:**
- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.1 Situational and Self Awareness

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

- Research
- Analysis
- Software

**Desired Deliverables Description:**

Since UQ and management in data is an overarching theme in this subtopic, an analysis of uncertainties in the processes and data must be present in all final deliverables, both in Phases I and II.

**Phase I:** For the areas selected in the proposal, the following deliverables would be in order:

1. Thorough but succinct analysis of the state of the art in the proposed area under investigation.
2. Detailed description of the problem used as the context for algorithm development, including substantiation for why this is a representative problem for a set of applications relevant to NASA missions.
3. Detailed description of the approach, including pseudocode, and the attendant design of experiments for testing and evaluation.
4. Hypotheses about the scalability and generalizability of the proposed approach.
realistic problems relevant to NASA missions.
5. Preliminary software and process implementation.
6. Preliminary demonstration of the software.
7. Thorough analysis of performance and gaps.
8. Detailed plan for Phase II, including the design reference mission and the attendant technical problem.
9. Items 1 to 8 documented in a final report for Phase I.

Phase II:

1. Detailed description and analysis of the design reference mission and the technical problem selected in Phase I, in collaboration with NASA Contracting Officer Representative (COR)/Technical Monitor (TM).
2. Detailed description of the approach/algorithms developed further for application to the Phase II design reference mission and problem, including pseudocode, and the design of experiments for testing and evaluation.
3. Demonstration of the algorithms, software, methods, and processes.
4. Thorough analysis of performance and gaps, including scalability and applicability to NASA missions.
5. Resulting code.
6. Detailed plan for potential Phase III.
7. Items 1 to 5 documented in a final report for Phase II.

State of the Art and Critical Gaps:

Despite progress in real-time data analytics, serious gaps remain that will present an obstacle to the operation of systems in NASA missions that require heavy participation of autonomous systems, both in human-machine teams and in uncrewed environments, whether temporary or permanent. The gaps come under two main categories:

1. Quality of the information based on various data sources—Trustworthiness of the data is essential in making decisions with desired outcomes. This gap can be summarized as the lack of reliable and actionable UQ associated with data, as well as the difficulty of detecting anomalies in data and combining data from disparate sources, ensuring appropriate quality of the result.
2. Representation of the data to decision-makers (human or machine) that is conducive to trustworthy decision-making—We distinguish raw data from useful information of appropriate complexity and form. Transforming data, single-source or fused, into information productive for decision-making, especially by humans, is a challenge.

Specific gaps are listed under the Scope Description as conditions the subsets of which must be addressed by proposers.

Relevance / Science Traceability:

The technologies developed as a result of this subtopic would be directly applicable to the Space Technology Mission Directorate (STMD), Science Mission Directorate (SMD), Human Exploration and Operations Mission Directorate (HEOMD), and Aeronautics Research Mission Directorate (ARMD), as all of these mission directorates
are heavy users of data and growing users of autonomous systems. For instance, the Gateway mission will need a significant presence of autonomous systems, as well as human-machine team operations that rely on autonomous systems for habitat maintenance when the station is uninhabited, continual system health management, crew health, robotic assembly, among other functions. Human presence on the Moon surface will require similar functions, as well as future missions to Mars. All trustworthy decision-making relies on trustworthy data. This topic addresses gaps in data trustworthiness, as well as productive data representation to human-machine teams for sound decision-making.

The subtopic is also directly applicable to ARMD missions and goals, because future airspace will heavily rely on autonomous systems. Thus, the subtopic is applicable to such projects as Airspace Operations and Safety Program (AOSP)/Advanced Air Mobility (AAM) and Air Traffic Management—eXploration ATM-X. The technologies developed as a result of this subtopic would be applicable to the National Airspace System (NAS) in the near future as well, because of the need to process data related to vehicle and system performance.

References:

- Frontiers on Massive Data Analysis, NRC, 2013
- NASA OCT Technology Roadmap, NASA, 2015
- Planetary Science Informatics and Data Analytics Conference, April 2018
and 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. NASA is also interested in digital assistants for operators and crew to improve safety and efficiency of facilities and vehicles. 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), and business or administrative. Digital assistants can fall into one of two categories: productivity multipliers and new capabilities. Productivity multipliers reduce the time that the engineer, scientist, facility operator, and vehicle crew member spend on tasks defined by NASA policies, procedures, standards and handbooks, on common and best practices in science and engineering domains within the scope of NASA’s missions, on standard operating procedures, on maintenance and troubleshooting, or on search and transformation of scientific and technical information. Proposals for productivity multipliers should demonstrate an in-depth understanding of NASA workflows and information needs for science, engineering, or operations. New capabilities are disruptive transformations of NASA’s engineering, science, facility, or vehicle environments that enable technological advances infeasible or too costly under current paradigms. Proposals for new capabilities should show clear applicability to NASA’s missions. Moreover, proposals relying on natural language processing (NLP) of scientific and technical information should demonstrate capability or define a work plan to train NLP algorithms for technical and scientific terms that are in common use within NASA or within a science and engineering discipline. Proposals targeting digital assistants for crew must be deployable to hardware meeting space, weight, and power (SWaP) constraints typical for the vehicle(s) of interest. Furthermore, digital assistants for spacecraft must execute all functions onboard and cannot rely on ground systems to function. Additionally, digital assistants should be hands free especially for activities where crew are wearing spacesuits or are using their hands such as performing maintenance tasks. Examples of potential digital assistants include but are not limited to:

- A digital assistant that uses the semantic, numeric, and graphical content of engineering artifacts (e.g., requirements, design, and 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 nonfunctional 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 or the crew of a vehicle. 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, and 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.).

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

**Primary Technology Taxonomy:**
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.4 Information Processing

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

- Prototype
- Hardware
- Software
Desired Deliverables Description:

The Phase I deliverable can be a detailed architecture for a digital assistant with supporting analysis or a set of individual or integrated software functions that substantiate features of the digital assistant considered key or high risk. 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 also to 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 more generally applied to the activities performed by engineers and scientists and made more easily accessible through technologies like speech recognition.

References:

- CIMON "Crew Interactive Mobile Companion"
  - https://www.nasa.gov/mediacast/space-to-ground-meet-cimon-07062018 [69]
  - https://www.space.com/41041-artificial-intelligence-cimon-space-exploration.html [70]
[71]

- Rohaidi, N., "How NASA Uses AI on Mars," GovInsider, [73], January 31, 2018
- Soderstrom, T., "A peek at artificial intelligence in action at NASA Jet Propulsion Laboratory," The Enterprisers Project, [74], May 9, 2019

T11.05 Model-Based Enterprise

Lead Center: ARC

Participating Center(s): HQ, LaRC, MSFC, SSC

Scope Title:

Model-Based Enterprise, Digitally interacting comprehensive frameworks and models, and Automated Decision-Making for Agency Operations

Scope Description:

Model-based enterprise targets the use of models in any function, from engineering to safety to finance to facilities and more (i.e., Model-based "Anything" or MBx), to enable high-complexity decision making embodying agile processes to achieve efficiency, accuracy, confidence, and adaptability in support of NASA’s mission, programmatic development, and institutional activities.

Consider the implementation of Model-based Institutional Management, as an example, where outputs from one functional model become real-time inputs to another functional model, resulting in a digital workflow for knowledge transfer and holistic decision making; thus enabling transformative gains in engineering, institutional, and management practices. Ultimately, functional area models will be digitally integrated to form a model-based enterprise.

NASA is seeking specific innovative, transformational, model-based solutions in the area of “Digital Twin” Institutional Management of Health/Automated Decision Support of Agency Facilities that would greatly enhance operational efficiencies, the quality and robustness and trustworthiness of information, the ability to identify and analyze risks earlier, and the overall velocity and robustness of knowledge transfer and decision making across the Agency, including interactions with internal/external partners and supply chain that are made possible through overarching an MBx Digital Twin Enterprise model(s).

Health/Automated Decision Support of Agency Facilities represents an opportunity to make revolutionary changes in how our Agency conducts business by investing in nascent technologies. The Agency’s newly minted Digital Transformation Office is interested in how this initiative can help reposition and accelerate the modernization of digital systems that support modern approaches to managing the Agency’s aging infrastructure.

Recent initiatives in "smart city" technologies focus on condition-based/preventive maintenance, smart buildings and smart lighting, autonomous transportation and traffic management, industrial automation, etc. As we mature our understanding and make progress toward these ends at individual centers, we need to align our efforts and
share lessons learned to help expedite NASA's learning curve.

Smart city technologies often rely on interconnected systems and interoperability of those systems, making it all the more important that we have a common approach and standards (e.g., around information technology (IT)/operational technology (OT) network architecture, communication protocols, and data management) to ensure interoperability of systems within and across centers. Without a cohesive approach, we risk limiting what NASA can achieve in terms of economies of scale and affordability, as well as interorganizational data integration.

The STTR vehicle offers the small business community an opportunity to have a hand in this process towards repositioning and accelerating the modernization of digital systems supporting the Agency's aging infrastructure to:

Save energy costs due to water and electricity usage that is poorly measured and managed.

Enable the deployment of nascent technological trends in data-driven decision making and support tools based upon statistical methods to help streamline and improve the efficiency of facility operations and maintenance activities.

Explore recent technologies in modeling (e.g., digital twin techniques). Explore how we can take advantage of the proliferation of emerging technologies, use a structured measurement and verification technique in and aim to vet them to determine if they will bring sufficient value, and broadly deploy them across the Agency if proven effective.

Set up a "proving ground," model, in the same spirit as GSA's emerging building technologies program [75]. Determine how well technologies using this model can be broadly deployed across NASA.

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

Primary Technology Taxonomy:
- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables—Reports identifying use cases, proposed tool views/capabilities, identification of NASA or industry leveraging and/or integration opportunities, test data from proof-of-concept studies, and designs for Phase II.

Phase II Deliverables—Delivery of models/tools/platform prototypes that demonstrate capabilities or performance
over the range of NASA target areas identified in use cases. Working integrated software framework capable of
direct compatibility with existing programmatic tools.

State of the Art and Critical Gaps:

Outside of NASA, industry is rapidly advancing Model-Based Systems Engineering (MBSE) tools and scaling them
to larger, more complex development activities. Industry sees scaling as a natural extension of their ongoing
digitization efforts. These scaling and extension efforts will result in reusable, validated libraries containing models,
model fragments, patterns, contextualized data, etc. They will enable the ability to build upon, transform, and
synthesize new concepts and missions, which has great attraction to both industry and government alike. Real-time
collaboration and refinement of these validated libraries into either “single source” or “authoritative sources” of
truth provide further appeal as usable knowledge can be pulled together much more quickly from a far wider
breadth of available knowledge than was ever available before.

One example of industry applying MB/MBe/MBSE is through Digital Thread™, a communication framework that
helps facilitate an integrated view and connected data flow of the product’s data throughout its life cycle. In other
words, it helps deliver the right information at the right time and at the right place. Creating an “identical” copy
(sometimes referred to as a “digital twin”) is another use, a digital replica of potential and actual physical assets,
processes, people, places, systems, and devices that can be used for various purposes. These twins are used to
conduct virtual cost/technical trade studies, virtual testing, virtual qualification, etc., that are made possible through
an integrated model-based network. Given the rise of MBSE in industry, NASA will need to keep pace in order to
continue to communicate with industry, manage and monitor supply chain activities, and continue to provide
leadership in spaceflight development.

Within NASA, our organization is faced with increasingly complex problems that require better, timelier, integration,
and synthesis of both models and larger sets of data, not only in the systems engineering or MBSE realm, but in
the broader MB Institution, MB Mission Management, and MB Enterprise Architecture. NASA is challenged to sift
through and pull out the particular pieces of information needed for specific functions, as well as to ensure
requirements are traced into designs, tested, and delivered; thus, confirming that the Agency gets what it has paid
for. On a broader cross-agency scale, we need to ensure that needed information is available to support critical
decisions in a timely and cost-effective manner. All of these challenges are addressed through the benefits of
model-based approaches. Practices such as reusability, common sources of data, and validated libraries of
authoritative information become the norm, not the exception, using an integrated, model-based environment. This
model-based environment will contribute to a diverse, distributed business model encompassing multicenter and
government-industry partnerships as the normal way of doing business.

Relevance / Science Traceability:

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

References:

1. https://www.sae.org/standards/content/as9100/ [76]
2. https://www.nasa.gov/offices/FRED [77]
4. https://OpenMBEE.org [79]
5. https://sercuarc.org/project/?id=64&project=Formal+Methods+in+Resilient+Systems+Design+using+a+Flexible+Co
   ntract+Approach [80]
T12.05 Use of Additive Manufacturing for Thermal Protection Systems

Lead Center: JSC

Participating Center(s): ARC, GSFC, LaRC

Scope Title:

Use of Additive Manufacturing for Thermal Protection Systems

Scope Description:

Background

NASA has a need to significantly improve the manufacturing processes of Thermal Protection Systems (TPS) used on human-rated spacecraft and robotic missions 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 (AM) techniques are needed such that both spacecraft TPS and structures can be manufactured with automated systems. Furthermore, a future capability to use AM to fabricate and repair TPS in space will be needed. Basic requirements and goals for the development of this technology are provided in this solicitation.

Objectives

The overall objective is to develop the materials and compatible AM technologies to automate the fabrication of an integrated spacecraft structure and TPS. There are two approaches to designing the spacecraft aeroshell: (1) parasitic TPS: design and fabricate the flight structure and apply the thermal protection to the structure surface and (2) integrated aeroshell: design and fabricate a high-temperature flight structure that forms the outer mold line and apply insulative thermal protection to the inner surfaces of the structure. Both of these approaches are of interest to NASA and have applications to future NASA missions.

For the first approach, the objective for this solicitation is to develop the materials and processes to deposit and adhere the thermal protection to an existing structure. It can be assumed that the structure has already been designed and fabricated. For the second approach, the objective is to develop the materials and processes to fabricate both the high-temperature structure and the integrated, internal insulation. The proposer should select one of the design approaches to address.

The intent of this solicitation is to develop the materials and technologies for automating the fabrication and integration of a thermal protection onto a spacecraft. Therefore, NASA is not interested in materials and methods to fabricate a better block of material that would need to be manually bonded onto a structure with gaps between the blocks.

Material Characteristics

AM has the potential to provide capabilities to design a material to achieve the desired properties and to vary the material constituents during the fabrication process. Fibers can be added and aligned to obtain desired mechanical and thermal properties. Additives can be used to reduce density and modify other key properties and to aid the fabrication process. Although it is not a requirement for this solicitation, material systems that have a potential
future development path for reusability are desirable.

The desired material properties depend on the spacecraft flight regime and the aeroshell design approach. For the purpose of this solicitation, three TPS options have been defined and the approximate desired material properties provided.

Low-Density, Low Heat Flux (<60 W/cm$^2$) Parasitic TPS:

- Density ~0.3 g/cc (or lower)
- CTE <5×10$^{-6}$ 1/°F
- Through-the-thickness thermal conductivity <0.1 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength >1.3 MPa

High Heat Flux (100 to 600 W/cm$^2$) Parasitic TPS:

- Density ~0.6 g/cc (or lower)
- CTE <5×10$^{-6}$ 1/°F
- Through-the-thickness thermal conductivity <0.2 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength >3 MPa
- Char yield >50%

Moderate Heat Flux (>200 W/cm$^2$) Integrated Aeroshell:

- Density: Structure ~1.5 g/cc; Insulation 0.3 to 0.5 g/cc
- CTE <5×10$^{-6}$ 1/°F
- Through-the-thickness thermal conductivity: Structure ~5 W/m/K; Insulation: <0.1 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength: Structure >120 MPa; Insulation: >1.3 MPa
- Char yield >50%

Since additive manufacturing techniques provide the capability to vary the material during fabrication, combinations of the materials in a single system is of interest. For example, a system may consist of an outer layer of High Heat Flux Parasitic TPS and then transition to a low-density, low heat flux material closer to the structure. The proposer can select one or a combination of the material categories to address in their proposal.

In order to achieve the desired properties and inhibit material failure in high aerodynamic shear environments, strategies that print a honeycomb or iso-grid reinforcement with filled cells may also be considered.

Printing and Curing Approach

The selected printing approach must be capable of fabricating the TPS using the selected materials and with limited manual intervention. The system must be scalable to fabricate TPS for flat and curved surfaces for vehicles several meters in diameter. A significant concern for all of the printed and cured materials is large porosity and voids. The proposer should describe controls to minimize these defects. Defects can be controlled by material and cure process selection and/or by print techniques. Print technique controls could include rollers/deflectors to consolidate the material and/or sensors and feedback loops during printing.

Material curing, depending on the resin system, is often achieved by a thermal cycle in an oven. For this solicitation, oven cures are acceptable as long as the thermal cycle does not exceed 180 °C for the parasitic TPS. This constraint is driven by temperature limits on the flight structure. If curing is needed, it is highly desirable to cure the material in situ using the material chemistry, local heating, laser sintering, or ultraviolet/radiofrequency energy.

The high-level goals for a scaled-up TPS additive manufacturing system are provided below.

1. System should include all of the elements for the entire workflow from material formulation to fabrication
and final finishing and print quality controls.

2. System functions should be automated with minimal manual processes such that it can be operated by fewer than three technicians.
3. Post-print processing should be minimized.
4. For parasitic TPS, a 5-m-diameter dome should be completely fabricated within 1 month; 3 months for an integrated aeroshell of this size.

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

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

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:

During Phase I, the proposer should:

1. Develop the conceptual design of the entire manufacturing process tailored to the appropriate feed-stock proposed.
2. Demonstrate the capability to fabricate using AM the candidate materials.
3. Conduct material property tests and compare to goals.
4. Conduct aerothermal tests of the printed material.
5. Deliver to NASA small test articles for testing.

During Phase II, the proposer should:

1. Design and assemble a prototype automated system to fabricate the TPS.
2. Demonstrate the capability to fabricate the TPS for nonplanar surfaces.
3. Conduct material property tests for larger range of conditions.
4. Conduct integrated TPS/structure tests such as flexure tests.
5. Conduct aerothermal tests of the printed material.

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 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.

References:
T12.06 Extensible Modeling of Additive Manufacturing Processes

Lead Center: JPL

Scope Title:

Process Modeling of Additive Manufacturing

Scope Description:

The subtopic of modeling of additive processes is highly relevant to NASA as the Agency is currently on a path to implement additive processes in spaceflight 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 spaceflight 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 multifunctional 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 microstructures 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 and 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.

Expected TRL or TRL Range at completion of the Project: 1 to 2

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

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

- A functional process model covering the specific area by the proposer, using open source or code shared with the Agency. The deliverables can be either stand-alone software or modules for existing, commercially available software.
- The Phase I deliverable should be preliminary modeling results, an accurate description of the software with
revision tracking, and an architecture plan demonstrating the output data (if stand-alone software) or modularity (if the software connects to commercially existing products).

- The Phase II deliverable should be a copy of the software, along with modeling results, as well as a final report stating relevant data, such as boundary conditions, assumptions, process simplifications used for quicker computing, etc. The output data should be in a clearly defined format with a clear description and discussion of how it can be imported into other modeling tools used for additive manufacturing, to create a truly extensible framework. If the product is a module for existing software, then the final report should demonstrate functionality with that software (including computing elements required, version of the software, etc.) and that the results can feed into other aspects of the commercially available software.

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

Additive manufacturing will be used for spaceflight 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 and 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.

**References:**

Stranza, M. et al., Materials Letters, accepted [https://doi.org/10.1016/j.matlet.2018.07.141](https://doi.org/10.1016/j.matlet.2018.07.141) [84]


Keller, T., et al., Acta Materiala [https://doi.org/10.1016/j.actamat.2017.05.003](https://doi.org/10.1016/j.actamat.2017.05.003) [85]

**T12.07 Design Tools for Advanced Tailorable Composites**

Lead Center: JSC

Participating Center(s): MSFC

**Scope Title:**

Design Tools for Advanced Tailorable Composites

**Scope Description:**
Affordable space exploration beyond the lower Earth orbit will require innovative lightweight structural concepts. Use of composite material systems is one of the means of lightweighting exploration vehicles, space habitats, and other space hardware. Lightweighting potential stemming from application of composite materials oftentimes fails to fully exploit the potential for reducing mass due to the lack of design tools tailored to yield designs with optimal load paths. Consequently, highly tailorable material systems are commonly used to produce quasi-isotropic (“black aluminum”) or otherwise off-optimal designs.

This solicitation seeks to advance the design capabilities for layered pre-impregnated composite materials reinforced with either continuous or short fibers and with a wide variety of ply thicknesses, from ultrathin (with the fiber areal weight in single digits when expressed in grams per square meter (gsm)), to standard (approx. in the 145- to 190-gsm range). A design tool development and its demonstration to a relevant structure is sought. The design tool shall be developed leveraging the broadly adopted and accessible engineering codes including but not limited to MSC.Patran/Nastran, Abaqus, Hypersizer, Hyperworks, LS-OPT, etc. Development in a form of “wrapper” or “plug-in” codes is strongly preferred over redeveloping functionalities that readily exist and can be incorporated within the design tool. Intuitive user-friendly code interfaces for the design definition set up are also highly desirable.

Demonstration problems of interest include fiber-steered or otherwise highly tailored structural designs representative of cryogenic tanks, pressurized habitats, and other primary space structure components, including dry and unpressurized, such as lander truss cages or landing gears. Advantages of a new highly tailored composite design shall be demonstrated by its weight-saving potential over a legacy/conventional design while observing typical manufacturability constraints (determined, e.g., based on a literature survey). Other aspects, such as improved damage tolerance, extended service time, reusability, lower cost, or multifunctionality are also considered significant. Demonstration of improved performance of a highly tailored design relative to a conventional composite design (e.g., black aluminum approach) satisfies the requirements of this solicitation. However, comparisons to the metallic designs are also of interest as they ultimately can demonstrate the design goodness progression in the three-element series involving metallic, conventional composite, and highly tailored composite designs. Examples of relevant applications include but are not limited to current vehicle architectures being constrained for the return to the Moon missions are to fit within a 15-ft-diameter shroud, thus tank and habitat maximum dimensions are likely on the order of this 15-ft-diameter constraint. For tanks, nominal operating pressures in the range of 40 to 65 psi are considered common. The internal pressures for habitats can be guided by the International Space Station’s internal pressure of 14.7 psi.

While a global-local analysis might be beneficial and warranted in the overall design process, demonstration problems can include smaller structural components, such as hardpoint attachment brackets, fittings, clevises, etc. Ability of the proposed design approach and related code to tailor not only general sections/acreages but also highly discontinuous sections of primary structures, such as hatches, windows, or hardpoint attachments present within the thin-wall overall architecture are highly sought features of the proposed design tool.

Expected TRL or TRL Range at completion of the Project: 5 to 6
Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures
Desired Deliverables of Phase I and Phase II:

- Analysis
- Software
- Research
Desired Deliverables Description:

Phase I of the award shall deliver a proposed implementation of the design tool with a functioning code, however, its capabilities can be truncated relative to the overall proposed development. The truncated code shall include enough capabilities to be able to produce a simplified demonstration case that would also constitute a part of the Phase I deliverable. The Phase II deliverable shall include a releasable version of the design tool with the complete proposed functionality and a refined demonstration study case. For both Phase I and II developments, an open code architecture is of value such that the end users can gain insight into the implementation and possibly alter or add functionalities. From a practical standpoint, use of Python in conjunction with Abaqus implementation or PCL in conjunction with MSC.Patran/Nastran implementation might be considered examples of “open architectures.” Use of an existing design optimization tool, for example, LSOPT, is also allowed and encouraged.

State of the Art and Critical Gaps:

Present composite designs are typically limited to straight fiber arrangements and lamination stacking sequences resulting in quasi-isotropic material properties. No commercially available design tools exist to produce advanced highly tailorable designs with optimized load paths.

Relevance / Science Traceability:

Examples of potential uses include: Space Technology Mission Directorate, Artemis/HLS programs, developers of air-launched systems (e.g., Generation Orbit Launch Services; Aeronautics Research Mission Directorate) next-generation airframe technology beyond "tube and wing" configurations (e.g., hybrid/blended wing body).

References:


T13.01 Intelligent Sensor Systems

Lead Center: SSC

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 advanced instruments should function as a modular node in a sensor network, capable of performing some processing, gathering sensory information, and communicating with other connected nodes in the network. The collected sensor network must be capable of integration with data from conventional data acquisition systems adhering to strict calibration and timing standards to support static propulsion system testing standards. Synchronization with Inter-Range Instrumentation Group—Time Code Format B (IRIG-B) and National Institute of Standards and Technology (NIST) traceability is critical to propulsion test data analysis.

Rocket propulsion test facilities also provide excellent testbeds for testing and using the innovative technologies for possible application beyond the static propulsion testing environment. 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. It is envisioned these advanced instrumentation would support sensing and control applications beyond those of propulsion testing. For example, inclusion of expert system or artificial intelligence technologies might provide great benefits for autonomous operations, health monitoring, or self-maintaining systems.

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 NIST traceability.
- Collected data must be time-stamped to facilitate analysis with other collected datasets.
- Transfer data in real time to other systems for monitoring and analysis.
- Interface to flight-qualified sensor systems, which could be used for multivehicle 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, autoconfiguring method of collecting data from multiple sensors, and relaying for integration with other acquired datasets.
• 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.

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.1 Infrastructure Optimization

Desired Deliverables of Phase I and Phase II:

• Prototype
• Hardware
• Software

Desired Deliverables Description:

For all above technologies, research should be conducted to demonstrate technical feasibility with a final report at 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 and 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. It supports all test programs at Stennis Space Center (SSC) and other propulsion system development centers, and potential advocates are the Rocket Propulsion Test (RPT) Program Office and all rocket propulsion test programs at SSC.

References:

7. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040053475.pdf [87]
8. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090026441.pdf [88]

T14.01 Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage

Lead Center: GRC

Participating Center(s): JSC

Scope Title:
Scope Description:

This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, and 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:

- A piecewise-smooth set of correlations for use in lumped node codes that models the complete cryogenic pool boiling curve for heat transfer between fluid and wall encountered in cryogenic storage (e.g., hot spots along the tank wall) or transfer systems. Six submodels should be developed, including (1) onset of nucleate boiling, (2) nucleate boiling heat transfer coefficient (HTC), (3) critical heat flux (CHF), (4) transition boiling HTC, (5) Leidenfrost point, and (6) film boiling HTC. There should be seamless coupling between all five submodels such that the boiling curve is a smooth function (heat flux as a function of wall superheat). Both quenching and heating configurations must be modeled. The model must be anchored to experimental cryogenic pool boiling data for helium, hydrogen, argon, nitrogen, oxygen, and methane. The complete cryogenic pool boiling model should be validated against cryogenic experimental data across the range of fluids, with a target accuracy of 25%. The quenching and heating pool boiling models and implementation scheme should be a deliverable. Phase I should have an emphasis on developing the CHF model for all cryogens while Phase II should include the remaining five models as well as microgravity applications.

- 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 a demonstration, perhaps using simulant or similar fluids.

- Advance nonliquid 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 cislunar 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 the art, the deliverable test article will support an electrical current density of at least 300 mA/cm² for at least 500 hr, support transient currents >750 mA/cm² for at least 30 sec, and support slew 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 hr 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 [50]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will
be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

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

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

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

- Hardware
- Software
- Prototype

**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 to 3,015 psia as possible to illustrate the potential viability range for lunar applications.

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

Cryogenic Fluid Management (CFM) 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 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. There are no complete cryogenic data-based pool boiling curves for propellants of interest.

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; CFM 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 the art for specific applications such as ISRU, lunar fuel cell power systems, or regenerative fuel cell energy storage systems. As 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 offline without active thermal control. This would enable a longer period between missions to refuel and recover the electrochemical system.

References:

3. NASA Technology roadmap (https://gameon.nasa.gov/about/space-technology-roadmap/[91]), §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.)

T15.04 Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations

Lead Center: AFRC

Participating Center(s): ARC, GRC, LaRC

Scope Title:

Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations

Scope Description:

NASA's Aeronautics Research Mission Directorate (ARMD) laid out a 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 that NASA will invest in 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 airspace. In response to the recently updated Strategic Thrust #4 (Safe, Quiet, and Affordable Vertical Lift Air Vehicles), a new subtopic titled “Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations” is being introduced.

Proposals are sought in the following areas: (1) design and execution of experiments to gather research-quality data to validate aerodynamic and acoustic modeling of full-scale, multirotor eVTOL aircraft, with an emphasis on rotor-rotor interactions and (2) development and validation of scaling methods for extending and applying the results of instrumented subscale model testing to full-scale applications. This solicitation does not seek proposals for designs or experiments that do not address full-scale eVTOL applications. Full-scale (2+ passenger) is defined as a payload capacity equivalent to two or more passengers, including any combination of pilots, passengers, or ballast.
Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Hardware
- Analysis
- Research
- Prototype

Desired Deliverables Description:

Expected deliverables of Phase I awards may include but are not limited to:

- Initial experiment test plans for gathering experimental results related to the aerodynamic and/or acoustic characteristics of a multirotor eVTOL aircraft, with an emphasis on interactions between rotors and between the rotors and the vehicle structure for either
  - a full-scale flight vehicle
  - a subscale vehicle with fully developed methods for scaling the results to full scale
- Expected results for the flight experiment using appropriate design and analysis tools.
- Design (CAD, OpenVSP, etc.) and performance models for the vehicle used to generate the expected results.
- Preliminary design of the instrumentation and data recording systems to be used for the experiment.
- Awardee may also provide kickoff, midterm, and final briefings as well as a final report.

Expected deliverables of Phase II awards may include but are not limited to:

- Experimental results that capture aerodynamic and/or acoustic characteristics of a multirotor eVTOL aircraft, with an emphasis on interactions between rotors and between the rotors and the vehicle structure for either:
  - a full-scale flight vehicle
  - a subscale vehicle with results extrapolated to full scale
- Design (CAD, OpenVSP, etc.) and performance models for the experimental vehicle.
- Experimental data along with associated as-run test plans and procedures.
- Details on the instrumentation and data logging systems used to gather experimental data.
- Comparisons between predicted and measured results.
- Awardee may also provide kickoff, midterm, and final briefings as well as a final report.

State of the Art and Critical Gaps:

Integration of Distributed Electric Propulsion (DEP) (4+ rotors) systems into Advanced Air Mobility eVTOL 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. Addressing ARMD’s Strategic Thrust #1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles), and #4 (Safe, Quiet, and Affordable Vertical Lift Air Vehicles) innovative approaches in designing and analyzing highly integrated DEP eVTOL aircraft are needed to reduce the energy use, noise, emissions, and safety concerns. Due to the rapid advances in DEP-enabling technologies, the current state-of-the-art design and analysis tools lack sufficient validation against full-scale eVTOL flight vehicles. This is especially true in the areas of aerodynamics and acoustics.
Relevance / Science Traceability:

The proposed subtopic supports ARMD’s Strategic Thrust #4 (Safe, Quiet, and Affordable Vertical Lift Air Vehicles). Specifically, the following ARMD program and project are highly relevant.

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

- Revolutionary Vertical Lift Technology (RVLT) project

References:

- ARMD/Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt [93]
- ARMD/Revolutionary Vertical Lift Technology (RVLT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt [94]
- ARMD/Convergent Aeronautics Solutions (CAS) Project: https://www.nasa.gov/aeroresearch/programs/tacp/cas [95]
- ARMD/University Innovation (UI) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ui [97]
- ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy [98]
- ARMD Urban Air Mobility Grand Challenge: https://www.nasa.gov/uamgc [99]