National Aeronautics and Space Administration

2020 NASA Technology Taxonomy

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CONTENTS

Letter from the Chief Technologist

"And as we renew our commitment to lead in space, let's go with confidence and let's go with faith. Faith in the vision and the goal that's articulated today: that we can achieve it; that Americans can achieve anything that we put our minds to. Faith in the extraordinary ingenuity and capability of the men and women of NASA and America's space enterprise, and their ability to meet those challenges if given the resources and the support to do it. And especially faith in the courage of the men and women who are now, and those who will join, the storied ranks of American astronauts—that next generation of restless pioneers that will carry American leadership into space. It's extraordinary to think of the heroes that will be forged in our renewed commitment to space." – Vice President Michael Pence

As NASA embarks on its renewed commitment to lead in space, we must overcome significant technical challenges to achieve the goal of a sustainable return to the surface of the Moon. We will build on six decades of leadership in space and our work in low-Earth orbit to pave the way to the Moon and on to Mars. The Artemis program will carry the first woman and next man to the Moon, and establish sustainable exploration with our commercial and international partners. NASA is pursuing an ambitious program to explore our solar system and beyond. Key priorities include a Mars Sample Return mission, launch of the James Webb Space Telescope and a robust program of Earth observation. In addition, our transformative aeronautics technology research is making air travel safer and more efficient, and pioneering the next generation of aircraft.

American ingenuity and innovation will be critical to the development of new technologies necessary to achieve NASA's important missions. As NASA undertakes an integrated technology research and development effort, a common technology taxonomy is more important than ever. For this reason, the *2020 NASA Technology Taxonomy* was created as an important update to the Technology Area Breakdown Structure (TABS) from the roadmaps of previous years.

The *2020 Taxonomy* is an update to the 2015 TABS. This new edition builds on previous releases and the insight from subject matter experts from across the Agency. The *2020 Taxonomy* has expanded the total number of technology areas to 17 and consolidated other areas. The update reflects a shift to a structure that aligns technology areas based on technical disciplines. The updates also include new technologies relevant to NASA, such as cybersecurity and advancements in artificial intelligence.

The technology Taxonomy is key to NASA's ability to manage and communicate its technology portfolio by providing a structure for articulating the diverse technologies relevant to NASA's mission. Together, NASA and its partners in other government agencies, international space agencies, academia, and industry, will pave the way to new frontiers in space and aeronautics.

Douglas Terrier
Chief Technologist

Introduction

NASA engages in a multitude of technology development activities to enable NASA missions by broadening knowledge of and capabilities in aeronautics, science, and space. To manage and communicate this extensive and diverse technology portfolio, NASA uses a technology taxonomy. This taxonomy identifies, organizes, and communicates the technology areas that NASA advances in order to achieve future space missions and aeronautics activities.

The 2020 NASA Technology Taxonomy is an update to the Technology Area Breakdown Structure (TABS) of the 2015 NASA Technology Roadmaps. The TABS, now referred to as the taxonomy, is deeply ingrained within NASA documentation, TechPort, solicitations, websites, and many other places domestically and internationally. In particular, the taxonomy provides a structure for articulating NASA's technology portfolio, which is key to NASA's ability to manage and communicate its technology development efforts.

The 2020 NASA Technology Taxonomy

NASA continues to push the boundaries of space missions and aeronautics activities, pursuing challenging goals that require advanced technological capabilities. Progressively ambitious space exploration presents challenges such as sustaining a human presence in space, efficiently navigating to previously inaccessible locations, and communicating over unprecedented distances. For aeronautics, increasing air traffic presents the need for next generation air traffic control; high fidelity, integrated, distributed simulation systems; and next generation vehicles that reduce noise and carbon output. Solutions to these and many other technical challenges require innovative technology development across many areas, building on proven capabilities as well as developing new ones.

The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The taxonomy identifies, categorizes, and communicates the technology areas relevant to advancing the Agency's mission. The 2020 revision is comprised of 17 distinct technical discipline based Taxonomies (TXs) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types. Level 1 represents the technology area, which is the title of that area (e.g. TX01: Propulsion Systems). Level 2 is a list of the subareas (e.g. TX01.1 Chemical Space Propulsion). Level 3 categorizes the types of technologies within the subareas (e.g. TX1.1.1 Integrated Systems and Ancillary Technologies). Also included is an example technologies section that provides a non-exhaustive sample of relevant technologies.

The taxonomy is a foundational element of NASA's technology management process. NASA's Mission Directorates (MDs) reference the taxonomy to solicit technology proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments. These investments are tracked in TechPort, a publically available web-based software system that serves as NASA's integrated Agency technology data source and decision support tool. TechPort uses the taxonomy in organizing the numerous, varied technology projects that NASA supports.

History

The 2020 NASA Technology Taxonomy is part of an evolution that began with the original roadmaps and TABS drafted in 2010, followed by updates in 2012 and 2015.

The effort to develop the roadmaps began in 2010 when NASA identified 14 Space Technology Areas, including top technical challenges and relevant

spaceflight missions. NASA publicly distributed a set of draft roadmaps that included the original TABS in December 2010. The National Research Council (NRC) conducted a review and released a final report, NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, early in 2012. The final versions of the roadmaps and related TABS were released to the public in April 2012.

The 2015 Technology Roadmaps enhanced and expanded the TABS of the 2012 Roadmaps, responding to NASA's changing needs, advances in technology, and recommended improvements from the NRC and other stakeholders. NASA began the effort to update the Technology Roadmaps by determining how the development process, roadmap scope, and roadmap content could be improved. NASA gathered input from the NASA Technology Executive Council (NTEC), a 2013 Technical Interchange Meeting, and the NASA Center Technology Council (CTC). Using the decisions from the NTEC, and the input from the CTC and external stakeholders, NASA made improvements to the development process and the roadmaps content and format.

In 2014, the Technology Roadmap development team was formed with members from across the Agency to create new draft TABS and roadmaps. As the draft roadmaps were developed, NASA held meetings with other government agencies to obtain insights and assess the technology candidates. The roadmaps went through an internal NASA review in the spring of 2015, with a release to the public for review and comment. These roadmaps and their TABS included several improvements such as an expanded scope and greater standardization.

The 2020 revision process began in 2017 and was led by NASA's CTC, along with the Office of the Chief Technologist (OCT) and subject matter experts (SMEs) from across the Agency with a review of the 2015 TABS. In addition, a survey of the 2015 Technology Roadmaps user community was conducted to provide insight on how the 2015 Roadmaps were being used. Based on the assessment, it was decided that the 2020 revision would decouple the TABS from the roadmaps and incorporate a technical discipline based taxonomy approach to align like technologies under a technology area.

The other major change in this revision is the shift from emphasis on generic roadmaps to MD-owned technology development strategies. This change focused on MD-identified strategic capabilities needs and their corresponding plans to mature the enabling technologies required. The new approach, the Strategic Technology Integration Framework (STIF), captures the capability needs of each MD and its associated technology investment strategies. The STIF provides traceability of actual technology investments, offering the technology development community insight into the strategic needs and technology plans of the Agency.

Development Process

During 2018, the CTC, working with OCT, performed the first round of structural realignment and content revisions of the new taxonomy. Agency SMEs, including Technical Fellows, Systems Capability Leaders, Principal Technologists, and other technical Agency experts, participated in this early round of revision. During this phase of development, it was recognized that the taxonomy revision would benefit from leveraging the SMEs' established Agency role as advisors to develop and maintain the NASA Technology Taxonomy. This SME presence would also provide consistency and continuity in subsequent revisions of the taxonomy.

The draft taxonomy, resulting from the initial realignment and revisions, underwent a broad two-phase review. The first was an internal NASA-wide review that solicited comments from NASA MDs, NASA Offices, NASA Centers, and the Jet Propulsion Laboratory. That review was followed by a public review and comment period. This combination of reviews further informed and refined the revision by providing additional realignments and clarifications to

both the restructuring and the technical elements of the 2020 NASA Technology Taxonomy.

In addition to the taxonomy revision, a companion document providing a crosswalk between the 2015 TAs and the updated 2020 TXs was developed. This document allows readers to identify where technology areas have moved with the update.

High-Level Changes from 2015-2020

The updated 2020 NASA Technology Taxonomy reflects a shift to a structure that aligns Technology Areas based on technical disciplines. To achieve this shift the revision retains, modifies and introduces new Level 1 and Level 2 technology areas while dissolving others and combining them with existing areas. The new structure expands to 17 Technology Areas and replaces the 4th level "Technology Candidates" with an unnumbered sub-section listing of example technologies for that section. Figure 1 shows the breakdown of the structure used in the 2020 Technology Taxonomy. The 2020 update also includes new technologies relevant to NASA, such as cybersecurity and advancements in artificial intelligence.

The following are highlights of the major changes in the new taxonomy structure:

- Added a Level 2 section at the end of each TX to capture those technologies not explicitly featured elsewhere in the TX but clearly belonging in the TX section (e.g. TX01.X, TX02.X etc.)
- Retained and updated a crosscutting section (TX00) with the addition of systems not explicitly featured in TX 1-17 that cross-map across the TX areas
- Combined TA1 Launch Propulsion Systems and TA2 In-Space Propulsion Technologies into one area, TX01 Propulsion, and included elements of propulsion for atmospheric systems
- Created TX02 Flight Computing and Avionics
- Split TA4 Robotics and Autonomous Systems into separate technology areas, TX04 Robotics and TX10 Autonomous Systems
- Removed TA10 Nanotechnology as an independent technology area; nanotechnologies are now represented in other technology areas as appropriate (e.g. nanopropellants are in TX01 Propulsion)
- Split TA15 Aeronautics into TX15 Flight Vehicle Systems and TX16 Air Traffic Management; incorporated other aeronautics technologies into other technology areas as appropriate
- Created TX17 Guidance, Navigation, and Control (GN&C)

Description of the TXs

The 2020 NASA Technology Taxonomy includes the following 17 TXs:

TX01: Propulsion Systems

This area covers technologies for chemical and non-chemical propulsion systems or their related ancillary systems for propulsion, space launch propulsion, or in-space propulsion applications.

TX02: Flight Computing and Avionics

This area covers unique electronics and computing hardware when applied to flight systems, whether in space or atmospheric.

TX03: Aerospace Power and Energy Storage

This area covers the different components of a power system—power generation, energy storage, and power management and distribution—that require technological improvements to enable or enhance NASA missions.

Figure 1. The second-level breakdown of the structure used in the 2020 Technology Taxonomy. This document contains details at the third level, with fourth-level technology examples provided in all cases.

TX04: Robotic Systems

This area covers technologies for robotic systems that will be leveraged as science explorers, precursor explorers preceding crewed missions, as crew helpers, as EVA mobility aids, and as caretakers of unattended assets.

TX05: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

This area covers technologies for transferring commands, spacecraft telemetry, mission data, and voice for human exploration missions, while maintaining accurate timing and providing navigation support. Orbital debris can be tracked and characterized by some of the same systems used for spacecraft communications and navigation, as well as by other specialized systems.

TX06: Human Health, Life Support, and Habitation Systems

This area covers technologies that are specific to the human element and those that directly affect crew needs for survival and wellbeing, including the environment and interfaces that crew encounter.

TX07: Exploration Destination Systems

This area covers the broad range of technologies associated with enabling successful activities in space, from mission operations to in-situ resource utilization.

TX08: Sensors and Instruments

This area covers technologies for instruments and sensors, including remote observation capabilities.

TX09: Entry, Descent, and Landing

This area covers entry, descent, and landing technologies needed to enable both current and future missions.

TX10: Autonomous Systems

This new area covers technologies that (in the context of robotics, spacecraft, or aircraft) enable the system to operate in a dynamic environment independent of external control.

TX11: Software, Modeling, Simulation, and Information Processing

This area covers modeling, simulation, and information technology as well as software technologies that increase NASA's understanding and mastery of the physical world and are the basis of new solution paradigms across the breadth of NASA's missions.

TX12: Materials, Structures, Mechanical Systems, and Manufacturing

This area covers technologies for developing new materials with improved or combined properties, structures that use materials to meet system performance requirements, and innovative manufacturing processes.

TX13: Ground, Test, and Surface Systems

This area covers technologies for preparing, assembling, validating, executing, supporting, and maintaining aeronautics and space activities and operations, on Earth and on other planetary surfaces.

TX14: Thermal Management Systems

This area covers technologies for acquiring, transporting, and rejecting heat, as well as insulating and controlling the flow of heat to maintain temperatures within specified limits.

TX15: Flight Vehicle Systems

This area covers technologies for aerosciences and flight mechanics. Aerosciences is the prediction of vehicle and component atmospheric flight performance and flow qualities to enable robust and efficient flight vehicle development, achieving performance requirements while

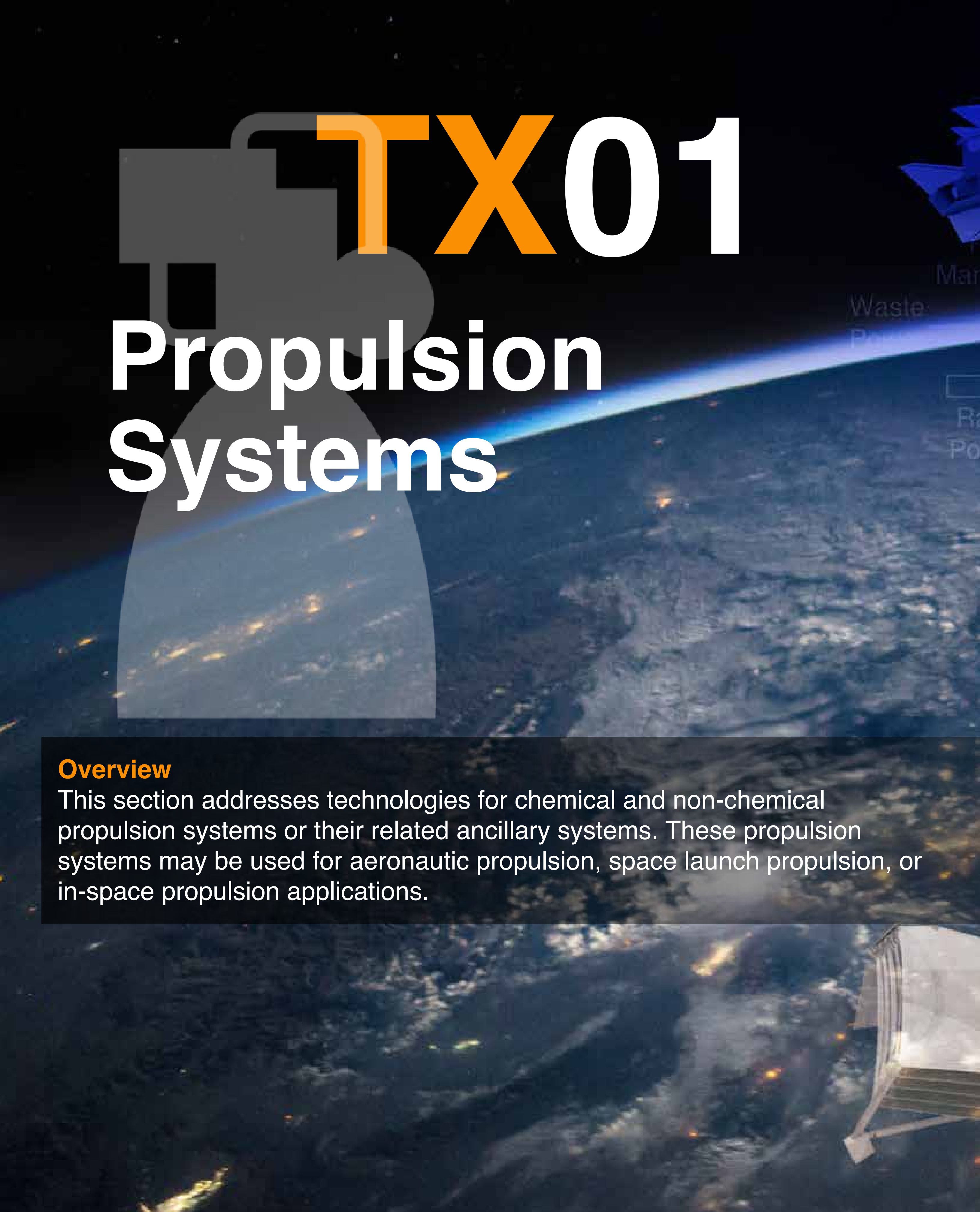
minimizing environmental impacts. Flight mechanics provides the analysis, prediction, measurement, and test of vehicle dynamics, trajectories, and performance.

TX16: Air Traffic Management and Range Tracking Systems

This area covers safety and automation technologies that include far reaching concepts and technologies for future planning and operations and ones that safely extend the capabilities and range of uses for air transportation and commercial space integration.

TX17: Guidance, Navigation, and Control (GN&C)

This area covers the unique GN&C system technologies that enable new missions; reduce cost, schedule, mass or power while maintaining or improving GN&C performance; improve system safety and longevity; or reduce environmental impact of aerospace vehicle operations.



TX01

Propulsion Systems

Overview

This section addresses technologies for chemical and non-chemical propulsion systems or their related ancillary systems. These propulsion systems may be used for aeronautic propulsion, space launch propulsion, or in-space propulsion applications.

TX01 Propulsion Systems

TX01.1 Chemical Propulsion

1.1.1
Integrated Systems and Ancillary Technologies

1.1.2
Earth Storable

1.1.3
Cryogenic

1.1.4
Solids

1.1.5
Hybrids

1.1.6
Gels

1.1.7
Cold Gas

1.1.8
Warm Gas

TX01.2 Electric Space Propulsion

1.2.1
Integrated Systems and Ancillary Technologies

1.2.2
Electrostatic

1.2.3
Electromagnetic

1.2.4
Electrothermal

TX01.3 Aero Propulsion

1.3.1
Integrated Systems and Ancillary Technologies

1.3.2
Turbine Based Combined Cycle

1.3.3
Rocket Based Combined Cycle

1.3.4
Pressure Gain Combustion

1.3.5
Turbine Based Jet Engines

1.3.6
Ramjet/Scramjet

1.3.7
Reciprocating Internal Combustion

1.3.8
All Electric Propulsion

1.3.9
Hybrid Electric Systems

1.3.10
Turboelectric Propulsion

1.3.11
Engine Icing

1.3.12
Alternative Low Carbon Jet Fuel

TX01.4 Advanced Propulsion

1.4.1
Solar Sails

1.4.2
Eletromagnetic Tethers

1.4.3
Nuclear Thermal Propulsion

1.4.4
Other Advanced Propulsion Approaches

TX01 Propulsion Systems

An RS-25 engine, the type used for NASA's upcoming Space Launch System (SLS), is test fired. (NASA)

TX01.1 Chemical Space Propulsion

Chemical propulsion includes systems that operate through chemical reactions that heat and expand a propellant (or use a fluid dynamic expansion as in a cold gas) to provide thrust.

TX01.1.1 Integrated Systems and Ancillary Technologies

This area covers systems and technologies that provide additional launch vehicle and in-space propulsion functions, other than primary ascent or propulsion. These systems include both mechanical and propulsive systems.

Example Technologies

For Launch Vehicles

- Thrust Vector Control (TVC)
- Main propulsion systems
- Reaction Control Systems (RCS)
- Roll Control Systems (RoCS)
- Separation motors
- Ullage settling motors
- Abort propulsion systems
- Propellant storage and transfer
- Nanocomposites
- Green propellants

For In-Space Propulsion

- CubeSat propulsion
- Propellant Management Devices (PMDs)
- Pressure regulation mechanisms
- Propellant thermal control systems
- Propellant vapor control systems
- Long-duration propellant-compatible materials
- High-performance main engines
- Low-impulse attitude-control systems
- Propellant slosh control
- Deep-throttling precision lander engines

TX01.1.2 Earth Storable

Earth storable propellants remain stable over a range of Earth terrestrial pressures and temperatures and can be stored in a closed vessel for long periods of time.

Example Technologies

- Kerosene
- Hydrazine
- Monomethylhydrazine
- Hydrogen peroxide
- Nitrogen tetroxide mixed oxides of nitrogen
- Green propellants (LMP-103S, AF-315E)
- Water
- Ionic liquids
- Ammonium dinitramide (ADN)-based propellants
- Hydroxylammonium nitrate (HAN)-based propellants

TX01.1.3 Cryogenic

Cryogenic propulsion systems or subsystems operate with propellants that are liquefied gases at low temperatures.

Example Technologies

- Liquid oxygen (LOX)
- Methane (CH_4)
- Pressure-fed main engine LOX
- Methane (CH_4) pump-fed main engine LOX
- Methane (CH_4) pump-fed main engine LOX
- Liquid hydrogen (LH) reaction and attitude control engine
- LOX/RP-1
- LOX/LH based engine

TX01.1.4 Solids

This area covers propulsion systems that operate with solid propellants, where the propellants are pre-mixed oxidizers and fuels.

Example Technologies

- Polybutadiene Acrylic Acid Acrylonitrile Prepolymer (PBAN)
- Hydroxyl Terminated Poly Butadiene (HTPB)

TX01.1.5 Hybrids

Hybrid propulsion systems or subsystems operate with propellants that utilize a hybrid of solid fuel and liquid oxidizer.

Example Technologies

- Acrylonitrile butadiene styrene thermoplastic
- Paraffin-based fuels

TX01.1.6 Gels

Gelled and metallized fuels are a class of thixotropic (shear-thinning) fuels that improve the performance of rocket and air-breathing systems.

Example Technologies

- Gelled oxygen (O_2)/hydrogen (H_2)
- Gelled MMH/IRFNA propellants
- Nanogelled propellants

TX01.1.7 Cold Gas

Cold gas propulsion systems use the stored pressure of inert gasses to increase thrust.

Example Technologies

- Cold gas systems for small satellites
- Upper stages
- Human space exploration

TX01.1.8 Warm Gas

Warm gas propulsion systems or subsystems use the energy of a heated gas to create thrust or increase the pressure in the system.

Example Technologies

- Pressurization for flight systems

Advanced Electric Propulsion Systems Contract, Technology Demonstration Unit, TDU-3 Check-out Test Hardware Installed in Vacuum Facility 5, VF-5. (NASA)

TX01.2 Electric Space Propulsion

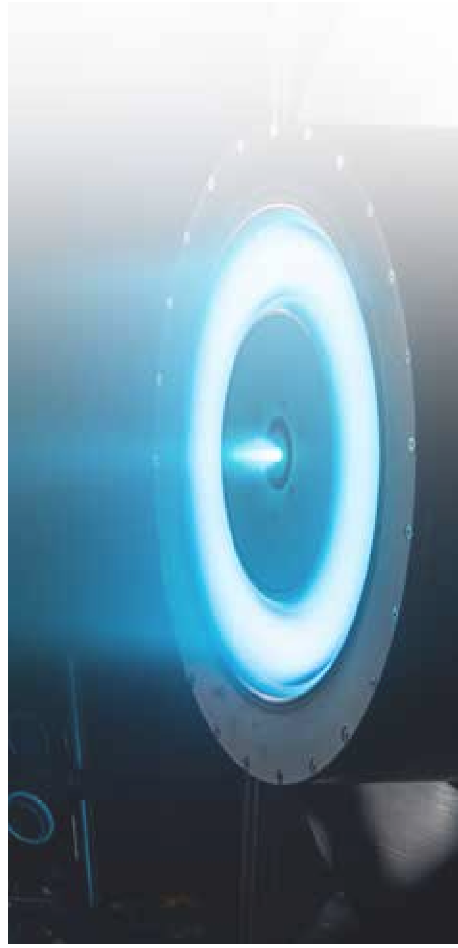
Electric propulsion converts electric energy to interact with and accelerate a reaction mass to generate thrust.

TX01.2.1 Integrated Systems and Ancillary Technologies

This area covers pertinent technology areas that are strongly coupled to, but are not part of, electric in-space propulsion, such that focused development within these related areas will allow significant improvements in performance for some in-space propulsion technology areas.

Example Technologies

- Engine health monitoring
- Materials and manufacturing
- Heat rejection systems for in space propulsion



A Hall ion thruster in operation. (NASA)

TX01.2.2 Electrostatic

This area covers electric propulsion systems that use electrostatic fields to ionize and accelerate a propellant.

Example Technologies

- Ion engines
- Hall thrusters
- Electrospray propulsion

TX01.2.3 Electromagnetic

This area covers electric propulsion that interacts with a reaction mass using electromagnetic fields.

Example Technologies

- Pulsed inductive thruster
- Magnetoplasmadynamic (MPD) thruster
- Electrodynamic launch, e.g. double-sided linear induction motor (DSLIM)

TX01.2.4 Electrothermal

This area covers electric propulsion that heats the propellant prior to expansion through a nozzle.

Example Technologies

- Resistojets
- Arcjets

This is an artist's concept of a possible Low Boom Flight Demonstration Quiet Supersonic Transport (QueSST) X-plane design. The award of a preliminary design contract is the first step towards the possible return of supersonic passenger travel – but this time quieter and more affordable. (NASA)

TX01.3 Aero Propulsion

Aero propulsion systems are designed to operate in Earth's atmosphere.

TX01.3.1 Integrated Systems and Ancillary Technologies

This area covers integrated systems and ancillary technologies relevant to enabling propulsion systems for atmospheric flight.

Example Technologies

- Engine health monitoring
- Materials and manufacturing
- Emissions control
- Noise management

TX01.3.2 Turbine Based Combined Cycle

A Turbine Based Combined Cycle is a combination propulsion system that consists of a turbine engine and ram or dual-mode scramjet.

Example Technologies

- Dual mode scramjet

TX01.3.3 Rocket Based Combined Cycle

A combined-cycle propulsion system generally consists of an ejector-ramjet or rocket mode for liftoff, followed by ramjet, scramjet, and rocket modes for acceleration to orbital velocity.

Example Technologies

- Ejector ramjet

TX01.3.4 Pressure Gain Combustion

Pressure gain combustion (PGC) describes a family of physical processes and configurations that provide an increase in total pressure during the combustion process within a fixed volume combustor. Each of these combustors uses gas dynamic waves to confine the combustion process (all but the pulsejet also pre-compress the fuel/air mixture) to achieve an approximation to constant volume combustion.

Example Technologies

- Pulse detonation engines (PDE)
- Rotating detonation engines (RDE)
- Pulsejets
- Wave rotors

TX01.3.5 Turbine Based Jet Engines

This area covers Brayton cycle-based air-breathing propulsion systems, the baseline of commercial aviation industry. This area includes adaptation of conventional jet engines as fly back booster engines designed to withstand the launch environment imposed by a conventional vertical rocket launch.

Example Technologies

- Turbine jet engine

TX01.3.6 Ramjet/Scramjet

A Ramjet/Scramjet is an adaptation of traditional ramjet and scramjet air breathing propulsion systems to provide acceleration of an Earth-to-orbit launch system within the atmosphere.

Example Technologies

- Ramjet/scramjet

The second and final qualification motor (QM-2) test for the Space Launch System's booster is seen, Tuesday, June 28, 2016, at Orbital ATK Propulsion System's (SLS) test facilities in Promontory, Utah. (NASA/Bill Ingalls)

TX01.3.7 Reciprocating Internal Combustion

In the reciprocating internal combustion technology area, multi cylinder engines, each containing a piston, turn a crankshaft to drive a propeller.

Example Technologies

- Air-cooled four- and six-cylinder piston engines

TX01.3.8 All Electric Propulsion

All electric systems use electrical energy storage as the only power source.

Example Technologies

- Permanent magnet synchronous motor
- Distributed electronic propulsion

TX01.3.9 Hybrid Electric Systems

Hybrid electric systems use a turbine driven generator combined with electrical energy storage as the power source.

Example Technologies

- Series/parallel partial hybrid

TX01.3.10 Turboelectric Propulsion

Turboelectric systems use a turbine driven generator as the power source. Partial turboelectric systems split the thrust between a turbo fan and the motor driven fans.

Example Technologies

- Partial turboelectric

TX01.3.11 Engine Icing

Engine icing technologies reduce or prevent ice formation on aircraft engines.

Example Technologies

- Electro-expulsive deicing
- Pneumatic deicing
- Thermal anti-icing systems
- Fluid-based deicing approaches
- Electro-impulsive approaches

TX01.3.12 Alternative Low Carbon Jet Fuel

Alternative jet fuels have lower carbon emissions than conventional petroleum-based fuels over the entire life cycle of the fuels.

Example Technologies

- Biojet fuels
- Hydrogen-based fuels

TX01.4 Advanced Propulsion

Advanced propulsion includes propellant-less and emerging technologies and physics concepts.

TX01.4.1 Solar Sails

Sail propulsion uses lightweight structures with a large surface area to produce thrust by reflecting solar photons (solar) or atmospheric molecules (drag), thereby transferring much of their momentum to the sail.

Example Technologies

- Solar sail

TX01.4.2 Electromagnetic Tethers

Electromagnetic tethers are long, lightweight cables that produce thrust through the Lorentz force by carrying electrical current and interacting with a planetary magnetosphere.

Example Technologies

- Electromagnetic tethers

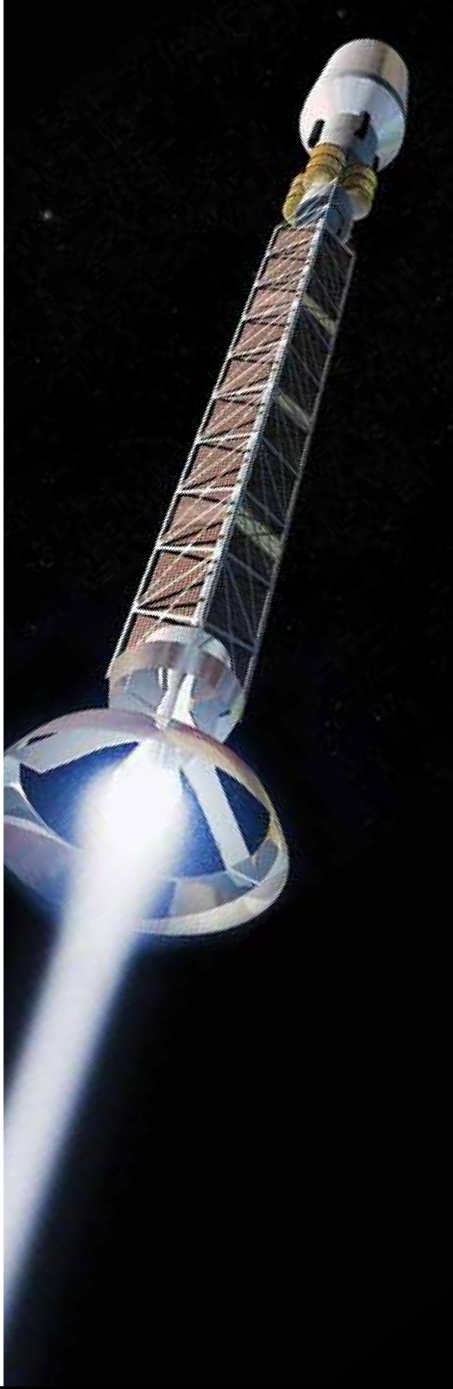
TX01.4.3 Nuclear Thermal Propulsion

Nuclear Thermal Propulsion (NTP) engines use a fission reactor (solid, liquid or gas) in the thrust chamber to heat large mass flow of propellant to extremely high temperatures for high specific impulse at high thrust.

Example Technologies

- Solid state NTP
- Gas and liquid ore NTP

A notional concept for an interplanetary vehicle using an advanced propulsion system. (NASA)



TX01.4.4 Other Advanced Propulsion Approaches

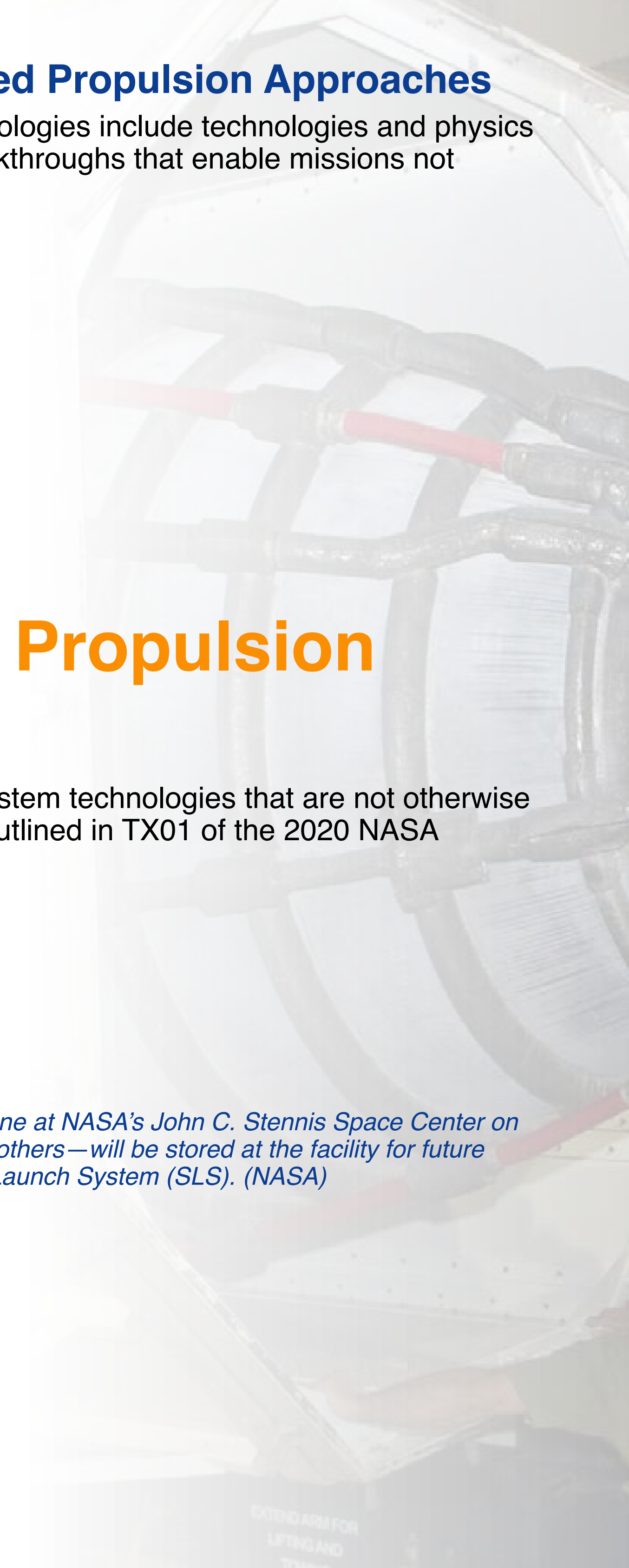
Other advanced propulsion technologies include technologies and physics concepts that could result in breakthroughs that enable missions not previously possible.

Example Technologies

- Beamed energy
- Fusion propulsion
- High energy-density materials
- Antimatter propulsion
- Advanced fission
- Breakthrough propulsion

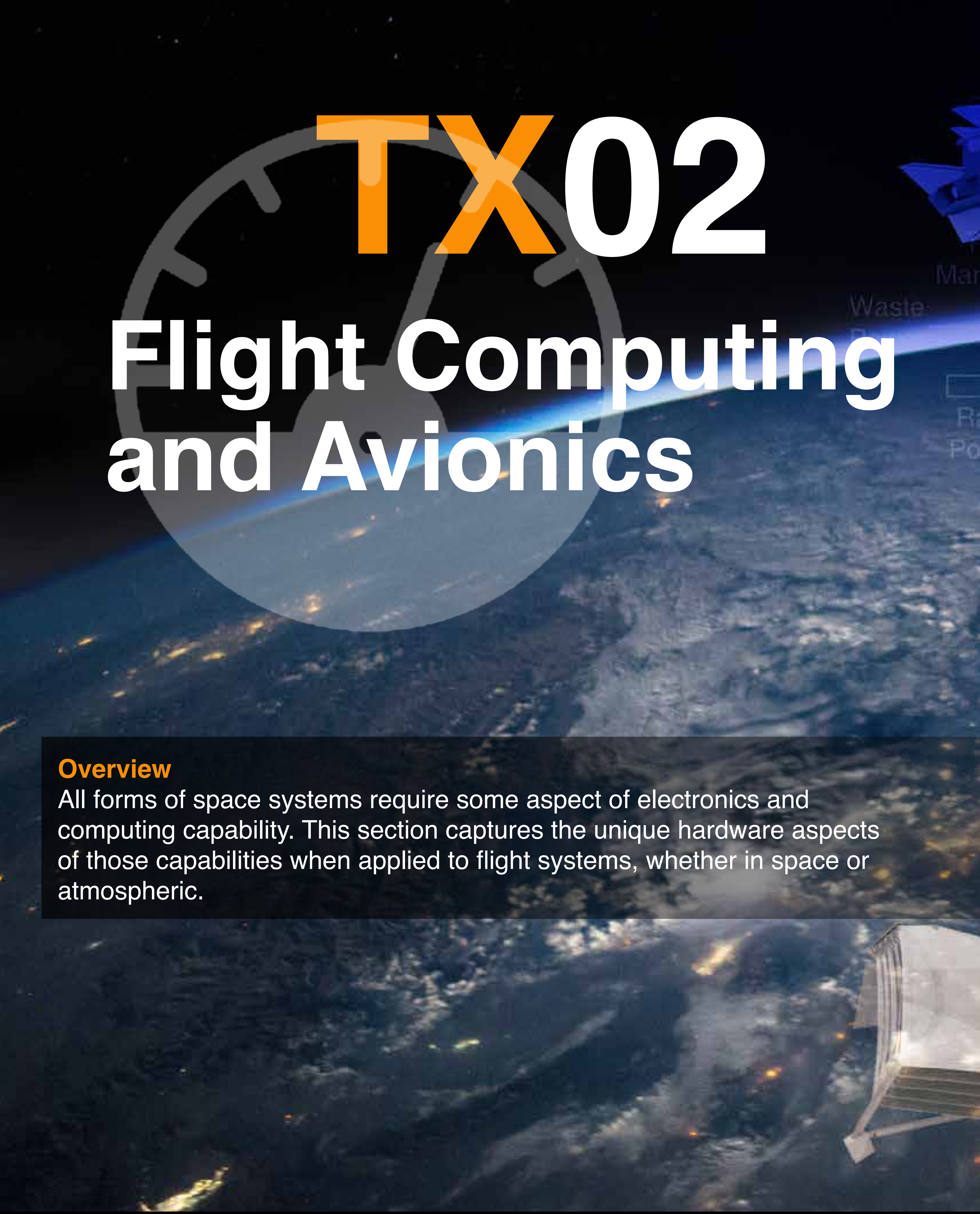
TX01.X Other Propulsion Systems

This section covers propulsion system technologies that are not otherwise covered by the sub-paragraphs outlined in TX01 of the 2020 NASA Technology Taxonomy.



Employees unload a RS25D rocket engine at NASA's John C. Stennis Space Center on January 17, 2012. The engine—and 14 others—will be stored at the facility for future testing and use on NASA's new Space Launch System (SLS). (NASA)

TX01 Propulsion Systems



TX02

Flight Computing and Avionics

Overview

All forms of space systems require some aspect of electronics and computing capability. This section captures the unique hardware aspects of those capabilities when applied to flight systems, whether in space or atmospheric.

TX02 Flight Computing and Avionics

TX02.1
Avionics Component Technologies

2.1.1
Radiation Hardened Extreme Environment Components and Implementations

2.1.2
Electronic Packaging and Implementations

2.1.3
High Performance Processors

2.1.4
High Performance Memories

2.1.5
High Performance Field Programmable Gate Arrays

2.1.6
Radiation Hardened ASIC Technologies

2.1.7
Point-of-Load Power Converters

2.1.8
Wireless Avionics Technologies

TX02.2
Avionics Systems and Subsystems

2.2.1
Spacecraft Command and Data Handling Systems (C&DH)

2.2.2
Aircraft Avionics Systems

2.2.3
Vision and Virtual/Augmented Reality Avionics

2.2.4
Low Power Embedded Computer Systems

2.2.5
High Speed Onboard Interconnects and Networks

2.2.6
Data Acquisition Systems

2.2.7
Data Reduction Hardware Systems

2.2.8
Use of Advanced Commercial-off-the-Shelf (COTS) Technologies

2.2.9
Hardware Enabling Secure Avionics

TX02.3
Avionics Tools, Models, and Analysis

2.3.1
Electronics Development Tools

2.3.2
Space Radiation Analysis and Modeling

2.3.3
Avionics Reliability and Fault-Tolerance Analysis and Modeling

2.3.4
Electromagnetic Environment Effects

TX02 Flight Computing and Avionics

TX02.1 Avionics Component Technologies

Component technologies constitute the electronic parts utilized in building avionics subsystems.

TX02.1.1 Radiation Hardened Extreme Environment Components and Implementations

Radiation Hardened (rad-hard) components are technologies tolerant to radiation and/or extreme temperatures. These technologies allow for miniaturization and increased ruggedness of spacecraft electronics for enhancing flexibility in vehicle configuration and design. This area also includes technologies for fabricating electronic components for space environments, rad-hard-by-design implementation techniques, and implementations developed to deal with extreme temperatures environments that would obviate the need for thermal management systems.

Example Technologies

- Radiation mitigation techniques
- Rad-hard/tolerant Graphical Processor Unit (GPU) and display elements
- Rad-hard/tolerant data processing
- Rad-hard/tolerant general purpose flight processor
- Rad-hard/tolerant high-capacity memory
- Nanoelectronics based memory devices
- Two-dimensional (high-capacity memory)
- Nano electronics-based memory devices
- 2D nanomaterials based electronics
- Components with on-chip thermal control capability
- Advanced passive technologies (e.g. super capacitors)

The GPM High Gain Antenna System (HGAS) in integration and testing at Goddard Space Flight Center. GPM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). The Core Observatory will link data from a constellation of current and planned satellites to produce next-generation global measurements of rainfall and snowfall from space. (NASA)

TX02.1.2 Electronic Packaging and Implementations

Advanced electronic packaging and implementations are novel methods, materials, and designs for packaging and integrating electronic circuits at the component, board, and box levels. These technologies improve mass, volume, and power of atmospheric and space vehicle avionics, and support analog and digital electronics for tolerance to both radiation and extreme temperatures.

Example Technologies

- Stacked or 2.5D/3D chips/packages/modules
- High density interconnect technologies
- Chip-on-board technologies
- Additively manufactured electronic packaging
- Solderless interconnects and interposers
- System-in-package
- Advanced passive device technologies (e.g. 3D passive arrays)

TX02.1.3 High Performance Processors

High Performance Processors provide advanced data processing functions at high speeds delivering powerful and reliable computing resources capable of executing computationally expensive algorithms in a short period. This area includes energy efficient computations, Single Event Effect (SEE) immune data systems, processing modules, resources supporting real time operating systems, data processing architectures, and scalable and multi-core computing architectures.

Example Technologies

- Scalable, multi-core processors
- Low-power processors
- Synaptic, brain-like processors
- Rad-hard/tolerant processors
- Fault-tolerant processors
- Digital signal processors (DSP)
- Graphics processing units (GPU)

TX02.1.4 High Performance Memories

High Performance rad-hard Memories utilize more advanced memory technologies (volatile and non-volatile) to provide increased memory bandwidth and improved power utilization at orders of magnitude increase in density.

Example Technologies

- Rad-hard high-density on-board memory
- Rad-hard/tolerant high-capacity memory
- Double Data Rate (DDR3/4)
- Magnetoresistive Random Access Memory (MRAM)

TX02.1.5 High Performance Field Programmable Gate Arrays

Field Programmable Gate Array (FPGA) technologies optimize aerospace application performance through implementation on one-time programmable devices or re-programmable devices. Embedded processors, signal processing, high-speed interfaces, and other elements implemented in FPGA fabrics are included.

Example Technologies

- Rad-hard/tolerant FPGAs
- Techniques for FPGA radiation hardening
- FPGA hard/soft cores

TX02.1.6 Radiation Hardened ASIC Technologies

Various Application-Specific Integrated Circuits (ASICs) and technologies that are rad-hard/tolerant for space/aero applications, including structured ASICs that offer an intermediate design approach between ASICs and FPGAs, potentially providing high performance and low cost.

Example Technologies

- Rad-hard/tolerant structured ASICs
- System-on-a-chip (SoC) devices
- Intellectual property (IP) cores
- Complex digital logic systems
- Rad-hard/tolerant housekeeping ASICs
- Network interface ASICs

TX02 Flight Computing and Avionics

TX02.1.7 Point-of-Load Power Converters

Miniature, highly efficient point-of-load (POL) convertors help eliminate the mass and complexity of traditional DC-DC power convertor slices. Developing fault tolerant, rad-hard point-of-load converters would reduce the mass and complexity of avionics assemblies.

Example Technologies

- Fault-tolerant point-of-load converters
- Rad-hard/tolerant point-of-load converters
- Multi-output point-of-load converters
- Digitally controlled point-of-load converters

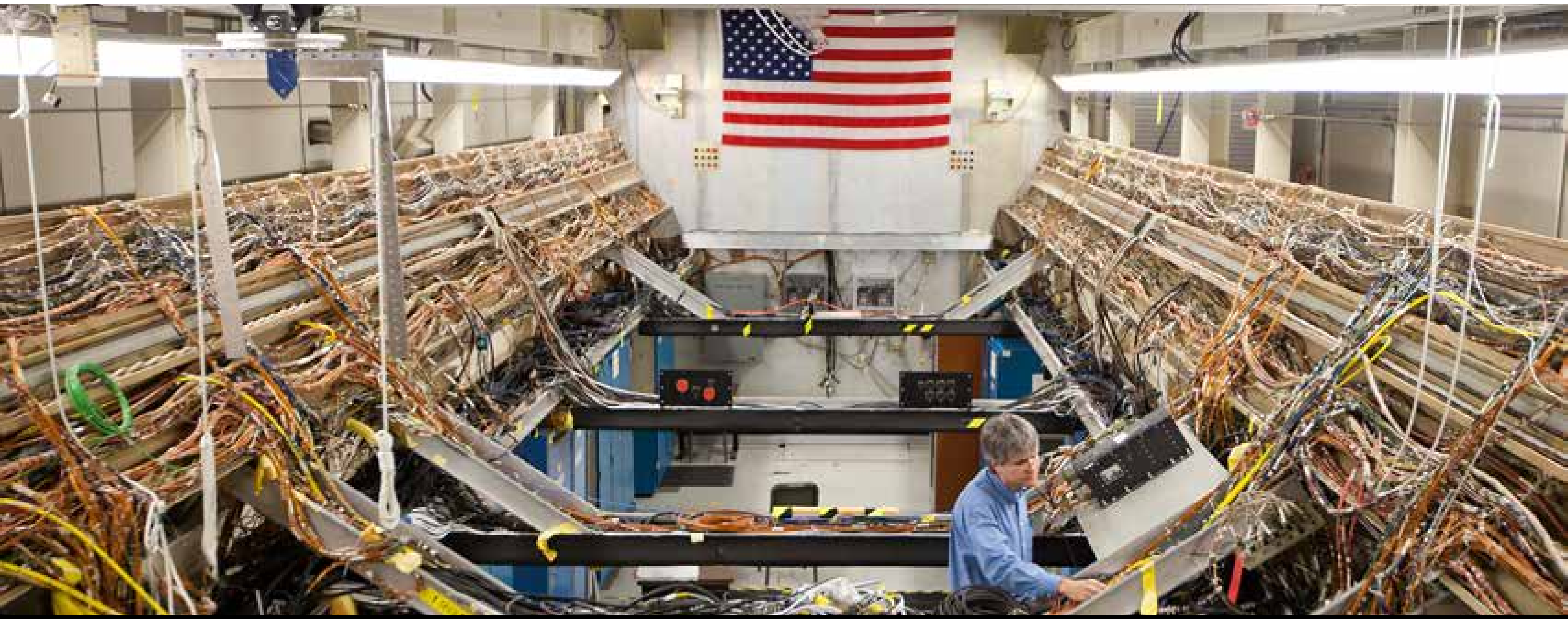
TX02.1.8 Wireless Avionics Technologies

Wireless avionics technologies interface with wireless networks such as Wi-Fi or Bluetooth, or utilize radio frequency identification (RFID) technologies, potentially reducing overall system mass and permitting easier reconfiguration by physically moving the sensor and/or changing the controlling software characteristics.

Example Technologies

- RFID-based sensors
- Wi-Fi-based sensors
- Utilization of wireless access points for data aggregation
- Wireless wearable sensors for monitoring astronauts

This is an overall view of the wiring for the simulated shuttle payload bay in the Shuttle Avionics Integration Laboratory (SAIL) at the Johnson Space Center in Houston on July 12, 2011. (NASA/ Houston Chronicle, Smiley N. Pool)



TX02.2 Avionics Systems and Subsystems

Avionics systems/subsystems are the building blocks for vehicles and spacecraft that implement key functionality for Command and Data Handling, Data Acquisitions, and other essential functions for NASA missions.

TX02.2.1 Spacecraft Command and Data Handling Systems (C&DH)

Spacecraft C&DH are the core integrated avionics systems for managing the spacecraft, including but not limited to the integration of command and telemetry processing, real-time control systems utilizing sensor inputs for state determination, network management, and data storage systems required to control spacecraft and meet mission requirements.

Example Technologies

- General purpose or specialized processing systems
- Data recorders and storage systems
- Health management systems
- Vehicle flight controls
- Hazard avoidance systems
- Crew input and display systems
- Spacecraft hi-rel fault-tolerant architectures
- Real-time control systems

NASA Ames Research Center has developed and tested a prototype low-cost avionics package for space launch vehicles that provides complete GNC functionality in a package smaller than a tissue box. (NASA)

TX02.2.2 Aircraft Avionics Systems

Aircraft avionics systems are the electronic systems used to control an aircraft directly, cooperatively, or autonomously, providing a means for both crew input control and feedback through displays and instruments. Aircraft avionics include but are not limited to the integration of real-time control systems utilizing sensor inputs for state determination, network management, and data storage systems required to control and operate an aircraft safely and effectively.

Example Technologies

- Aircraft control systems
- Autopilots
- Flight deck management systems
- Terrain awareness/warning systems
- Collision avoidance systems
- Health management systems
- General purpose or specialized processing systems
- Crew input and display systems
- Aircraft hi-rel fault-tolerant architectures

TX02.2.3 Vision and Virtual/Augmented Reality Avionics

This area covers vision systems combined with advanced displays and pilot/crew input devices to provide effective situational awareness and interactive data management of modern aircraft and spacecraft through both traditional and virtual/augmented reality system approaches.

Example Technologies

- External visions systems for safe take-off/landing
- Integrated data and real-time imaging into heads-up displays
- Augmented reality interactive guidance systems
- Augmented reality systems to manage information and improve crew efficiency

TX02 Flight Computing and Avionics

TX02.2.4 Low Power Embedded Computer Systems

Low power embedded computers are designed to have low size, weight, and power (SWaP) to implement specific aerospace applications. These processing systems could be embedded within subsystems and instruments.

Example Technologies

- Rad-hard/tolerant embedded computers or microcontroller systems
- Real-time prcoessor boards/systems
- Instrument or peripheral embedded processing systems
- Power saving implementations and techniques

TX02.2.5 High Speed Onboard Interconnects and Networks

High speed onboard networks support future onboard processing needs for increased numbers and performance of processing elements and memory devices with increased capacity and performance.

Example Technologies

- Digital high-speed interconnects/fabrics
- Gigabit Ethernet
- Fiber optic network waveguide
- Rad-hard/tolerant network switches and routers
- PCI Express

TX02.2.6 Data Acquisition Systems

Data acquisition systems collect and deliver data in an environment with an increasing selection of heterogeneous instruments and sensors that generate larger volumes of data at higher rates.

Example Technologies

- Structural health monitoring and thermal health monitoring (SHM/THM) system integration
- Sensor webs
- High analog-bandwidth/sampling rate
- Multiplexed analog to digital converters (ADC)
- Advanced standards for data acquisition interfaces and data storage

WESH-TV 2 News Anchor Wendy Chioji sits in the cockpit of a space shuttle while touring Kennedy Space Center. (NASA)

TX02.2.7 Data Reduction Hardware Systems

This area covers data reduction hardware systems used to reduce and/or manage large volumes of data.

Example Technologies

- Data duplication hardware
- Near real-time video loss less compression
- Lossy video compression
- Radio frequency (RF) compression
- Real-time data compression

TX02.2.8 Use of Advanced Commercial-off-the-Shelf (COTS) Technologies

Commercial-off-the-shelf (COTS) technologies offer higher performance, ready availability, and potential SWaP advantages. These advantages may come at the cost of unknown radiation and reliability performance; lack of guaranteed process, traceability, and configuration control; and shorter product life cycles. Successful use of advanced COTS benefits from the availability of and attention to guidelines, best practices, lessons learned, risk mitigation techniques, and other information sharing to ensure the components meet the requirements for the mission, environment, applications, and lifetime.

Example Technologies

- Uses of advanced commercial microcircuits, semiconductors, and passives
- Guidelines of using prediction-error minimization (PEM) with Cu wire bonds, and nano- and composite connectors
- Implimentation of commercial processors, FPGAs, memories, analog-to-digital/digital-to-analog converters (ADC/DAC)
- Power management

TX02.2.9 Hardware Enabling Secure Avionics

This area covers subsystems and/or devices needed to support the elements of secure operations.

Example Technologies

- Secure boot loaders
- Encryption/decryption devices
- Specialized secure hardware

James Peckham, an nLogic Inc. test engineer supporting the Stages Office at the Marshall Center, runs an avionics flight simulation to see how SLS will perform during launch. (NASA/Boeing)

TX02.3 Avionics Tools, Models, and Analysis

This area covers tools, models, analyses, databases, design techniques and processes for avionics evaluation, development, and support.

TX02.3.1 Electronics Development Tools

This area covers advanced digital design tools that will enable complex systems to be implemented quickly and cost effectively, while having the fault tolerance to operate reliably in the space environment. As technology scales to smaller fabrication processes, higher clock speeds, and greater miniaturization, design tools will need to adapt.

Example Technologies

- Automated hardware development toolsets
- Electronic design automation tools
- Assitive manufactured electronics development tools
- High-level synthesis tools
- Printed circuit board (PCB) design tools
- Cable design tools
- Techniques for circuit design correctness and validation

TX02.3.2 Space Radiation Analysis and Modeling

Space radiation analysis and modeling tools include models of the radiation environments, radiation transport codes for estimating particle fluxes/doses for sensitive components, SEE rate estimation packages, databases of historical radiation test data, and physics-based codes to simulate device radiation response and other tools/techniques needed to ensure correct operation in mission environments.

Example Technologies

- IRENE, ESP, and PSYCHIC environmental models
- CRÈME-96 and CRÈME-MC SEE rate estimation software packages
- MULASSIS, Monte Carlo N-Particle/ Monte Carlo N-Particle eXtended (MCNP/MCNPX), NOVICE transport codes
- DAVINCI, SPICE part and circuit simulation routines, model-based system engineering, and mission assurance approaches

TX02.3.3 Avionics Reliability and Fault-Tolerance Analysis and Modeling

This area covers analysis and modeling of the reliability and fault tolerance of avionics system hardware. Reliability and fault tolerance are key properties of aerospace avionics systems that become increasingly more important and difficult to understand and implement as avionics systems become more complex and utilize new components and technologies. This area includes analysis and modeling of these properties of the avionics system hardware.

Example Technologies

- Fault tolerance modeling and coverage estimation
- Fault injectors
- Reliability estimation
- Failure Mode and Effects Anlysis/Failure Mode, Effects, Criticality Analysis (FMEA/FMECA) generators and coverage estimation tools

TX02.3.4 Electromagnetic Environment Effects

The discipline known as Electromagnetic Environmental Effects (E3) encompasses various forms and sources of electromagnetic interference and its control, including nuclear electromagnetic pulse (EMP); lightning EMP; electrostatic charge accumulation and discharge, triboelectrification (AKA p-static), and plasma vehicle charging; hazards of electromagnetic radiation to personnel (HERP), fuel (HERF), and ordnance (HERO); switching transients in hardware and on platforms; LRU level conducted and radiated electric and magnetic field emissions and susceptibility; transmission line applications; signal and power integrity; electrical bonding; electrical referencing (AKA "grounding"); electromagnetic shielding, cable shielding; and other related areas as they pertain to avionics, electrical power, and multiple other discipline areas and systems.

Example Technologies

- E3 2D and 3D modeling capability, including Finite Difference Time Domain (FDTD) and integral electromagnetic solvers, with aerodynamic and thermal environment interfaces
- E3 analysis tools, including SPICE and Signal and Power integrity software
- Electromagnetic interference/electromagnetic pulse/electrostatic discharge (EMI/EMP/ESD) transient filtering and protection circuitry and techniques

TX02.X Other Flight Computing and Avionics

This area covers Fight Computing and Avionics technologies that are not otherwise covered by the sub-paragraphs outlined in TX02 of the 2020 NASA Technology Taxonomy.

In Orbiter Processing Facility-1 at NASA's Kennedy Space Center in Florida, the cockpit of space shuttle Discovery is brightly lit for the last time as preparations are made for the shuttle's final power down during Space Shuttle Program transition and retirement activities. (NASA)

TX03

Aerospace Power and Energy Storage

Overview

Many state of the art power systems are too heavy, bulky, or inefficient to meet future mission requirements, and some cannot operate in extreme environments. The different components of a power system—power generation, energy storage, and power management and distribution (PMAD)—each require technological improvements to enable or enhance the missions currently in NASA's plans.

TX03 Aerospace Power and Energy Storage

TX03.1
Power Generation and Energy Conversion

3.1.1
Photovoltaic

3.1.2
Heat Sources

3.1.3
Static Energy Conversion

3.1.4
Dynamic Energy Conversion

3.1.5
Electrical Machines

3.1.6
Other Advanced Concepts for Generating/Converting Power

TX03.2
Energy Storage

3.2.1
Electrochemical: Batteries

3.2.2
Electrochemical: Fuel Cells

3.2.3
Advanced Concepts for Energy Storage

TX03.3
Power Management and Distribution

3.3.1
Management and Control

3.3.2
Distribution and Transmission

3.3.3
Electrical Power Conversion and Regulation

3.3.4
Advanced Electronic Parts

TX03 Aerospace Power and Energy Storage

Technicians test the deployment of one of the three massive solar arrays that power NASA Juno spacecraft. (NASA/JPL-Caltech/Lockheed Martin)

TX03.1 Power Generation and Energy Conversion

Power generation and conversion identifies the methods of generating power from chemical, solar, and nuclear sources, as well as energy conversion technology.

TX03.1.1 Photovoltaic

Photovoltaic electrical power generation converts photons into electrical power, including photovoltaic cells, cell integration, and mechanical and structural technologies for cell arrays.

Example Technologies

- 25-150 kW-class solar arrays
- Reliably retractable solar arrays
- Reduced-cost photovoltaic blankets
- Extreme environment solar cells and panels

TX03.1.2 Heat Sources

Thermal energy source technology captures nuclear or solar irradiation for electrical power generation or process heat.

Example Technologies

- Conventional radioisotope, fission, or solar-thermal heat sources linked with novel aspects of heat collection such as heat pipes, heat pumps, etc.

TX03.1.3 Static Energy Conversion

Static energy conversion generates electrical power through the conversion of heat using non-mechanical processes.

Example Technologies

- Enhanced multi-mission radioisotope thermoelectric generators
- Thermionic generators

TX03 Aerospace Power and Energy Storage

TX03.1.4 Dynamic Energy Conversion

Dynamic energy conversion generates electrical power or mechanical work through the conversion of heat using mechanical heat engines.

Example Technologies

- Advanced Stirling radioisotope generator
- 1-10 kWe Stirling fission power system
- Brayton and Rankine cycle generators with solar, fission, or chemical energy sources

TX03.1.5 Electrical Machines

Electric machines include motors, generators, and other devices that exchange electrical energy and mechanical work.

Example Technologies

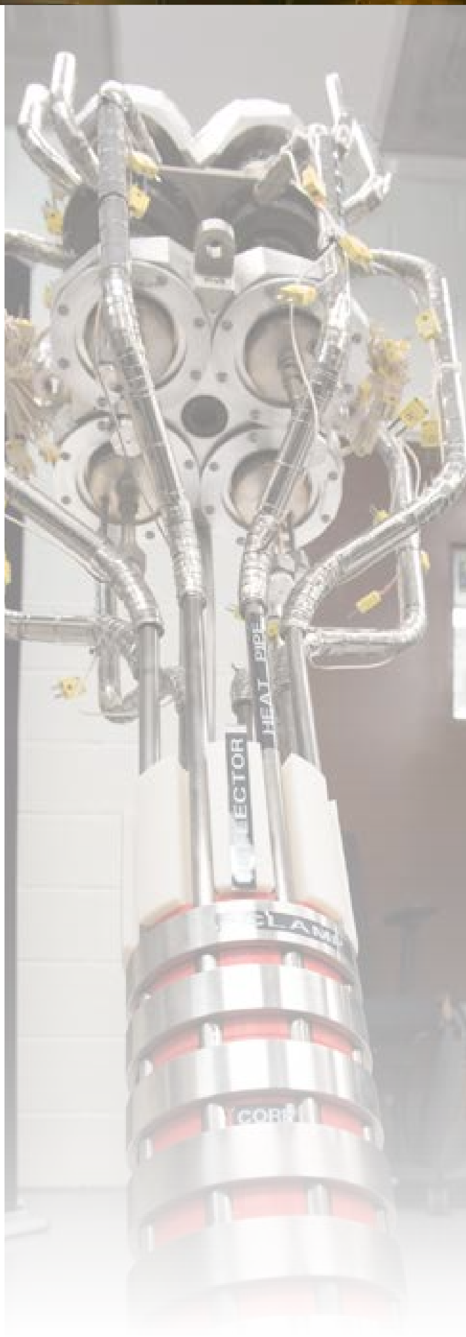
- High-efficiency, high-power motors/generators for electric aircraft
- Wind turbines
- Shape memory alloy and piezoelectric motors and actuators

TX03.1.6 Other Advanced Concepts for Generating/ Converting Power

This area covers advanced concepts for generating and converting power.

Example Technologies

- Electrodynmaic tether energy harvesting
- Nuclear fusion heat sources
- Nuclear thermionic avalanche cells
- Alpha/beta voltaics
- Thermophotovoltaics



A Kilopower fission reactor power generator prototype is on display in the Stirling Research Lab at NASA's Glenn Research Center. The Kilopower Reactor Using Stirling Technology (KRUSTy) test was successfully completed at the Nevada National Security Site in March 2018. (NASA)

TX03 Aerospace Power and Energy Storage

TX03.2 Energy Storage

Energy storage includes methods of storing energy after it has been generated from solar, chemical, or nuclear sources.

TX03.2.1 Electrochemical: Batteries

Batteries store and convert chemical energy to electricity.

Example Technologies

- High-specific-energy
- Human-rated advanced secondary chemistries beyond lithium-ion
- Nanoelectronics
- Super/ultracapacitors
- Extreme environment energy storage
- Flow batteries

TX03.2.2 Electrochemical: Fuel Cells

Fuel cells store and convert chemical energy to electricity.

Example Technologies

- Regenerative fuel cells
- Hydrogen/oxygen-based regenerative fuel cells
- Solid oxide fuel cells
- Fuel reformation or electrolysis

TX03.2.3 Advanced Concepts for Energy Storage

Advanced concepts for energy storage include solutions that could be transformational for aerospace applications, including electro-mechanical systems (e.g. flywheels) and solar-chemical systems based on in-situ resources.

Example Technologies

- Flywheel technologies including broad temperature range applications
- Advanced high-strength flywheel materials
- Superconducting bearings
- Solar energy stored as high-energy-density chemical fuels
- Superconducting magnetic energy storage
- Other non-chemical storage devices

The X-57 Battery System. (NASA/Electric Power System)

TX03.3 Power Management and Distribution

Power management and distribution technologies manage and control electric power generated from a source.

TX03.3.1 Management and Control

Management and control includes the control algorithms, models, and sensors needed to control a spacecraft, rover, probes, aircraft power bus, or other vehicles, to include fault detection, isolation, and recovery.

Example Technologies

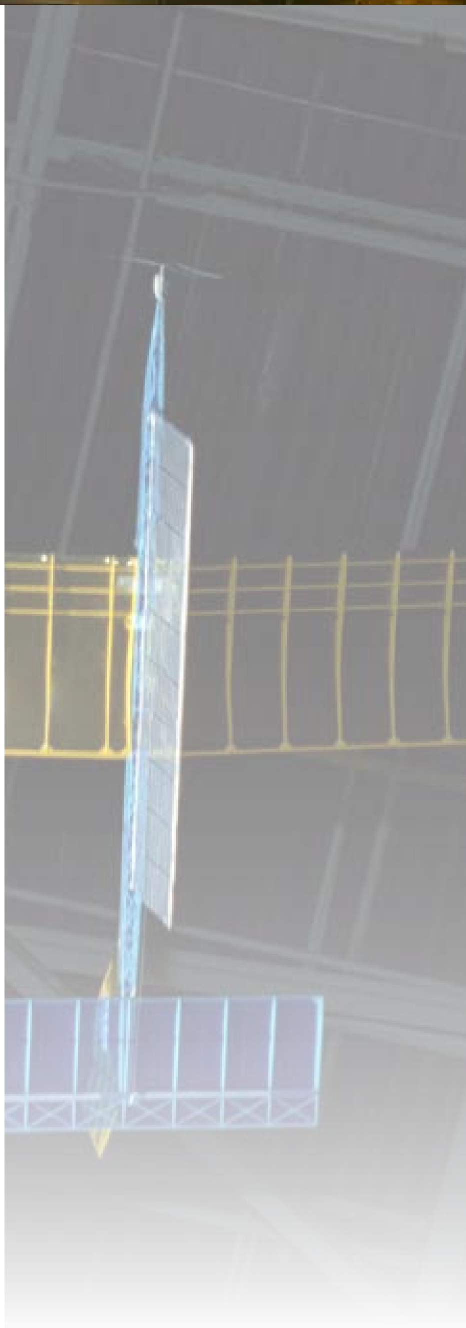
- Autonomous fault detection, isolation, and recovery (FDIR) algorithms and technologies for complex power systems
- Heirarchical and distributed control of a power system
- Power source and energy storage control
- Real-time power system simulation

TX03.3.2 Distribution and Transmission

Distribution and transmission includes the switchgear, wiring, and other components necessary for electric power transmission, wired or wireless, as well as the fault protection aspects of the distribution system.

Example Technologies

- High-conductivity carbon nanotube wire
- High-voltage power distribution
- Modular switchgear development
- All forms of wireless power transmission (magnetic, radio frequency, and optical)



An experimental radio-controlled model aircraft is seen here in flight powered only by light energy beamed to it by a spotlight. (NASA)

TX03.3.3 Electrical Power Conversion and Regulation

Electrical power conversion and regulation focuses on electrical power conversion from one form to another, including power regulators, power converter topologies and architectures, and modular standards for conversion.

Example Technologies

- Modular power converters
- Electrical propulsion power processing units (power electronics related to electric propulsion)
- High-voltage power topologies for instrument power supplies
- Solar energy stored as high-energy-density chemical fuels
- Superconducting magnetic energy storage
- Other non-chemical storage devices

TX03.3.4 Advanced Electronic Parts

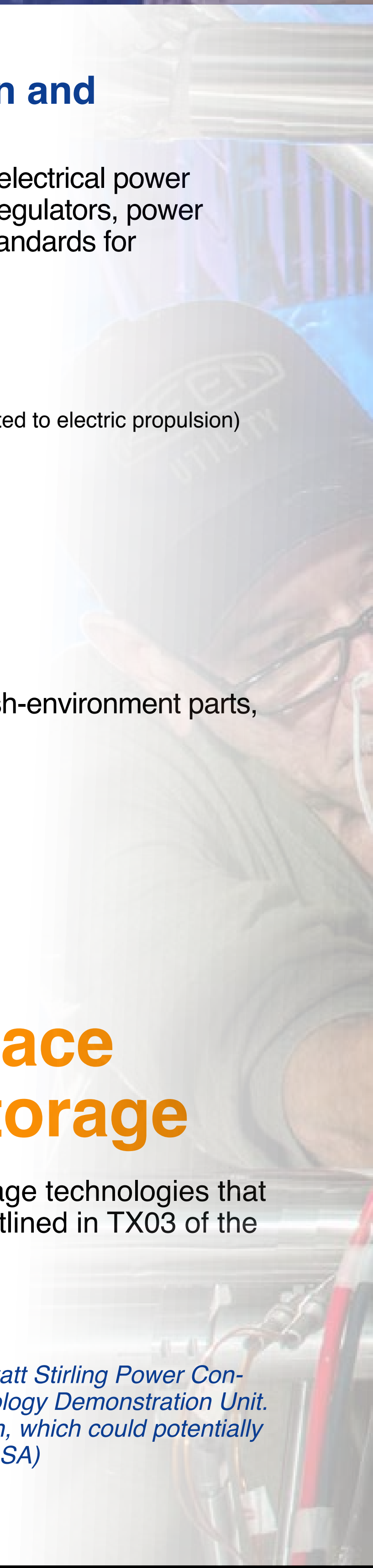
Advanced electronic parts include high-power and harsh-environment parts, components, and subsystems.

Example Technologies

- High-voltage semiconductors and passive components
- Extreme radiation-hardened power distribution

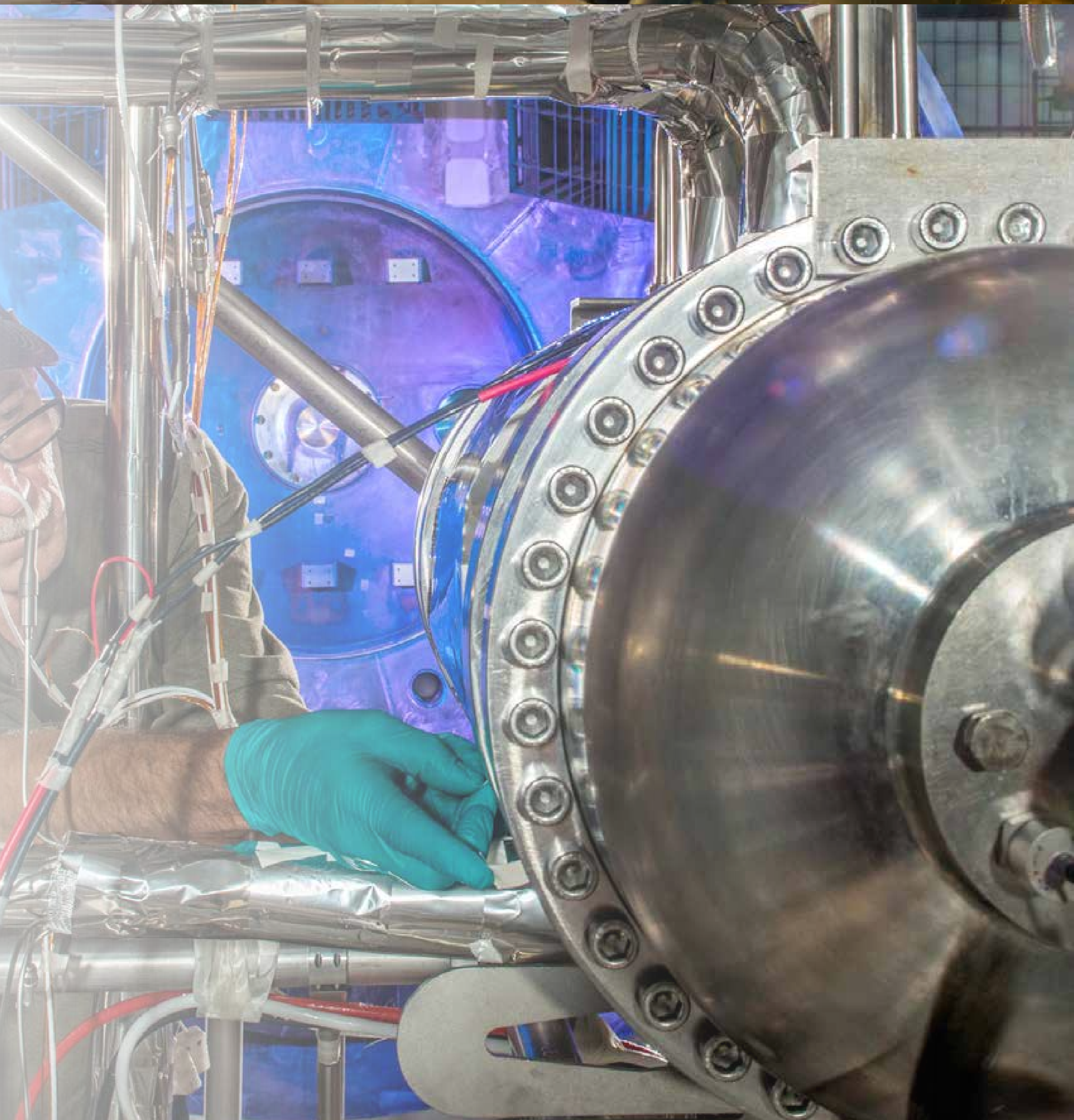
TX03.X Other Aerospace Power and Energy Storage

This area covers Aerospace Power and Energy storage technologies that are not otherwise covered by the sub-paragraphs outlined in TX03 of the 2020 NASA Technology Taxonomy.



NASA Glenn Technician Mark Springowski works on a 10-kilowatt Stirling Power Conversion Unit, which is part of the Fission Surface Power Technology Demonstration Unit. This is a system level demonstration of a surface power system, which could potentially be used to support manned missions to the moon or Mars. (NASA)

TX03 Aerospace Power and Energy Storage



TX04

Robotic Systems

Overview

For human exploration, robots will be leveraged as precursor explorers preceding crewed missions, as crew helpers, as extravehicular activity (EVA) mobility aids, and as caretakers of assets left behind. For science exploration, robots will blaze new trails on distant and hostile worlds to better our understanding of the universe and to extend the reach of the human race. By expanding our planetary access capability, manipulating assets and resources, and understanding planetary bodies using remote and in-situ sensors, we can prepare planets for human arrival, support crews in-space operations, and manage assets left behind.

TX04 Robotic Systems

TX04.1 Sensing and Perception

4.1.1 Sensing for Robotic Systems

4.1.2 State Estimation

4.1.3 Onboard Mapping and Data Analysis

4.1.4 Object, Event, and Activity Recognition

TX04.2 Mobility

4.2.1 Below-Surface Mobility

4.2.2 Above-Surface Mobility

4.2.3 Small-Body and Microgravity Mobility

4.2.4 Surface Mobility

4.2.5 Robot Navigation and Path Planning

4.2.6 Collaborative Mobility

TX04.3 Manipulation

4.3.1 Dexterous Manipulation

4.3.2 Grappling Technologies

4.3.3 Contact Dynamics Modeling

4.3.4 Sample Acquisition and Handling

TX04.4 Human-Robot Interaction

4.4.1 Multi-Modal and Proximate Interaction

4.4.2 Distributed Collaboration and Coordination

4.4.3 Remote Interaction

TX04.5 Autonomous Rendezvous and Docking

4.5.1 Relative Navigation Sensors

4.5.2 Rendezvous and Docking Algorithms

4.5.3 Rendezvous, Proximity Operations, and Capture (RPOC) Flight and Ground Systems

4.5.4 Capture Sensors

4.5.5 Capture Mechanisms and Fixtures

4.5.6 Robot Control for Vehicle Capture and Berthing

4.5.7 Modeling, Simulation, Analysis, and Test of Rendezvous, Proximity Operations, and Capture

TX04.6 Robotics Integration

4.6.1 Modularity, Commonality, and Interfaces

4.6.2 Modeling and Simulation for Robots

4.6.3 Robot Software

TX04 Robotic Systems

NASA's R5 robot studying a doorknob during the Darpa Robotics Challenge in Miami in December 2013. (NASA)

TX04.1 Sensing and Perception

Sensing and perception provides situational awareness for exploration robots, human-assistive robots, and autonomous vehicles and improves drones and piloted aircraft navigation and flight.

TX04.1.1 Sensing for Robotic Systems

Robotic sensing capabilities and situational awareness are needed for robotic operations that involve interaction with the environment. Additional sensing types increase the exploration range of surface and below-surface mobility systems, assist in detecting landing hazards in planetary exploration, and enable robotic manipulation in space without close human supervision.

Example Technologies

- Space-qualifiable force and torque sensors
- Space-qualifiable tactile sensors
- Three dimensional (3D) range imaging sensors for surface mobility, above-surface mobility, and manipulation
- In-situ camera geometric calibration diagnostics and self-calibration

TX04.1.2 State Estimation

State estimation uses inputs from inertial sensors, vision systems, and other sensors to provide essential knowledge of the relative position, attitude, and motion of the vehicle near or on the surface of other bodies, as well as the internal state of the system (i.e. system health status).

Example Technologies

- Vision-based aiding of dead reckoning for navigation of surface vehicles
- Map-based position estimation for navigation of surface vehicles
- Vision-based aiding of dead reckoning for above-surface vehicles
- Map-based position estimation for navigation of above-surface vehicles
- Radio frequency (RF) navigation aiding for above-surface vehicles
- Altimeter for small above-surface vehicles
- Manipulator state estimation
- Manipulation object state estimation

TX04.1.3 Onboard Mapping and Data Analysis

Onboard mapping and analysis provides maps of natural terrain and human-made surfaces and structures, as well as surface and subsurface property maps that aid in robot navigation or manipulation of objects. Onboard mapping of complex 3D structures, such as lava tubes and human-made space structures, is needed for some advanced planetary characterization scenarios, as well as in-space robotic servicing.

Example Technologies

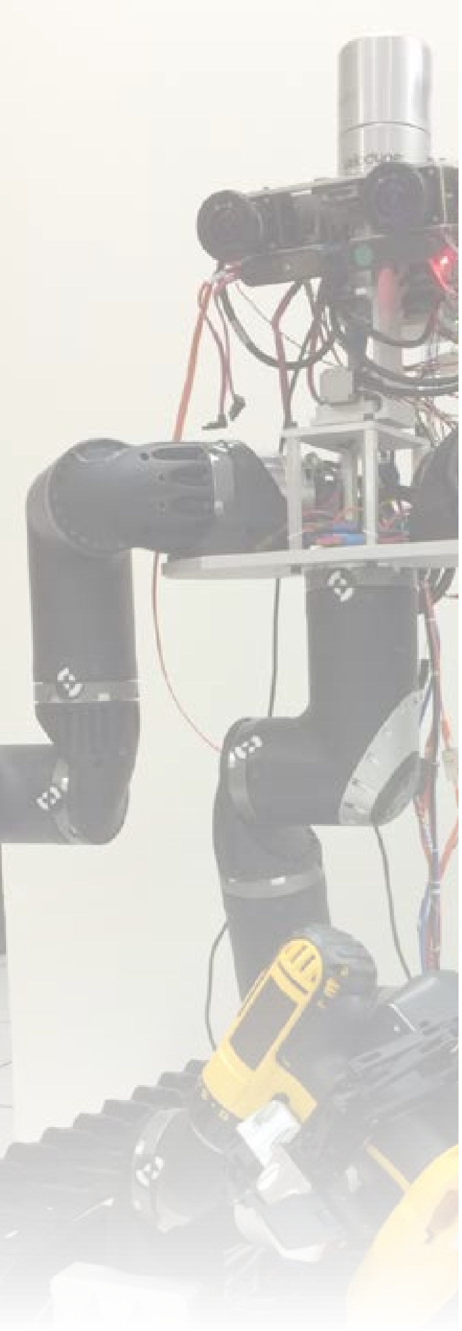
- Terrain mapping and classification
- Landmark mapping from image sequences and other navigation data
- Three dimensional (3D) modeling from multiple observations

TX04.1.4 Object, Event, and Activity Recognition

Object, event, and activity recognition of static objects, dynamic natural events, and dynamic human activities near the vehicle provides awareness of these items and enables onboard decisions about how to react to them. Natural objects that are important to recognize include: landmarks that facilitate navigation; obstacles to rovers or landers; and objects that are important to science investigations, such as geologic targets and atmospheric phenomena.

Example Technologies

- Natural object recognition
- Human-made object recognition
- Event recognition



TX04.2 Mobility

Mobility provides coverage and access for space exploration and can be enhanced or expanded through advances in component technologies, such as actuation and structures.

TX04.2.1 Below-Surface Mobility

Below-surface mobility offers access to traverse across and in extreme terrain topographies, through natural and human-made cavities and holes including deep craters, gullies, canyons, lava tubes, and soft, friable terrains for finding the best samples for scientific analysis.

Example Technologies

- Subsurface access through natural cavities
- Subsurface access through human-made holes
- Burrowing mobility
- Long-endurance submerged mobility

TX04.2.2 Above-Surface Mobility

Above-surface mobility provides longer range and greater coverage of planetary surfaces at a more rapid pace, independent of the terrain topography and in substantial gravity and extreme heat or cold.

Example Technologies

- Ballistic systems
- Static-lift systems
- Dynamic-lift systems
- Power-lift systems

The Surrogate robot ("Surge") was built at NASA's Jet Propulsion Laboratory in Pasadena, California. Researchers are developing it in order to extend humanity's reach into hazardous environments to perform tasks such as using environmental test equipment, closing valves, or gaining access to closed compartments. (NASA)

TX04.2.3 Small-Body and Microgravity Mobility

Small-body and microgravity mobility provides surface coverage and in-situ access to designated targets on small bodies with low gravity, as well as in-space mobility inside and around the International Space Station (ISS) or other space assets. Major challenges include fine control of mobility platforms, power, communication, thermal cycling, and mobility in shadowed regions.

Example Technologies

- Free-floating robots
- Hopping/tumbling surface robots
- Anchoring robots
- Wheeled/tracked/hybrid robots

TX04.2.4 Surface Mobility

Surface mobility provides long-range exploration with large payload mass fractions and modest energy budgets while increasing the traverse speed of both manned and unmanned planetary rovers.

Example Technologies

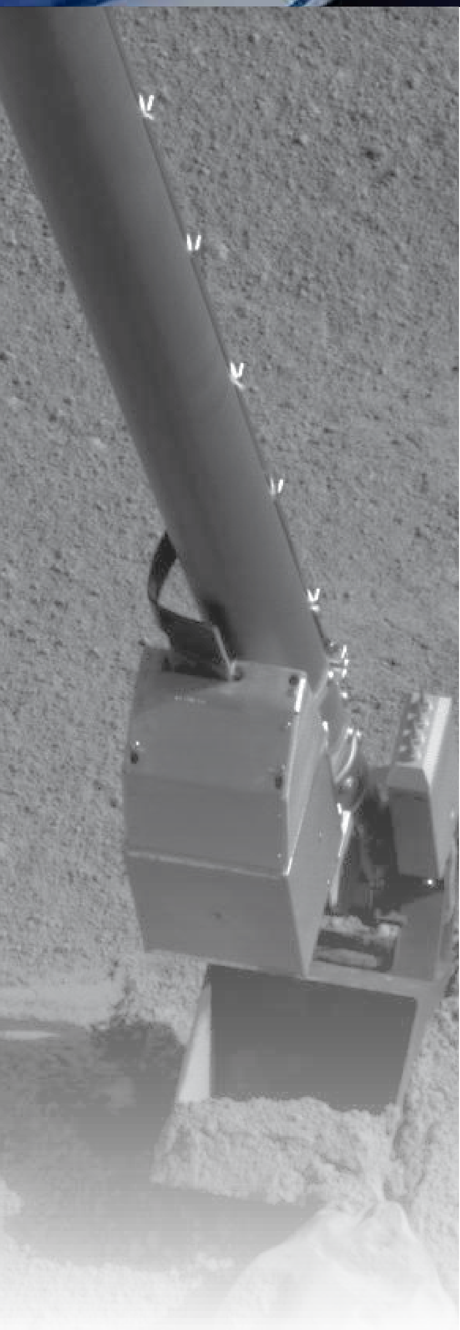
- Mobility subsystem for crewed surface transport
- Mobility system for uncrewed surface transport
- Rappelling mobility systems
- Climbing mobility systems
- Soft/friable terrain mobility systems

TX04.2.5 Robot Navigation and Path Planning

Robot navigation and path planning provides a highly reliable, well-characterized, and fast autonomous or semi-autonomous mobility capability to navigate to designated targets on planetary surfaces (surface, below-surface, or above-surface).

Example Technologies

- Adaptive autonomous surface navigation
- Autonomous navigation for tethered systems
- Onboard real-time planning and scheduling
- Ground-based mixed initiative planning and scheduling
- Plan/sequence/schedule verification tools
- Onboard executives and state management
- Low-altitude above-surface navigation
- Below-surface and small-body/microgravity navigation



Phoenix robotic arm connects with "Alice," a rock of interest on the Martian surface. (NASA)

TX04.2.6 Collaborative Mobility

Collaborative mobility provides an ability to distribute or collaborate on tasks using multiple mobile platforms or using a combination of platforms and crew. It also provides cooperative mobility including cooperation of surface and above-surface assets for both terrestrial and planetary science missions (for example, mapping, seismic sounding or atmospheric transmission spectroscopy), and additionally can expedite engineering and construction of habitats.

Example Technologies

- Collaborative mobility algorithm
- Manipulation for collaborative mobility, including swarms

TX04.3 Manipulation

Manipulation positions crewmembers and instruments in space and on planetary bodies. It also provides the capability to extract and handle samples of multiple forms and scales from various depths.

TX04.3.1 Dexterous Manipulation

Dexterous manipulation provides the capability for a robot to reliably handle, position, and control objects and interfaces on spacecraft, equipment, tools, flexible bags, and natural objects. Dexterous manipulation also allows robots to achieve compliant force/force resolution for safe operations in the vicinity of humans and in deep-space environments.

Example Technologies

- Dexterous manipulator arms
- Dexterous manipulator end effectors
- Robust, safe, and efficient manipulator control schemes

TX04.3.2 Grappling Technologies

Grappling technologies capture, hold, and manipulate natural and human-made free-flying objects. Grappling systems that can operate in deep space environments enable capturing of orbiting sample caches for sample return missions, and increase vision and control system capabilities to handle larger structures for assembly of on-orbit spacecraft for future human exploration missions to near-Earth asteroids (NEAs) and planetary bodies.

Example Technologies

- Robots that can grapple objects and free-flying spacecraft using surface features, then berth them to the robot's spacecraft through a rigidized interface
- Advanced ground control techniques
- Advanced vision and control systems for enhancing situational awareness and control of large objects

TX04.3.3 Contact Dynamics Modeling

Contact dynamics modeling provides an understanding of forces/torques generated on objects and platforms through mobility or manipulation. The results can be used to prevent harm to the contacting bodies and assure that the contact characteristics support the mission.

Example Technologies

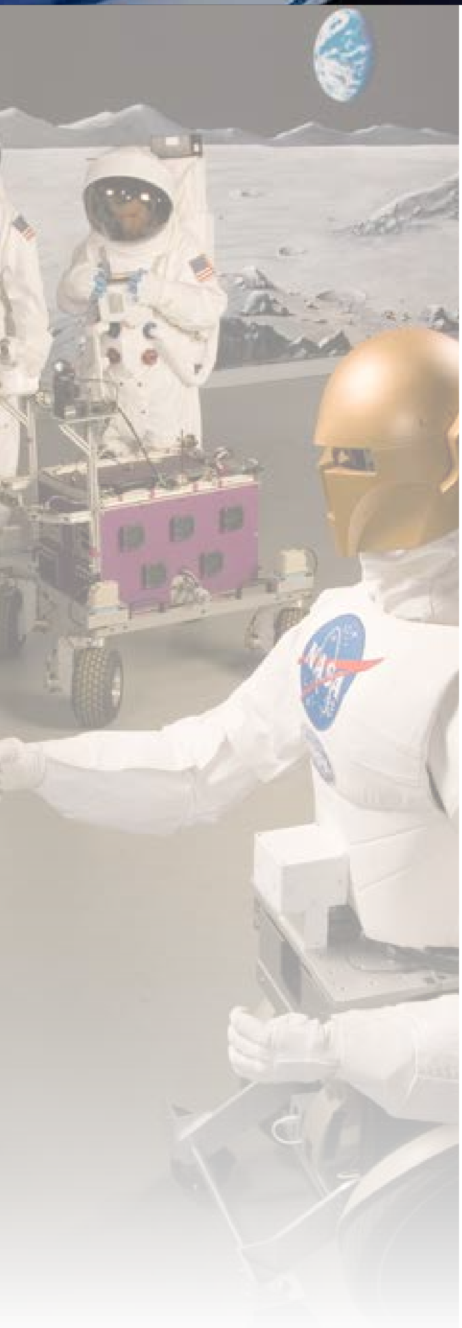
- End-to-end systems modeling
- Modeling of contact dynamics
- Dynamic simulation
- Granular media simulation

TX04.3.4 Sample Acquisition and Handling

Sample acquisition and appropriate handling includes the actions and means to extract or collect, move, transfer, or modify samples (regolith, cuttings, volatile samples) that have been acquired, loading them into instruments or packaging systems for analysis.

Example Technologies

- Robotic and deep robotic drilling
- Surface/shallow robotic sample acquisition
- Subsurface robotic sample acquisition
- Sample handling
- Regolith/volatiles sample handling and transfer
- Robotic excavation
- Sterilization of drilling equipment at destination
- Biobarriers for drilling equipment to maintain sterile condition



Johnson Space Center's Robonaut (foreground) performing a mock weld while Ames Research Center's K10 robot assists two EVA crew inspecting a previously welded seam. (NASA)

TX04.4 Human-Robot Interaction

Human-robot system interaction is crucial for future space exploration and must be effective, efficient, and natural. Space exploration requires human-system interaction across multiple spatial ranges, in the presence of multiple control loops, and over a wide range of time delays. A robot may be remotely operated by an astronaut in close proximity, by an astronaut in-orbit above a planetary surface, or by mission controllers on Earth with progressive reductions in situational awareness and response time. The ultimate efficacy of robotic systems depends greatly upon the interfaces that humans use to operate them.

TX04.4.1 Multi-Modal and Proximate Interaction

Multi-modal interaction allows for humans to interact with robots using multiple modes of communication, e.g. voice, gesture recognition. Proximate interaction allows for humans to interact with a robot side-by-side. Technologies to assist in these can enable humans to safely and efficiently control a larger number of robotic and autonomous assets, reducing overall demands on astronauts' time for future exploration missions.

Example Technologies

- Virtual environment (VE)
- Multi-modal dialogue
- Robot-to-suit interfaces
- Intent recognition and reaction
- Feedback displays for proximate interaction

TX04.4.2 Distributed Collaboration and Coordination

Distributed collaboration and coordination provides a distributed system that is capable of managing control and telemetry information among heterogeneous agents and offers more effective interaction between humans and machines, reducing overall demands on astronauts' time for future missions.

Example Technologies

- Interaction architecture
- In-line performance metrics
- Notification and summarization

TX04.4.3 Remote Interaction

Remote interaction allows supervisory control of complex remote systems across a space in the presence of varying communication latencies, bandwidths, and dropouts.

Example Technologies

- Supervisory control
- Decision support tools for remote interaction

TX04.5 Autonomous Rendezvous and Docking

Autonomous rendezvous and docking (AR&D) enable future human and robotic missions. The goal is to provide a robust, safe AR&D capability for human and robotic systems that reduces the reliance on human interaction.

TX04.5.1 Relative Navigation Sensors

Relative navigation sensors improve detector sensitivity, reliability, field of view, and performance, thus permitting two vehicles to rendezvous, perform proximity operations, and dock/capture anywhere in the solar system, independent of communications with the ground.

Example Technologies

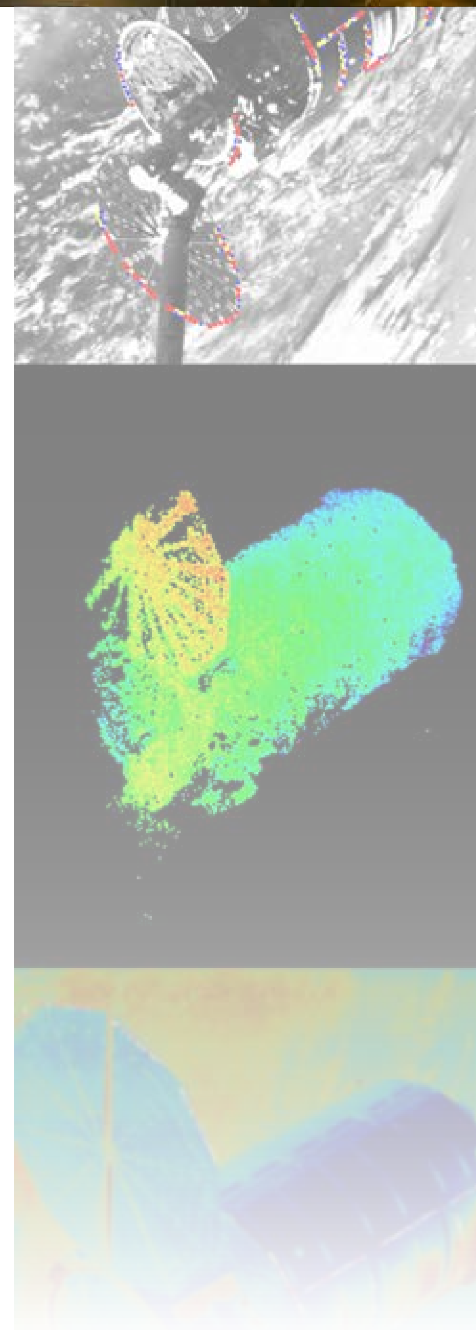
- Three dimensional (3D) imaging sensor
- Visible camera
- Long-wave infrared (LWIR) camera

TX04.5.2 Rendezvous and Docking Algorithms

Rendezvous and docking algorithms are independent of gravity fields and provide more robust and flexible software at lower cost to address a wider range of future missions that require AR&D.

Example Technologies

- Rendezvous targeting
- Proximity operations/capture/docking guidance



Raven, attached to ISS, is designed to test autonomous rendezvous. Raven images in visible (top), lidar (center), and infrared (bottom) of a Cygnus spacecraft visiting the ISS. (NASA)

TX04.5.3 Rendezvous, Proximity Operations, and Capture (RPOC) Flight and Ground Systems

Rendezvous, proximity operations, & capture (RPOC) flight and ground systems include tools and techniques for RPOC system architectures, requirements, and specifications; fault management and fault tolerance; development of standards; operations tools and best practices; and other system support functions related to RPOC.

Example Technologies

- Cislunar module aggregation/assembly flight system RPOC architecture
- Large telescope assembly aggregation/servicing flight system RPOC architecture
- Gateway visiting vehicles RPOC monitoring architecture
- Lunar/Mars sample return RPOC architecture
- Precision formation flying architecture
- Robotic grapple and berth (Low Earth Orbit (LEO), Beyond LEO, Crew Assisted, Autonomous)
- Small sat inspection of large assets
- Legacy vehicle servicing RPOC architecture
- Orbit debris remediation
- Cislunar/Mars RPOC ground/mission system architecture

TX04.5.4 Capture Sensors

Capture sensors, which include force, moment, strain, contact, and proximity sensors, sense the close proximity or contact with spacecraft or natural objects during capture.

Example Technologies

- Robot arm force moment sensor
- Robotic tool contact sensors
- Robot close proximity sensors
- Docking and berthing contact sensors

TX04.5.5 Capture Mechanisms and Fixtures

Technologies that enable a spacecraft to affect capture and release of another spacecraft or natural space object (small body) include robotic manipulators and tools for grapple, small body sampling systems, orbiting sample collection systems, orbit debris capture systems, and any other system used to affect capture of an object. Additionally, these technologies can include those that are specifically designed to facilitate capture, such as passive grappling. Note: The docking and berthing aspect of mechanism fixtures is captured in TX12.3.8 Docking and berthing mechanisms and fixtures.

Example Technologies

- Dexterous / long reach robotics
- Grapple tools (cooperative, Marman Ring, Rock, Sample Canister)
- Other grippers
- Touch and go sampling mechanism
- Sample canister retrieval mechanism
- Robotic grapple and berth (Low Earth Orbit (LEO), Beyond LEO, Crew Assisted, Autonomous)
- Orbiting sample capture mechanism
- Harpoon, net, passive grapple

TX04.5.6 Robot Control for Vehicle Capture and Berthing

Robot control technologies primarily constitute the development of robust, reliable, and computationally efficient mathematical algorithms and processes for the functions of autonomous real-time control of robotic manipulators to meet mission requirements.

Example Technologies

- Robotic manipulator capture of free-flying spacecraft
- Robotic manipulator positioning of grappled vehicle for berthing (both with low mass ratio and high mass ratio between captured and capturing vehicles)

TX04.5.7 Modeling, Simulation, Analysis, and Test of Rendezvous, Proximity Operations, and Capture

Technologies/techniques for the development of advanced software tools to model, simulate and analyze the dynamic response of space vehicles, robotic manipulators, and other capture systems to forces exerted by actuators (e.g. thrusters, wheels, motors), the environment, or an active spacecraft on a nearby object (contact dynamics, thruster plume impingement). Also included are technologies for the development of modern ground-based guidance navigation and control (GN&C), robotic, and capture motion simulation testbeds.

Example Technologies

- Multi-vehicle closed loop hi-fidelity attitude and orbit simulation
- Capture contact dynamics
- Flexible modes analysis
- Finite element modeling (FEM) analysis
- Proximity operations thruster plume impingement modeling and analysis
- Robotic manipulator kinematic simulation (reach and access, etc.)
- Robotic manipulator high fidelity dynamics simulation of capture and berthing
- Relative navigation sensor hardware-in-the-loop (HWIL) testing of vehicle and small body proximity operations
- Grapple, berthing, docking, and small body contact (Touch-and-Go (TAG)/landing) HWIL testing with high fidelity 6DOF motion and contact dynamics
- High fidelity synthetic image generation for testing of vehicle- and terrain-relative pose/nav estimation systems

TX04.6 Robotics Integration

Robotic systems are inherently multi-disciplinary and complex, and they may include heterogeneous teams that work together or with humans to achieve a common goal. Systems engineering provides the framework for achieving this coordination and integration.

TX04.6.1 Modularity, Commonality, and Interfaces

Modularity, commonality, and interface aims to increase the flexibility of robotic systems, such as cooperating heterogeneous robots and common human-robot interfaces. Desired technical capabilities include modular and common interfaces to allow for changes in operations and services in the field.

Example Technologies

- Refueling Interfaces
- Self-assembling robots
- Self-configuring robots
- Marsupial robot interfaces
- Human machine interface standards

TX04.6.2 Modeling and Simulation for Robots

Robot modeling and simulation includes software tools to assist in synthesis, trade studies, and optimization of complex robotic systems. They also include the ability to preview and optimize operations using concurrent dynamic simulation of alternative control options.

Example Technologies

- End-to-end system modeling
- Modeling of contact dynamics
- Dynamic simulation
- Granular media simulation
- Human-in-the-loop assessment systems

Astrobee is a system of three free-flying, cube-shaped robots and a recharging station that operates inside the International Space Station. (NASA)

TX04.6.3 Robot Software

Robot software provides architectures, frameworks, design patterns, and advances in software to enable the realization of intelligent robots from component technologies and provide standardized interfaces and messages. Challenges include managing overall software complexity, striking the right balance between flexibility and complexity, and addressing heterogeneity of hardware.

Example Technologies

- Robotic architectures and frameworks
- Standardized messaging protocols
- Model-based robotic software
- Robot operating systems

TX04.X Other Robotic Systems

This area covers robotic system technologies that are not otherwise covered by the sub-paragraphs outlined in TX04 of the 2020 NASA Technology Taxonomy.

Drew Smith, a robotics engineer, makes adjustments to the Regolith Advanced Surface Systems Operations Robot (RASSOR) during testing in the regolith bin inside Swamp Works at NASA's Kennedy Space Center in Florida on June 5, 2019. (NASA)

TX04 Robotic Systems

TX05

Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Overview

Space communications and navigation infrastructure is the means of transferring commands, spacecraft telemetry, mission data, and voice for human exploration missions, while maintaining accurate timing and providing navigation support. Orbital debris can be tracked and characterized by some of the same systems used for spacecraft communications and navigation, as well as by other specialized systems. Orbital debris tracking and characterization systems can be improved using radio frequency and optical techniques similar to those used in communications and navigation systems, as well as other dedicated systems.

TX05 Communications, Navigation, and Orbital Debris Tracking and Characterization

TX05.1 Optical Comm

5.1.1 Detector Development

5.1.2 Large Apertures

5.1.3 Lasers

5.1.4 Positioning, Acquisition, and Tracking (PAT)

5.1.5 Atmospheric Mitigation

5.1.6 Optimetrics

5.1.7 Innovative Signal Modulations

TX05.2 Radio Frequency

5.2.1 Spectrum-Efficiency

5.2.2 Power-Efficiency

5.2.3 Atmospheric Characterization and Mitigation

5.2.4 Flight and Ground Systems

5.2.5 Launch and Re-Entry Comm

5.2.6 Innovative Antennas

5.2.7 Innovative RF Technologies

TX05.3 Inter-networking

5.3.1 Disruption Tolerant Networking

5.3.2 Adaptive Network Topology

5.3.3 Information Assurance

5.3.4 Integrated Network Management

TX05.4 Network Provided PNT

5.4.1 Timekeeping and Time Distribution

5.4.2 Revolutionary PNT Technologies

TX05.5 Revolutionary Comm Technologies

5.5.1 Cognitive Networking

5.5.2 Quantum Comm

5.5.3 Hybrid Radio and Optical Technologies

TX05.6 Networking and Ground Based Orbital Debris Tracking and Management

5.6.1 Orbital Debris Tracking

5.6.2 Orbital Debris Characterization

5.6.3 Orbital Debris Mitigation

5.6.4 Orbital Debris Monitoring Software

TX05.7 Acoustic Comm

TX05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

This is a 3-foot 1-meter aperture main telescope located at the NASA Jet Propulsion Laboratory Optical Communications Telescope Laboratory ground station. (NASA)

TX05.1 Optical Communications

Optical communications includes technologies required to make communications with light practical and take advantage of the virtually unconstrained bandwidth available in the optical spectrum.

TX05.1.1 Detector Development

Detector development includes the development of high detection efficiency, low-dark-count, low-jitter photon counting detectors and readout systems for both ground and flight applications.

Example Technologies

- Tungsten silicide (WSi) superconducting arrays
- High T superconducting arrays (e.g., MgB2)
- Indium gallium arsenide (InGaAs) flight arrays

TX05.1.2 Large Apertures

Large apertures are multi-meter diameter optical apertures for both ground (> 10 meters diameter) and flight (> 5 meters diameter) applications.

Example Technologies

- Virtual, large, ground-based apertures
- Lightweight, space-based, large aperture optics
- Space-based optical arrays

TX05.1.3 Lasers

Lasers in this area are high direct current-to-optical power efficiency, high peak-to-average power, reliable, and flight-qualified.

Example Technologies

- High direct current-optical efficiency
- Greater than 10W
- Space-qualified pulse-position modulation (PPM) laser transmitter

TX05.1.4 Pointing, Acquisition, and Tracking (PAT)

PAT techniques and technologies provide efficient, accurate pointing of the optical terminal and acquisition and tracking of the optical signal, primarily in flight. PAT may also include interaction with the ground terminals or be "beaconless."

Example Technologies

- Disturbance-free platform
- Autonomous high-accuracy star tracker

TX05.1.5 Atmospheric Mitigation

Atmospheric mitigation measures and models the atmospheric channel and its effects on optical propagation, as well as mitigating atmospheric effects on both uplink and downlink.

Example Technologies

- Solar differential image motion monitor (DIMM)
- Daytime adaptive optics for uplink and downlink
- Weather forecasting for handover

TX05.1.6 Optimetrics

Optimetrics includes optical techniques for ranging, Doppler, and astrometric measurement derived from the optical communications signal.

Example Technologies

- Embedded optical tracking for spacecraft navigation

TX05.1.7 Innovative Signal Modulations

Innovative signal modulations include technologies for modulating intersatellite links and direct-to-Earth communications with optics receivers.

Example Technologies

- Coherent modulation/demodulation systems
- Modulating retro-reflectors

TX05.2 Radio Frequency

Radio frequency technology development seeks to increase the productivity of the constrained spectrum bands that are allocated to space users.

TX05.2.1 Spectrum-Efficiency

Spectrum-efficiency includes flight and ground techniques and technologies that allow more efficient utilization of the radio frequency (RF) spectrum.

Example Technologies

- Advanced interference management
- Adaptive spectrum sharing/management
- Bandwidth efficient modulations

TX05.2.2 Power-Efficiency

Power-efficiency includes flight and ground techniques and technologies that make more efficient use of the available system power.

Example Technologies

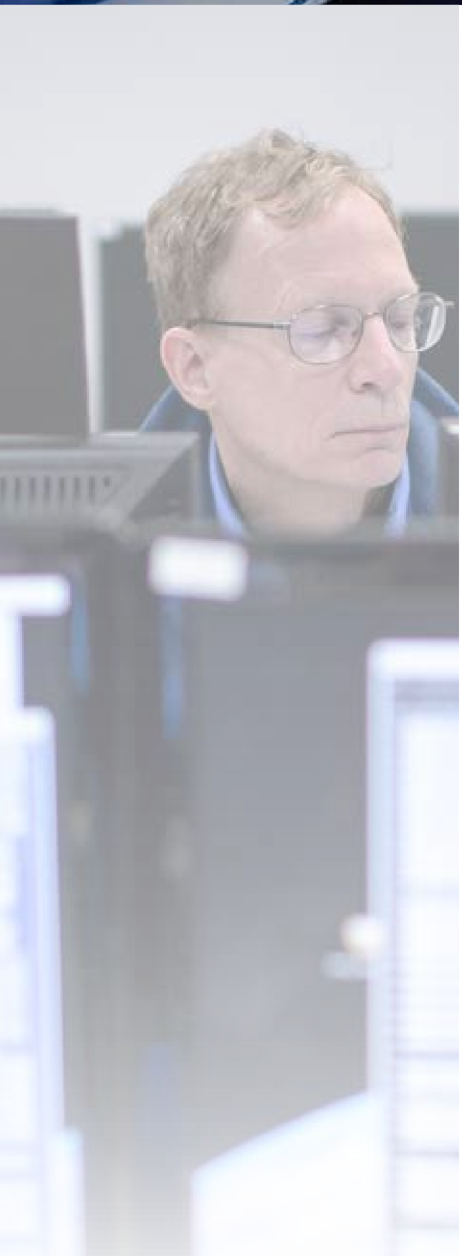
- Traveling wave tube amplifiers (TWTAs)
- Solid-state power amplifiers (SSPAs)

TX05.2.3 Atmospheric Characterization and Mitigation

Atmospheric characterization and mitigation measures and models the RF channel and its effects on RF propagation, as well as mitigating these effects.

Example Technologies

- LEO Ka-band propagation studies



NASA GPM Radio Frequency Engineer David Lassiter monitors the progress of an all-day launch simulation for the Global Precipitation Measurement (GPM) Core Observatory at the Spacecraft Test and Assembly Building 2 (STA2). (NASA/Bill Ingalls)

TX05.2.4 Flight and Ground Systems

Flight and ground systems aim to reduce mass, power, and cost requirements on spacecraft; reduce dependence on manual control from Earth; and reduce ground operations reconfiguration times (while improving network security).

Example Technologies

- Cognitive networks
- Ultra wideband systems
- Intelligent, multipurpose software defined radio

TX05.2.5 Launch and Re-Entry Communications

Launch and re-entry communications mitigate the communications and tracking effects occurring during Earth launch and reentry.

Example Technologies

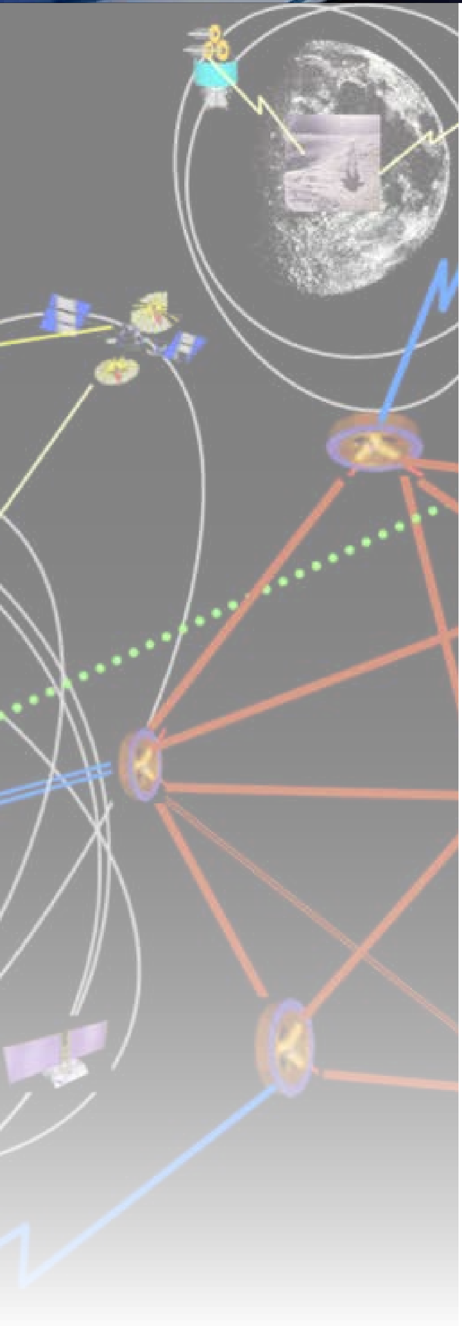
- Mitigation of reentry plasma effects

TX05.2.6 Innovative Antennas

Flight and ground antennas provide more innovative effective apertures than those currently in operation, with high efficiency but lower mass per unit area and accurate pointing.

Example Technologies

- Deployable antennas
- Phased array antennas
- Atmospheric phase compensation for uplink arrays at Ka-Band
- Small-satellite distributed multiple input multiple output (MIMO)
- Conformal, low-mass antenna systems
- Antenna array architecture enablers



The Disruption Tolerant Network protocols will enable the Solar System Internet, allowing data to be stored in nodes until transmission is successful. (NASA)

TX05.2.7 Innovative RF Technologies

Innovative RF technologies include flight and ground radio frequency electronics that are higher frequency, wider bandwidth, more efficient, and more linear than those currently in operation.

Example Technologies

- GaN on diamond
- Monolithic Microwave Integrated Circuit (MMIC)
- Non-hermetic hybrids
- Advanced substrate materials
- Advanced printed wiring board (PWB) materials
- Advanced interconnects
- Use of digital CMOS technology for RF applications

TX05.3 Internetworking

Internetworking deals with the adaptation of Earth's Internet technology and processes throughout the solar system.

TX05.3.1 Disruption Tolerant Networking

Disruption tolerant networking (DTN) techniques and technologies provide data delivery across multiple data links that may be disrupted and/or have long delays.

Example Technologies

- DTN basic services

TX05.3.2 Adaptive Network Topology

Adaptive network topologies and protocols, including mesh networking, are capable of optimizing data connectivity among elements in spaceflight or on planetary surfaces.

Example Technologies

- Ad hoc and mesh networking of mobile elements
- Disruption tolerant networking routing
- Disruption tolerant networking quality of service

TX05.3.3 Information Assurance

Information assurance techniques and technologies ensure system safety, data integrity, availability, and confidentiality and enable use of all available links and networks—some of which may be provided by other agencies or countries.

Example Technologies

- Security and key Management protocols and techniques for DTN networks
- Techniques to enable dual use of links and networks
- Protocols to enable system self-awareness
- Bundle security protocol

TX05.3.4 Integrated Network Management

Integrated network management architectures and protocols effectively support network operations when network topology includes nodes with disrupted and/or long delay links.

Example Technologies

- Protocols to effectively support autonomous operations with network monitoring, configuration, and control mechanisms

TX05.4 Network Provided Position, Navigation, and Timing

Network Provided Position, Navigation, and Timing (PNT) technologies support onboard space platform guidance, navigation, and control (GN&C) autonomy by reducing reliance on Earth-based systems for ground-based tracking, ranging, trajectory and orbit determination, and maneuver planning and execution functions. This area also includes technologies for space flight dynamics/mission design tools and techniques.

TX05.4.1 Timekeeping and Time Distribution

Timekeeping and time distribution technologies include integrated, space-qualified systems with ultra-high time accuracy and frequency stability, long lifetimes, high operability and reliability, as well as technologies and architectures for distributing precise time and frequency signals or information to distributed points in a network.

Example Technologies

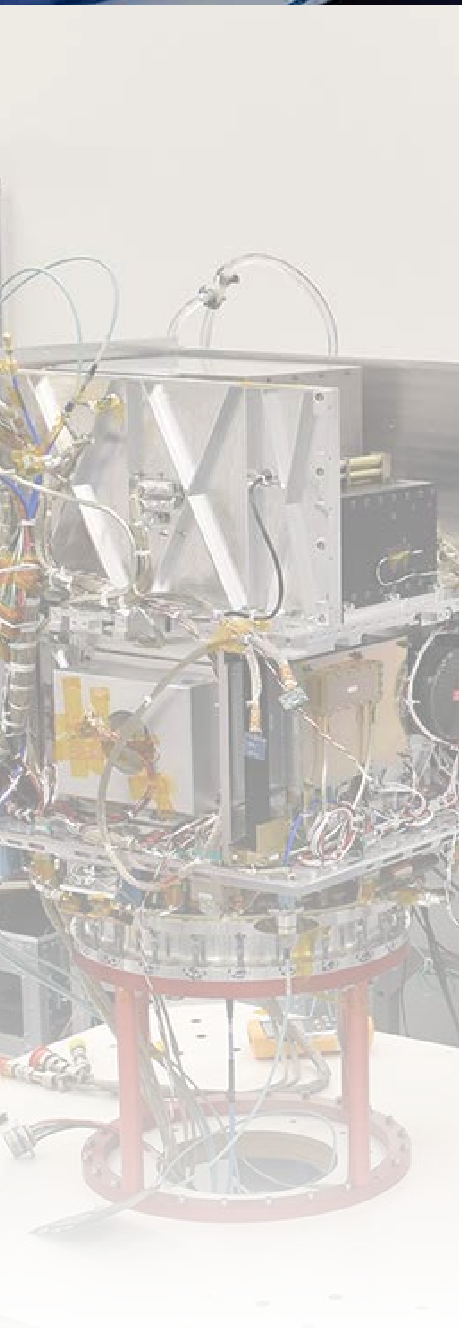
- Atomic clocks
- Ultra-high performance crystal oscillators

TX05.4.2 Revolutionary Position, Navigation, and Timing Technologies

Revolutionary PNT technologies are navigational concepts and technologies that have the potential to enable "game changing" capabilities for future mission architectures.

Example Technologies

- X-Ray navigation
- Neutrino-based navigation and tracking technologies



NASA's integrated Atomic Clock Payload on General Atomics Electromagnetic Systems US's Orbital Test Bed Spacecraft. (NASA)

TX05.5 Revolutionary Communications Technologies

Revolutionary communications concepts and technologies have the potential to enable "game changing" capabilities for future mission and network architectures.

TX05.5.1 Cognitive Networking

Cognitive networking adapts to different scenarios by changing the network and various channels, applying machine learning and artificial intelligence for the system to self-identify networks that are to be used at any given time and self-respond to changing situations.

Example Technologies

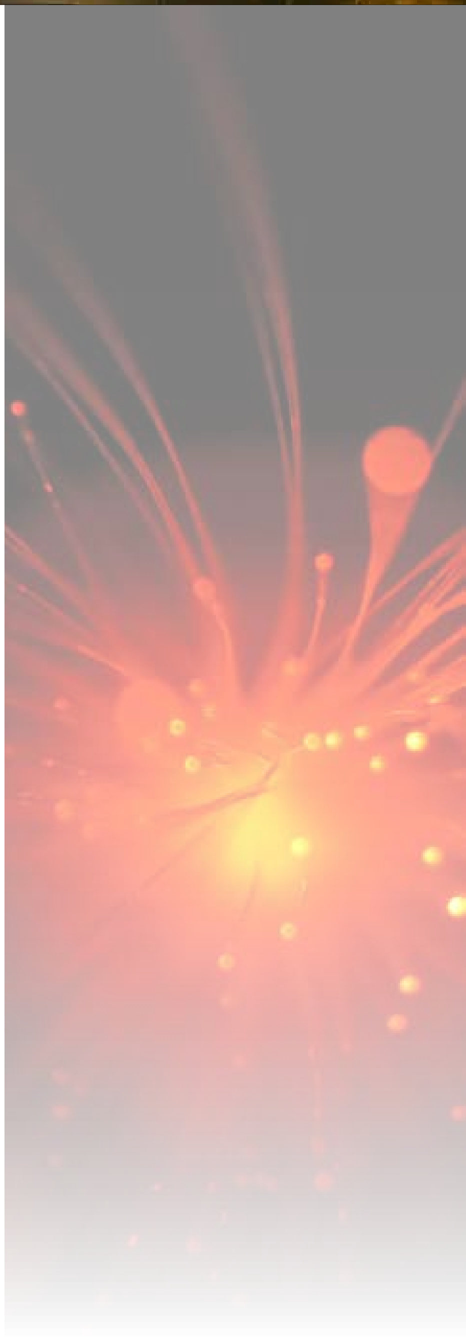
- Cognitive networks
- Cognitive radios
- Cognitive antennas

TX05.5.2 Quantum Communications

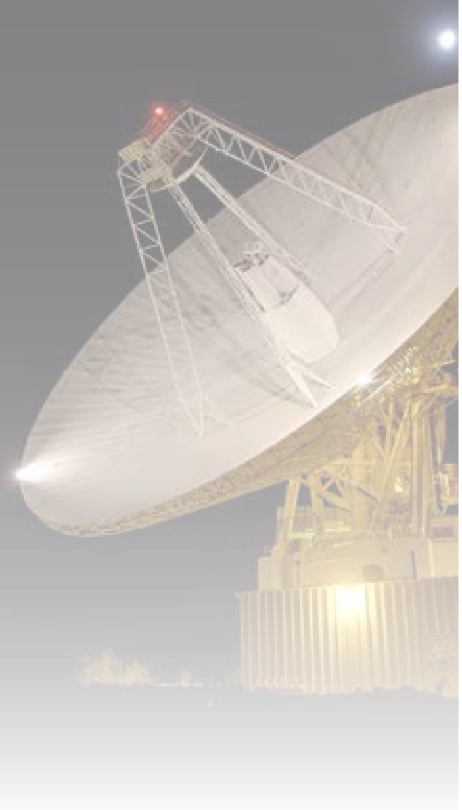
Quantum communications use entangled photons for transmissions, enabling highly secure communication systems.

Example Technologies

- High efficiency photon entangled sources
- Quantum repeaters
- High efficiency quantum detectors
- Quantum cryptography



This image shows crystals used for storing entangled photons, which behave as though they are part of the same whole. Scientists use crystals like these in quantum teleportation experiments. (NASA/Félix Bussières/University of Geneva)



The Goldstone Deep Space Communications Complex, located in the Mojave Desert in California, is one of three complexes that comprise NASA's Deep Space Network (DSN). (NASA/JPL-Caltech)

TX05.5.3 Hybrid Radio and Optical Technologies

Game changing hybrid technologies offer the flexibility of providing high data rates on the RF and optical domain with interchangeable primary and secondary links to optimize data throughput.

Example Technologies

- Teletenna
- Vibration isolation platforms
- Beaconless pointing
- Cognitive control systems
- High data rate protocols

TX05.6 Networking and Ground Based Orbital Debris Tracking and Management

Networking and Ground Based Orbital Debris Tracking and Management aims to develop an international and global network to acquire and track orbital debris or other uncooperative targets to protect space assets.

TX05.6.1 Orbital Debris Tracking

Orbital debris tracking includes environment definition, orbit determination and prediction models, acquisition and tracking technologies, cooperative and uncooperative targets, and monitoring and communications.

Example Technologies

- Radars
- Optical sensors
- Laser ranging

TX05.6.2 Orbital Debris Characterization

Orbital debris characterization technologies provide knowledge of debris characteristics such as shape, behavior, and mass, allowing for better long term orbital predictions and improved modeling for drag, solar radiation pressure (SRP), and altitude dependent forces.

Example Technologies

- Three dimensional (3D) range image sensors for sample acquisition
- Environment modeling
- Autonomous telescope and sensor technologies
- Space-qualifiable tactile sensors

TX05.6.3 Orbital Debris Mitigation

Orbital debris monitoring and collision avoidance limits collision activities, mitigates mission-ending risks to operational payloads, and mitigates risks to human space activities.

Example Technologies

- Robotics
- Sensors for high performance navigation architectures
- Space tubs
- Conductive or momentum-exchange tethers
- Drag augmentation devices
- Solid rocket moor de-orbit devices
- Solar sails
- Sensor systems that feed Light Detection and Ranging (LIDAR) and optical feature recognition data to guidance system including autonomous systems
- Mitigation and remediation technologies and characterization
- Lasers

TX05.6.4 Orbital Debris Monitoring Software Platforms

Orbital debris monitoring software platforms ingest orbital tracking observations, calculate orbits and uncertainties, predict potential collisions, and monitor for orbital changes and collisions.

TX05.7 Acoustic Communication

Acoustic communication technologies make communications with elastic waves at sonic or ultrasonic frequencies and enable transmission through water and ice.

Example Technologies

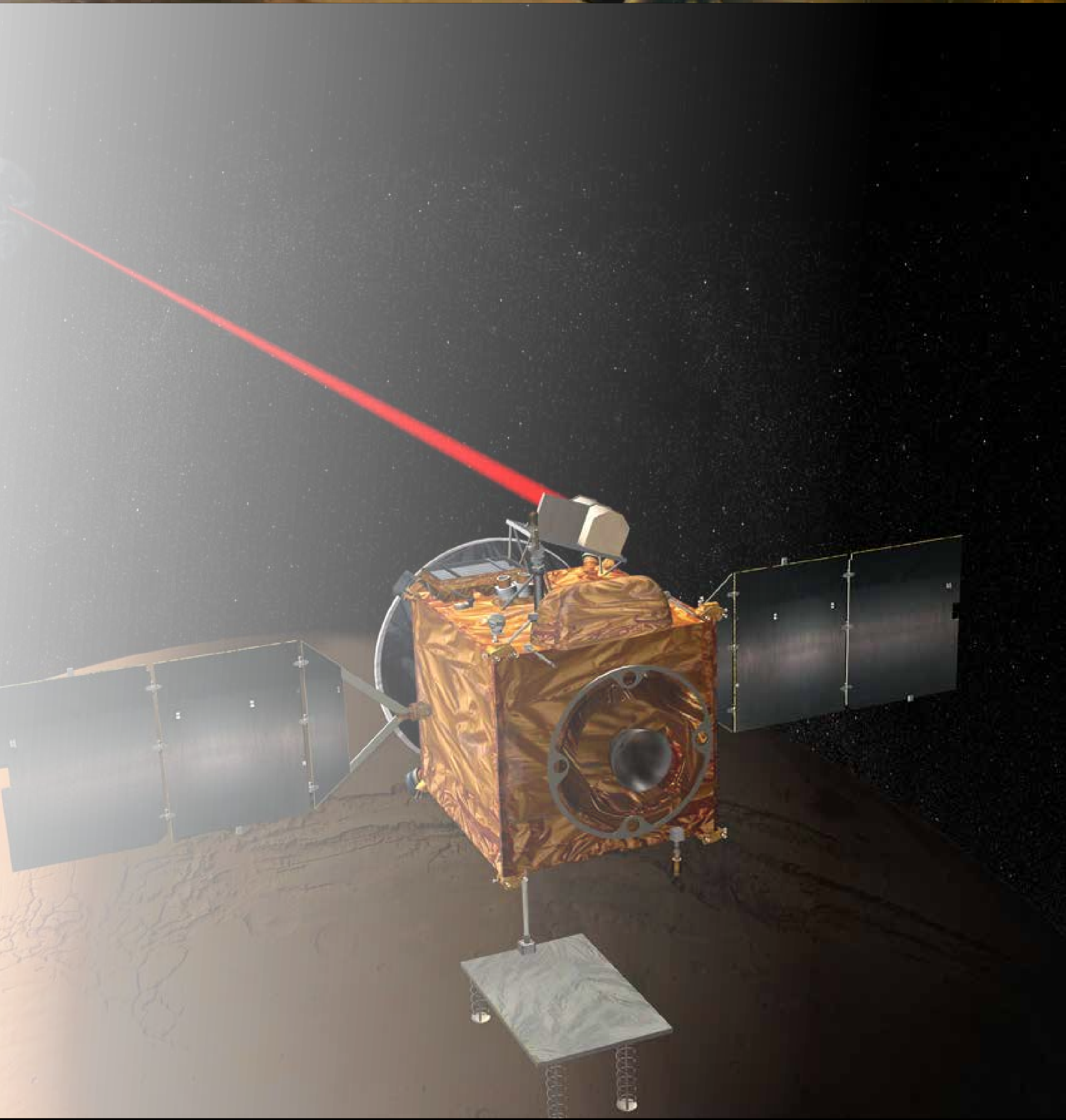
- Sonar
- Acoustic sensors
- Active and passive sensors including geophones and seismic receivers

TX05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

This area covers communications, navigation, and orbital debris tracking and characterization systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX05 of the 2020 NASA Technology Taxonomy.

This illustration depicts a concept for operation of an optical communications system on NASA Mars Telecommunications Orbiter. (NASA)

TX05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems



TX06 Human Health, Life Support, and Habitation Systems

Overview

This section covers technologies that are specific to the human element and directly affect crew needs for survival and wellbeing, including the environment to which the crew is exposed and interfaces that crewmembers encounter.

TX06 Human Health, Life Support, and Habitation Systems

TX06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

6.1.1 Atmosphere Revitalization

6.1.2 Water Recovery and Management

6.1.3 Waste Management

6.1.4 Habitation Systems

6.1.5 ECLSS Modeling and Simulation Tools

TX06.2 Extravehicular Activity Systems

6.2.1 Pressure Garment

6.2.2 Portable Life Support System

6.2.3 Informatics and Decision Support Systems

6.2.4 Decompression Sickness Mitigation

TX06.3 Human Health and Performance

6.3.1 Medical Diagnosis and Prognosis

6.3.2 Prevention and Countermeasures

6.3.3 Behavioral Health and Performance

6.3.4 Contact-less / Wearable Human Health and Performance Monitoring

6.3.5 Food Production, Processing, and Preservation

6.3.6 Long Duration Health

6.3.7 System Transformative Health and Performance Concepts

TX06.4 Environmental Monitoring, Safety, and Emergency Response

6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.2 Fire: Detection, Suppression, and Recovery

6.4.3 Protective Clothing and Breathing

6.4.4 Remediation

TX06.5 Radiation

6.5.1 Radiation Transport and Risk Modeling

6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.3 Protection Systems

6.5.4 Space Weather Prediction

6.5.5 Monitoring Technology

TX06.6 Human Systems Integration

6.6.1 Human Factors Engineering

6.6.2 Training

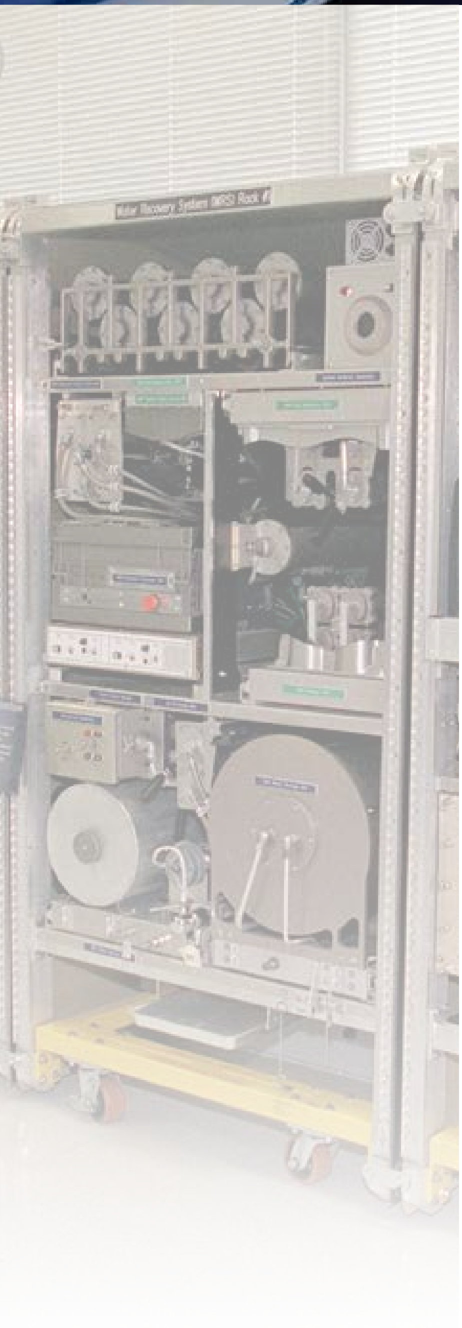
6.6.3 Habitability and Environment

6.6.4 Operations Effectiveness

6.6.5 Integrated Systems Safety

6.6.6 Maintainability and Supportability

TX06 Human Health, Life Support, and Habitation Systems



A mockup of the Water Recovery System (WRS) section of the ECLSS used aboard the International Space Station (ISS). (NASA)

TX06.1 Environmental Control and Life Support Systems (ECLSS) and Habitation Systems

Life support and habitation systems maintain an environment suitable for sustaining human life throughout the duration of a mission.

TX06.1.1 Atmosphere Revitalization

Atmosphere revitalization maintains a safe and habitable atmosphere within a spacecraft, surface vehicle, or habitat.

Example Technologies

- CO2 removal (closed loop), oxygen recovery
- Trace contaminant control
- Particulate and microbial control
- Cabin ventilation
- Oxygen supply
- High-pressure oxygen supply

TX06.1.2 Water Recovery and Management

Water recovery and management provides a safe and reliable supply of potable water to meet crew consumption and operational needs, including supply and storage, recycling, and management through dormant mission periods.

Example Technologies

- Wastewater collection
- Wastewater processing
- Brine processing
- Potable water microbial control

TX06.1.3 Waste Management

Waste management provides for safe collection, processing, resource recovery, and volumetrically efficient storage of waste.

Example Technologies

- Metabolic waste management
- Planetary methane waste control
- Contingency urine collection
- Trash volume reduction and stabilization
- Long duration trash storage
- Trash/waste removal systems

TX06.1.4 Habitation Systems

Habitation systems enable the crew to efficiently utilize vehicle systems (i.e. ECLSS), maintain vehicle hygiene including through uncrewed mission periods, store/prepare/consume food, perform crew hygiene, and sleep effectively.

Example Technologies

- Distributed and integrated lighting and noise mitigation
- Long-wear clothing or clothes cleaning
- Lightweight crew quarters with minimal CO2 accumulation
- Lightweight mobility aides
- Smart habitat automation of crew housekeeping (vacuum cleaner) and maintenance functions
- High oxygen compatible fabrics
- Reusable/repurposable packaging materials

TX06.1.5 ECLSS Modeling and Simulation Tools

ECLSS modeling and simulation tools help develop and understand next generation life support systems that often present special cases not available in industry tools.

Example Technologies

- Chemical process modeling (e.g. complex fluid precipitation thresholds) and biological system modeling (higher plant metabolisms
- Microbial behavior in bioprocessors or undesired biofilm contamination

A suit technician fits the communications carrier on an astronaut stand-in before pressurizing the spacesuit at NASA Kennedy Space Center in Florida. (NASA/Cory Huston)

TX06.2 Extravehicular Activity Systems

Extravehicular activity (EVA) systems are those associated with enabling astronauts to perform work outside of a spacecraft's habitable environment.

TX06.2.1 Pressure Garment

The suit, or pressure garment, is the set of components a crewmember wears and uses, including the torso, arms, legs, gloves, joint bearings, helmet, and boots. The suit employs a complex system of soft-goods and mobility elements to optimize performance while pressurized without inhibiting unpressurized operations. The Launch, Entry, and Abort (LEA) suit also contains provisions to protect the crewmember from both nominal and off-nominal environments (e.g. acceleration, noise, chemical) encountered during launch, entry, and landing, as well as potential descent/ascent to planetary surfaces.

Example Technologies

- LEA arm mobility via soft constant volume joints and enhanced patterning
- LEA in-suit waste containment
- Pressurized and non-pressurized rear-entry suit ingress systems
- Dust protectant mobility bearings and mechanisms
- Pressure Garment System (PGS) Materials Layup – Vacuum
- Mars PGS Layup
- PGS for 1st to 99th Percentile American
- Advanced helmet and extravehicular visor systems
- Lightweight structures
- High-performance EVA gloves
- Higher-performance intravehicular activity (IVA) gloves
- Reusable drink/nutrition bag
- LEA occupant protection materials, analytical tools, and technologies
- Human waste containment and removal

TX06.2.2 Portable Life Support System

The Portable Life Support Systems (PLSS) performs functions required to keep a crewmember alive during an EVA. These functions include maintaining thermal control of the astronaut, providing a pressurized oxygen (O2) environment, and removing products of metabolic output such as carbon dioxide (CO2) and water (H2O). Control of all life support functions requires a system of critical avionics to transfer and monitor data, supply and store power, provide voice and data communication, and alert IVA and EVA crew of potential system faults.

Example Technologies

- Closed-loop heat rejection system with zero consumables Spacesuit Water Membrane Evaporator (SWME)-radiator hybrid
- Heat pump radiator hybrid
- Closed-loop heat rejection system with zero consumables
- PLSS radiator
- PLSS fan
- PLSS pressure sensor
- Closed-loop on-back regenerable CO2 and humidity control
- Closed-loop consumable CO2 removal, low mass
- Alternate CO2 sorbent
- Atmospheric constituent sensor
- Alternate Contaminant Control Cartridge (CCC) Sorbent
- CO2 and H2O membrane
- Battery package
- Integrated radio/audio system
- Autonomous checkout

TX06.2.3 Informatics and Decision Support Systems

The Informatics system collects and transfers several types of non-critical data to and from other mission assets, provides avionics hardware to perform numerous data display and in-suit processing functions, and furnishes information and decision support systems to supply data and guidance that enables crewmembers to perform their tasks with more autonomy, higher performance, and/or greater efficiency.

Example Technologies

- EVA informatics
- Suit-integrated personal locating technologies
- Graphical displays
- Advanced crew to informatics interfaces

A medical pack aboard the International Space Station. (NASA)

TX06.2.4 Decompression Sickness Mitigation

Decompression sickness mitigation includes tools to quantitatively measure astronaut risk due to decompression sickness (DCS) and tools to improve operations, planning, and system design for planetary surface missions for which existing microgravity DCS countermeasures are not applicable. This area also includes integrated countermeasures that reduce decompression sickness risk, operational overhead, vehicle design impacts (e.g. materials flammability, consumables manifesting, etc.), and human performance impacts (e.g. fatigue, injury risk, reduced performance at higher suit pressures).

Example Technologies

- Probabilistic DCS risk models
- Reduced ppN2 vehicle atmospheres
- Venous gas emboli monitoring
- Adjunctive (e.g. pharmaceutical) DCS treatments
- Variable pressure space suits

TX06.3 Human Health and Performance

Human Health and Performance technologies and solutions support optimal and sustained performance throughout the duration of a mission and promote the health of the crew pre-, during, and post-mission.

TX06.3.1 Medical Diagnosis and Prognosis

This functional area provides a suite of medical technologies, knowledge, and procedures that reduce the likelihood and/or consequence of both nominal and off-nominal medical events during exploration missions.

Example Technologies

- Emerging screening technologies
- Preventative countermeasures
- Low resource imaging modalities
- Laboratory analysis platforms and assays
- Sterile fluid generation
- Medication packaging options and long-term medication storage
- Medical equipment re-use and in-situ manufacturing
- Integrated medical equipment and software suite, autonomous clinical care and decision support

TX06.3.2 Prevention and Countermeasures

Prevention and countermeasure tools validate technologies to address the effects of the space environment on human systems and countermeasures to maintain crew physical health, behavioral health, and sustained performance on extended-duration missions.

Example Technologies

- Cell/tissue culture, animal models
- Induced pluripotent stem cells
- Exercise equipment systems (hardware and software)
- Integrated prevention and treatment for visual changes and non-invasive intracranial pressure measuremen
- Water control standards for microbes, probiotic delivery, antimicrobial medications
- Integrated technologies to monitor crew health and performance during exercise
- Countermeasure effectiveness
- Vibration isolation technologies for exercise equipment

TX06.3.3 Behavioral Health and Performance

Behavioral health and performance technologies provide countermeasures and conduct monitoring to reduce the psychosocial, neurobehavioral, and performance risk associated with extended space travel and return to Earth.

Example Technologies

- Psychomotor Vigilance Task (PVT)
- Objective sleep measures for spaceflight operations
- Optimal use of light as a countermeasure
- Medications to promote sleep, alertness, and circadian entrainment
- Scheduling software
- Countermeasure to enhance behavioral health
- Tool to predict, detect, and assess decrements in behavioral health
- Cognitive assessment tool
- Tools for treating behavioral health problems during long-duration spaceflight missions
- Tool to effectively monitor and measure team health and performance fluctuations
- Social support countermeasures
- Advanced exercise software to enhance psychological and physiological benefits

TX06.3.4 Contact-less/Wearable Human Health and Performance Monitoring

Wearable and flexible sensors and electronics are technologies for human health and performance monitoring that are either a) contact-less and vehicle-integrated or b) sufficiently lightweight, flexible, and unrestrictive to be wearable by the astronaut.

Example Technologies

- Biometric wireless sensors
- Soft, stretchable sensors
- Metal-rubber, textile sensors

TX06.3.5 Food Production, Processing, and Preservation

Food production, processing, and preservation technologies include both space and Earth technologies that safely produce and handle food to reduce up-mass and retain maximum nutritional value.

Example Technologies

- Bioregenerative food system
- Vegetable production system
- Packaged food mass reduction
- Vegetable cleaning and safety verification
- Stabilized foods
- Low oxygen permeability barrier films
- Plants habitat

TX06.3.6 Long Duration Health

Technology advancements are needed to identify, characterize, and prevent or reduce long-term health risks associated with space travel, exploration, and return to terrestrial life.

Example Technologies

- Defining metrics for long-term health
- Understanding trade-offs between in-mission health and long-term health
- Technologies to enable occupational surveillance

TX06.3.7 System Transformative Health and Performance Concepts

This area covers technologies to fundamentally transform the manner in which human health and performance occur in space.

Example Technologies

- Autonomous clinical care
- Artificial gravity
- Bioengineering

TX06.4 Environmental Monitoring, Safety, and Emergency Response

Environmental monitoring, safety, and emergency response technologies ensure crew health and safety by protecting against spacecraft hazards and ensuring effective response should an accident occur.

TX06.4.1 Sensors: Air, Water, Microbial, and Acoustic

Air, water, microbial, and acoustic sensors monitor the environmental health of aircraft and accurately determine and control the physical, chemical, and biological environments of crew living areas and their environmental control systems.

Example Technologies

- Atmosphere quality sensors
- Airborne particle sensor
- Water quality sensor
- Biocide sensor
- Water total organic carbon sensor
- Microbial sensor
- Acoustic monitoring

Spacecraft Atmosphere Monitor (SAM) is one of the smallest (mass and power) autonomous GCMS instruments ever built and will continuously monitor the major components found in air in real-time. (NASA)

TX06.4.2 Fire: Detection, Suppression, and Recovery

Spacecraft fire safety technologies ensure crew health and safety by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, and/or system.

Example Technologies

- Combustion model in low and partial gravity
- Cabin fire: detection system, cabin fire extinguisher

TX06.4.3 Protective Clothing and Breathing

Protective clothing and breathing apparatuses address off-nominal situations within the habitable compartments of the spacecraft, including events such as fire, chemical release, microbial contamination, and unexpected depressurization.

Example Technologies

- Advanced respirator
- Advanced clothing
- Common filtering cartridge mask

TX06.4.4 Remediation

Remediation provides the crew with the ability to clean the habitable environment of the spacecraft in the event of an off-nominal situation, including fire, an inadvertent chemical release, or microbial contamination.

Example Technologies

- Contingency air scrubber
- Contingency microbial remediation
- Post-fire air scrubber

TX06.5 Radiation

Radiation technologies increase crew mission duration in the free-space radiation environment while remaining below the space radiation permissible exposure limits.

TX06.5.1 Radiation Transport and Risk Modeling

Radiation transport and risk modeling tools enable, quantify, and reduce uncertainty in assessing astronaut risk due to space radiation exposure, as well as improve mission operations, mission planning, and system design for LEO, deep-space, lunar, and Mars missions.

Example Technologies

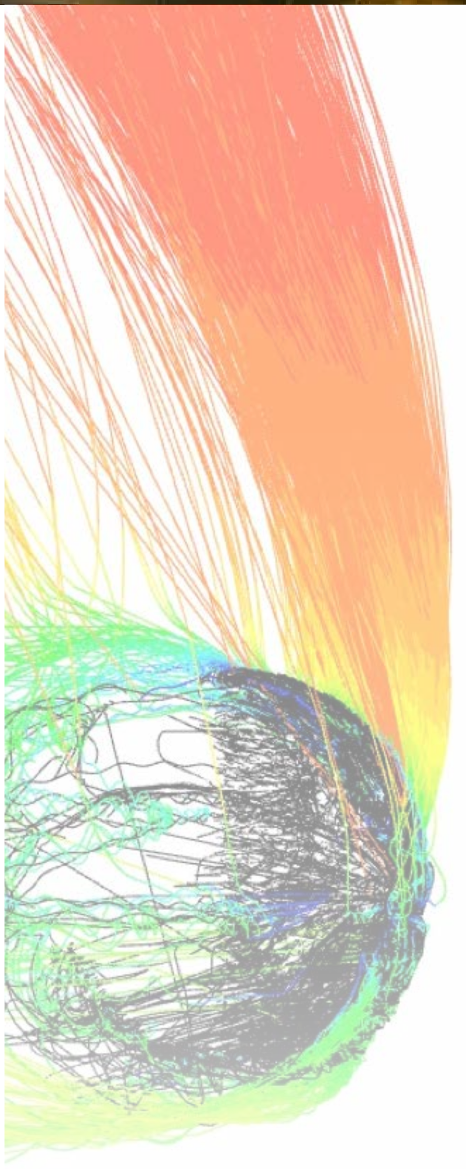
- Integrated mortality risk projection model tool
- Cancer risk projection model
- Degenerative risk projection model (includes heart and circulatory)
- Central nervous system (CNS) risk projection model
- Performance degradation model set (acute and central nervous system)
- Digital twin
- Transport and nuclear physics modeling tool(s) for radiation exposure (transport codes)

TX06.5.2 Radiation Mitigation and Biological Countermeasures

Radiation mitigation and biological countermeasures aim to minimize or prevent physical, cognitive, and behavioral disorders due to space radiation without adverse side effects and loss of life.

Example Technologies

- Countermeasures for in-flight acute radiation syndrome
- Countermeasures for in-flight CNS effects
- Countermeasures against degenerative effects
- Countermeasures against cancer
- Combined pharmaceutical interaction tool
- Individual sensitivity toolkit



This computer simulation, based on data from NASA's Mars Atmosphere and Volatile Evolution, or MAVEN, spacecraft, shows the interaction of the streaming solar wind with Mars' upper atmosphere. (NASA)

TX06.5.3 Protection Systems

Integrated radiation protection shielding technologies provide passive or active shielding through design advances, advanced materials, lightweight structures, and in-situ resources.

Example Technologies

- Radiation protective materials and material systems for primary and secondary structures
- In-situ passive shielding from and in the spacecraft
- In-situ passive shielding from planetary surface materials
- High-temperature superconductor technology and performance for active shielding systems
- Lightweight structural materials for magnet fixtures for active shielding systems
- Cooling systems for active shielding
- Integrated design tool
- Uncertainty models for thick shielding
- Active shielding modeling tool set

TX06.5.4 Space Weather Prediction

Solar particle event (SPE) forecasting and alert systems seek to minimize operational constraints for missions outside the protection of Earth's geo-magnetic field.

Example Technologies

- Tool for all-clear forecasting of SPE onset
- Tool for forecasting SPE intensity and evolution
- Probabilistic models (tools) of SPE spectral characteristics and astronaut risks
- Ensemble coronal mass ejection forecasting for mission impact assessment
- High-performance computing architecture that supports real-time implementation of operation forecasts

TX06.5.5 Monitoring Technology

Radiation Monitoring technologies are active electronic devices composed of dedicated sensors and dedicated readout and processing electronics. Radiation sensors are specific to the type of radiation being detected (e.g., charged particles, neutrons, gamma-rays). The processing electronics are specific to the sensor it is paired with as well as the quantity of the radiation field being measured. Radiation monitoring is used to characterize the radiation environment that crew and spacecraft are being exposed to during phases of mission. The radiation monitoring can also inform the impacts of a given radiation environment exposure to humans and spacecraft hardware.

Example Technologies

- Active personal dosimetry for Intravehicular activities and extravehicular activities
- Compact biological dosimetry (biodosimetry)
- In-situ active warning and monitoring dosimetry
- Miniaturized low-power charged-particle spectrometers with active warning
- Miniaturized low-power neutron spectrometers with active warning

TX06.6 Human Systems Integration

Human Systems Integration (HSI) focuses on improving total system performance by integrating human considerations throughout the design, implementation, and operation of hardware and software through application of technologies that support analysis, testing, and modeling of human performance, interface controls/displays, and human-automation interaction. Human system domain activities associated with human factors engineering, training, habitability, operations effectiveness, safety, and maintainability are considered concurrently and integrated with all other system design activities.

The 20-G Centrifuge at NASA Ames Research Center. (NASA/Dominic Hart)

TX06.6.1 Human Factors Engineering

Human factors engineering focuses on ensuring that the system design is integrated and compatible with human tasks, and the sensory, perceptual, mental, and physical attributes of the user personnel who will operate, control, maintain, train, and support the equipment, system, or facility throughout its life cycle.

Example Technologies

- Frameworks for dynamic multi-agent function allocation
- Advanced user interfaces
- Tools to augment human physical and cognitive performance
- Integrated human-system verification and validation (V&V) methods
- Human physical and cognitive performance models
- Human-systems interfaces for increased autonomy and new environments
- New con-ops models for crew-vehicle-ground interactions

TX06.6.2 Training

Training focuses on enabling users, operators, maintainers, trainers and support personnel to acquire, maintain or enhance their knowledge and skills, and concurrently develops their cognitive, physical, sensory, team dynamics, and adaptive abilities to conduct operations. The goal of the training/instructional system should be to develop and sustain ready, well-trained personnel, while considering options that can reduce life-cycle costs and provide positive contributions to the system.

Example Technologies

- Framework for an integrated training design that supports skill acquisition, retention, and transfer
- Simulators designs based on human perception capabilities that provide the necessary level of fidelity to ensure training transfer to the operational environment
- Just-in-time training capabilities for in-mission or on-the-job initial and refresher training

TX06.6.3 Habitability and Environment

Habitability and environment technologies focus on external and internal environment considerations for human habitat, and exposure to the natural environment, including factors of living and working conditions necessary to sustain the safety, health, performance, and morale of the user population which directly affect personnel effectiveness and mission success.

Example Technologies

- Robust countermeasures to mitigate environmental impacts on human performance and capability to perform
- Integrated habitat support system
- Long-duration microgravity workstation and habitat tools

TX06.6.4 Operations Effectiveness

This area covers technologies for applying human system integration knowledge and processes to enable robust, cost-effective operations while minimizing risk of human error. Operations effectiveness influences mission architecture, system design, command and control structure, operations system design, and operations planning and execution for increased mission performance. This area includes operability and human effectiveness for flight and ground crews to drive system design and development phases, as well as trades for function allocation, automation, and autonomy.

Example Technologies

- Mission architecture modeling for crew size determination in response to mission task/function definition
- Formal allocation of functions between crew, ground operators, and automation/autonomy, as well as among multiple loci of control
- Operations design for multiple communications time-delay regimes
- Control and display design to maximize situational awareness and reduce distraction
- Training methodologies to ensure effective human response when automation/autonomy fails in time-critical situations

TX06.6.5 Integrated Systems Safety

The focus of this domain is to address hazards and to minimize the risk of death, injury, acute or chronic illness, or disability; and/or reduced job performance of personnel who operate, maintain, train, or support the system. Special attention should be given to integration, since some hazards may occur due to the integration of components, and not the design of the component.

Example Technologies

- Integrated risk and hazard analysis tools
- Integrated failure analysis tools
- System safety taxonomies
- Root-cause analysis tools

TX06.6.6 Maintainability and Supportability

This area focuses on design to simplify maintenance and optimize human resources, spares, consumables, and logistics, which are essential due to limited time, access, and distance for space missions.

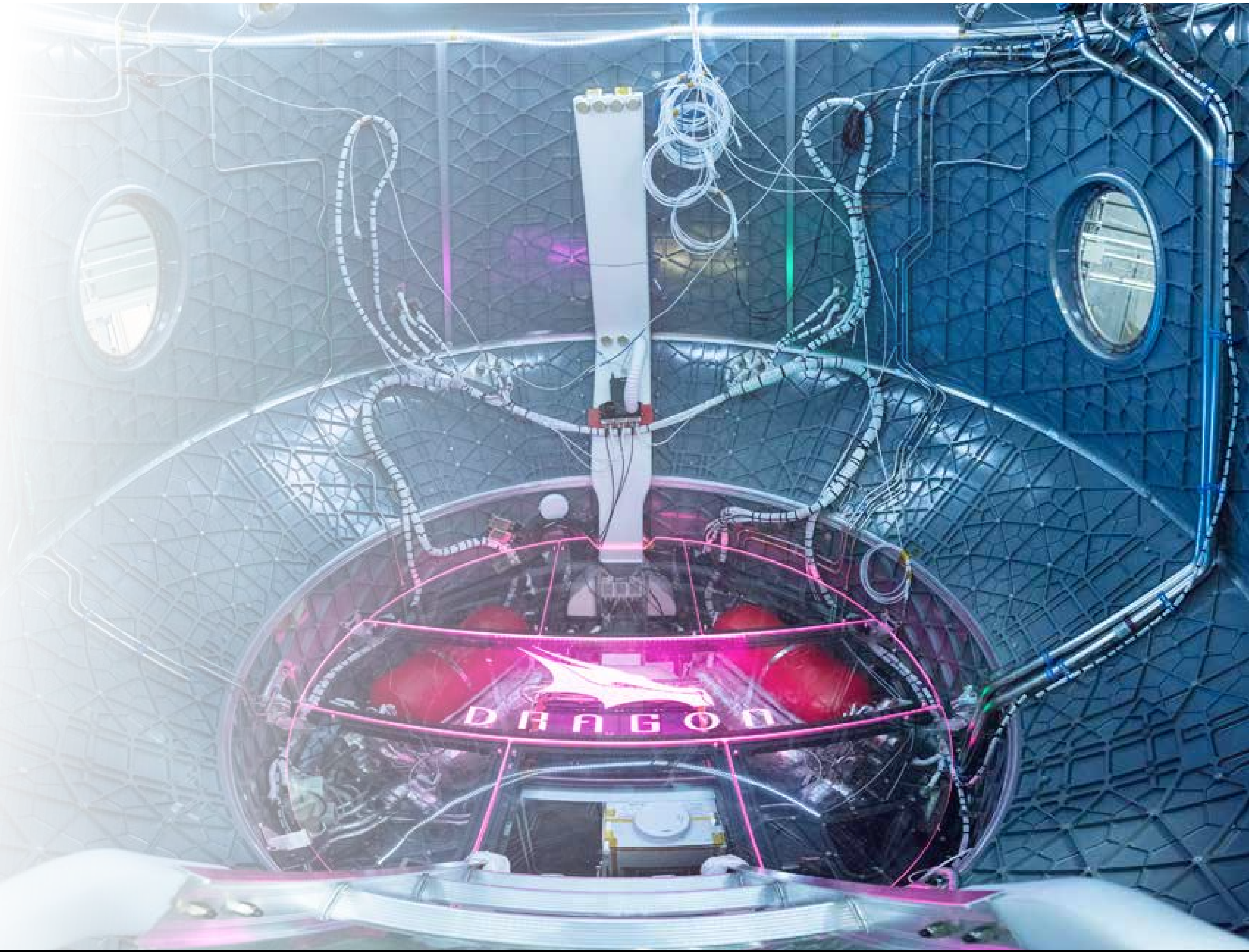
Example Technologies

- Integrated electronic technical manuals
- Tool management system
- Onboard skills training
- Reliable reliability analyses
- Onboard failure prediction, detection, and diagnostics system
- Human task assistance system (may include “robots”)
- Onboard, on-demand component fabrication (note: must address cable, IC, suit component/fabric, and computer display fabrication, in addition to mechanical fab)
- Integrated ecological system (sewage and organic matter—including anaerobic products such as methane, H_2, and succinates—processing by organisms, plant growth for food and air)
- Onboard biotechnology capability to deal with unforeseen medical and ecological failures
- Onboard logistics and stowage management system

The interior of the ECLSS module inside SpaceX’s headquarters and factory in Hawthorne, California. The module is the same size as the company’s Crew Dragon spacecraft and is built to test the Environmental Control and Life Support System, or ECLSS, that is being built for missions aboard the Crew Dragon including those by astronauts flying to the International Space Station on flights for NASA’s Commercial Crew Program. (NASA/SpaceX)

TX06.X Other Human Health, Life Support, and Habitation Systems

This area covers human health, life support, and habitation systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX06 of the 2020 NASA Technology Taxonomy.



TX07

Exploration Destination Systems

Overview

Exploration destination systems covers the broad range of technologies associated with enabling successful activities in space, from missions operations to in-situ resource utilization.

TX07 Exploration Destination Systems

TX07.1 In-Situ Resource Utilization

7.1.1
Destination Reconnaissance and Resource Assessment

7.1.2
Resource Acquisition, Isolation, and Preparation

7.1.3
Resource Processing for Production of Mission Consumables

7.1.4
Resource Processing for Production of Manufacturing, Construction, and Energy Storage Feedstock Materials

TX07.2 Mission Infrastructure, Sustainability, and Supportability

7.2.1
Logistics Management

7.2.2
In-Situ Manufacturing, Maintenance, and Repair

7.2.3
Surface Construction and Assembly

7.2.4
Micro-Gravity Construction and Assembly

7.2.5
Particulate Contamination Prevention and Mitigation

TX07.3 Mission Operations and Safety

7.3.1
Mission Planning and Design

7.3.2
Integrated Flight Operations Systems

7.3.3
Training

7.3.4
Integrated Risk Assessment Tools

7.3.5
Planetary Protection

Robotic construction of lunar infrastructure. A NASA Innovative Advanced Concept (NIAC) project. (NASA)

TX07.1 In-Situ Resource Utilization

In-situ resource utilization technologies identify, acquire, and utilize local resources, both natural and discarded, for useful products and services.

TX07.1.1 Destination Reconnaissance and Resource Assessment

Destination reconnaissance and resource assessment technologies characterize, sample, and map the surface environment to quantify the locations and abundances of material and energy resources accessible from the surface. Orbital remote sensing or deployed surface devices and instruments are used to probe, sample, and analyze possible dynamic atmospheric and surface/subsurface material composition and physical/chemical properties. This mapping includes the combination of environmental, terrain, geological, and resource information to estimate accessibility and plan extraction operations.

Example Technologies

- Instruments and devices to: detect, locate, and quantify specific surface and subsurface chemical species (such as water or other high-value elements or minerals)
- Determine properties of the destination atmosphere including composition, dynamic behavior, and other environmental factors related to utilization of atmospheric resources; measure geotechnical (mechanical) properties of the destination surface and subsurface for assessments of resource accessibility
- Assess or measure interactions between the surface environment and exploration capabilities (e.g. rocket plumes) that may affect resource accessibility
- Models and simulations to extend discrete-site resource sampling into a broader mapping of accessible resources

TX07.1.2 Resource Acquisition, Isolation, and Preparation

Resource acquisition, isolation, and preparation technologies access, extract, isolate, concentrate, modify, and purify resource-bearing materials in preparation for further processing. Resource-bearing materials include locally acquired materials and byproducts of mission operations that become available for recycling.

Example Technologies

- Instruments and devices functioning in the relevant gravity environment to: penetrate, cut, drill, extract, or excavate surface and subsurface regolith that is either resource-bearing or inert overburden
- Prepare granular regolith through grinding, crushing, sorting, and mixing; collect, filter, isolate, and accumulate resource-bearing atmospheric gases
- Collect, separate, and purify recyclable water and organic and inorganic by-products of mission operations
- Convey resource-bearing granular surface materials or atmospheric gases from the point of extraction to resource processing assets
- Separate target resources from extraterrestrial materials and gases including beneficiation and atmospheric gas separation
- Models and simulations to identify and quantify opportunities for systemic power reduction, durability, and reliability enhancements for resource acquisition systems

TX07.1.3 Resource Processing for Production of Mission Consumables

This area covers resource processing technologies that produce mission consumables, such as water, breathable oxygen, inert gases, and propellants, from pre-processed resources.

Example Technologies

- Instruments and devices functioning in the relevant gravity environment including: thermal mechanical components and reactors to extract end-product resources from inert materials (e.g. thermal reactors for volatile extraction from regolith
- Chemical, electrochemical, and biological materials, catalysts, components, and reactors to extract and combine resources to produce end-products (e.g. catalytic reactors to produce methane, electrolysis devices to produce oxygen, etc.)
- Phase-change devices to extract or distill end-product gases from by-product recycling sources (e.g. cryocoolers for gas product drying)
- Filtration and purification devices for meeting mission-critical end use requirements
- Crosscutting technologies for enhancing production system durability and reliability in harsh environments (e.g. dust tolerant seals and bearings)
- Crosscutting technologies for utilizing sources of high-temperature thermal energy for process heating (e.g. integrated solar concentrators
- Models and simulations to identify and quantify opportunities for systemic reductions in power requirements and enhancements in durability and reliability for resource processing systems

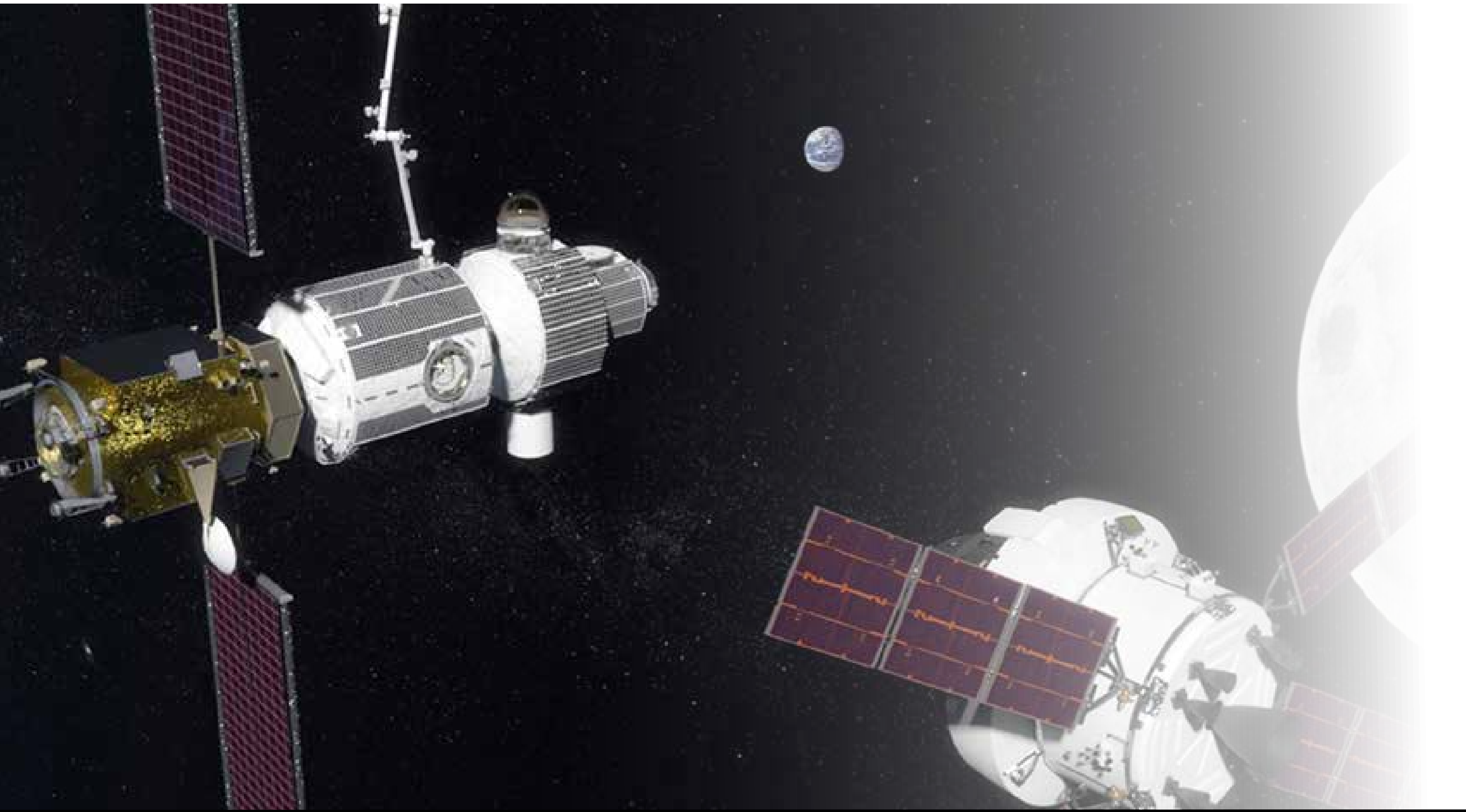
TX07.1.4 Resource Processing for Production of Manufacturing, Construction, and Energy Storage Feedstock Materials

This area covers resource processing technologies that produce feedstock for in-situ manufacturing, construction, and thermal energy storage systems.

Example Technologies

- Instruments and devices functioning in the relevant gravity environment, including: production of granular material by grinding, crushing, sorting, and mixing
- Chemical, electrochemical, and biological processing to extract and combine resources to produce manufacturing feedstock (e.g. metal extraction and separation, ceramic materials extraction, plastic production, etc.)
- Physical, chemical, thermal, and biological pretreatment of raw feedstock materials to meet purity standards required for manufacturing or construction processes
- Evaluation of suitability of locally-produced and recycled material batches for intended construction and assembly processes
- Conveyance of feedstock to manufacturing and construction assets
- Models and simulations to identify and quantify opportunities for systemic reductions in power requirements and enhancements in durability and reliability for resource processing systems

The next step in human spaceflight is the establishment of U.S. preeminence in cislunar space through the operations and the deployment of a U.S.-led Gateway, here seen with an Orion spacecraft. (NASA)



TX07.2 Mission Infrastructure, Sustainability, and Supportability

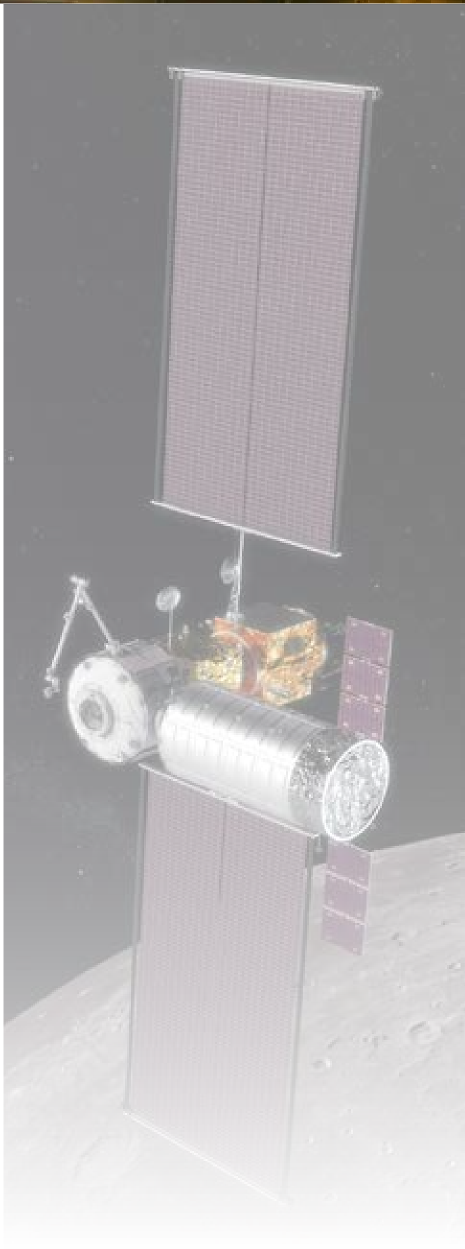
This area covers technologies required to establish a self-sufficient, sustainable, and affordable space exploration program.

TX07.2.1 Logistics Management

Logistics management technologies institute a centralized logistic depot to manage and optimize the use of Earth-supplied consumables at the exploration destination via residual recovery, repurposing, recycling, commonality, and parts repurposing.

Example Technologies

- Propellant scavenging
- Flexible, vacuum-rated liquid storage bags
- Power scavenged wireless sensor tag systems
- Dense zone technology (radio frequency identification enclosure)
- Sparse zone technology
- Logistics complex event processing
- Six degrees of freedom logistics tag system
- Packaging foam
- Additive printer feedstock
- Autonomous logistics translation and unpacking
- Logistical waste (e.g. food packaging, cargo transfer bags, etc.) repurposing or recycling into new materials, logistics carriers, packaging, and restraint systems



In this artist's concept image, the Gateway is shown mid-assembly. The first logistics module carrying cargo and other goods is docked to the spaceship as it orbits the Moon. (NASA)

TX07.2.2 In-Situ Manufacturing, Maintenance, and Repair

In-situ manufacturing, maintenance, and repair technologies manufacture items using feedstock produced from in-situ resources and recycled materials and provide system evaluation, preventive maintenance, and corrective actions for human exploration systems.

Example Technologies

- Design tools configured to accommodate broad-specification feedstock properties into design safety factors and manufacturing tolerances
- Instruments and devices functioning in the relevant gravity environment, including: additive manufacturing using broad-specification feedstock from terrestrially delivered, locally produced, and recycled materials
- Subtractive manufacturing using broad-specification feedstock from terrestrially delivered, locally produced, and recycled materials
- Evaluating suitability of locally produced and recycled material batches for intended manufacturing processes
- Quality assurance and mission suitability of devices and parts manufactured using terrestrially delivered, locally produced, and recycled materials
- Devices to conduct routine, early fault detection of operational surface systems

TX07.2.3 Surface Construction and Assembly

Surface construction and assembly covers technologies for construction, assembly, disassembly, and reverse assembly of surface structures, including both traditional construction, assembly, and disassembly concepts and advanced systems.

Example Technologies

- Instruments and devices functioning in the relevant gravity environment, including consolidation and stabilization of regolith on large scales, including microwave and concentrated solar irradiation and the addition of physical or chemical additives
- Manufacturing of structural elements using feedstock derived from locally-produced and recycled materials
- Assembly of structural and environmental barrier systems from terrestrially-delivered and/or locally-derived elements
- Quality assurance and mission suitability of structural elements and environmental barrier systems constructed and assembled in-situ
- Design tools configured to accommodate broad-specification feedstock properties into design safety factors and manufacturing tolerances for construction and assembly systems
- Human-robotics (e.g. low-latency telerobotics), autonomous robotic systems

TX07.2.4 Micro-Gravity Construction and Assembly

Micro-gravity construction and assembly technologies transform the way we manufacture, assemble, disassemble, reverse assemble, and repair large structures in space, providing a robust space infrastructure freed from launch window scheduling, launch vehicle mass limitations, and astronaut safety concerns.

Example Technologies

- On-orbit three dimensional (3D) manufacturing
- Robotic arms/manipulators
- In-space truss manufacturing
- Low-latency telerobotics

TX07.2.5 Particulate Contamination Prevention and Mitigation

Particulate contamination prevention and mitigation provides a layered engineering defense that incorporates technologies for contamination prevention, exterior cleaning and protection, interior cleaning and protection, and gas quality preservation, as well as technologies associated with modeling plume and soil interactions.

Example Technologies

- “Tunnels” to minimize regolith transfer during extravehicular activities (EVAs)
- Air and airlock cleaning; sample handling; dust covers
- Dissipation, reduction, and/or elimination of triboelectric charge build-up
- Passive cleaning
- Dust repellant, dust shedding materials and coatings
- Electrodynamic removal
- Electron discharge and bombardment
- Magnetic brushes and dust removal brushes
- Self-cleaning connectors
- Forced gas showers and forced gas cleaning of hard surfaces
- Failure Isolation, Detection, and Recovery (FIDR)
- Plume mitigation
- Deployable landing surfaces and deployable/erectable blast curtain around landing site
- Plume-resistant concrete
- High fidelity, two-phase flow modeling for plume-soil interaction

U.S. Navy divers, Air Force pararescuemen and Coast Guard rescue swimmers practice Orion recovery techniques at the Neutral Buoyancy Laboratory (NBL) at the agency's Johnson Space Center in Houston. (NASA)

TX07.3 Mission Operations and Safety

This area covers mission operations and safety technologies to manage space missions, usually from the point of launch through the end of the mission.

TX07.3.1 Mission Planning and Design

Mission planning and design technologies manage space missions from the point of launch through the end of the mission for long-duration missions over long time delays. Technologies should address the integrated coupling of trajectory, spacecraft, and system design.

Example Technologies

- Software for rapid mission development and analysis
- Toolsets for spacecraft design and mission simulation
- Concurrent engineering tools and processes
- Rapid prototyping

TX07.3.2 Integrated Flight Operations Systems

Integrated flight operations for long-duration, deep-space missions will require striking complex balances between ground and space operations, with a shift towards increasing crew autonomy that will benefit from autonomous systems and comprehensive, highly-integrated operational systems. Transparent and resilient systems and procedures must be designed that enable the human role in flight-critical systems.

Example Technologies

- Autonomous crew operations
- Autonomous ground operations
- Validated adaptive decision support for Earth-independent operations and contingency response
- Technologies to enable real-time situation understanding and shared intent between humans and machines
- Validated resilient teaming of humans and machines in limited nominal and off-nominal conditions that properly allocate roles and responsibilities
- Advanced ground launch operations for ascent vehicles
- Mission architecture modeling: ensuring mission objectives can be met by the combination of human performance and system capability
- Informing mission architecture selection
- Automated FDIR

TX07.3.3 Training

Training technologies support efficient and effective crew and mission operations training and multi-agent teaming for complex systems for nominal, off-nominal, infrequent, and unexpected events.

Example Technologies

- Training methodologies to ensure effective human response when automation/autonomy fail in time-critical situations
- Efficient and effective multi-agent team training and performance
- Just in time training technologies based on understanding of acquisition and maintenance of skilled performance and expertise
- Training environments and task support tools that are integrated with system design
- New training methods and tools required for evolving skills and tasks
- Intelligent software utilizing expert systems
- Data mining algorithms
- Advanced or intelligent hardware (such as lightweight, low-power virtual reality (VR) systems, situational awareness sensors, etc.)

TX07.3.4 Integrated Risk Assessment Tools

Integrated risk assessment tools for deep space, long-duration missions help identify and analyze risks, reducing threats to crew and missions.

Example Technologies

- Probabilistic Risk Assessment (PRA) toolset

TX07.3.5 Planetary Protection

These technologies address threats to the Earth-Moon system from astronauts, hardware, and extraterrestrial samples returning from Mars.

Example Technologies

- Sterilization modalities beyond time/temperature
- Cleanable adhesive surfaces for variable gravity
- Cleaning protocols beyond alcohol and bleach
- Microbial burden identification and monitoring and particle transport modeling
- Recontamination prevention and modeling
- Debris quantification for planetary material
- Biobarriers for whole spacecraft
- Dust analyzers
- Standoff detection of biological contamination
- Post-return sample containment and sample containment systems
- Trajectory analysis

TX07.X Other Exploration Destination Systems

This area covers exploration destination systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX07 of the 2020 NASA Technology Taxonomy.

Inside Laboratory 1 in Building 836 at Vandenberg Air Force Base, California, planetary protection samples are analyzed prior to processing the payload fairing for NASA's upcoming InSight mission to Mars. (NASA)

TX07 Exploration Destination Systems

In the Astrotech payload processing facility near Kennedy Space Center in Florida, spacecraft technicians move a lifting device toward the Juno spacecraft, enclosed in an Atlas payload fairing, during operations to lift the spacecraft onto a transporter for its trip to Space Launch Complex 41. The fairing will protect the spacecraft from the impact of aerodynamic pressure and heating during ascent and will be jettisoned once the spacecraft is outside Earth's atmosphere. (NASA)

TX08

Sensors and Instruments

Overview

This area focuses on the development of technologies for instrumentation and sensing, including remote observation capabilities.

TX08 Sensors and Instruments

TX08.1
Remote Sensing Instruments/ Sensors

8.1.1
Detectors and Focal Planes

8.1.2
Electronics

8.1.3
Optical Components

8.1.4
Microwave, Millimeter-, and Submillimeter-Waves

8.1.5
Lasers

8.1.6
Cryogenic/Thermal

TX08.2
Observatories

8.2.1
Mirror Systems

8.2.2
Structures and Antennas

8.2.3
Distributed Aperture

TX08.3
In-Situ Instruments/Sensor

8.3.1
Field and Particle Detectors

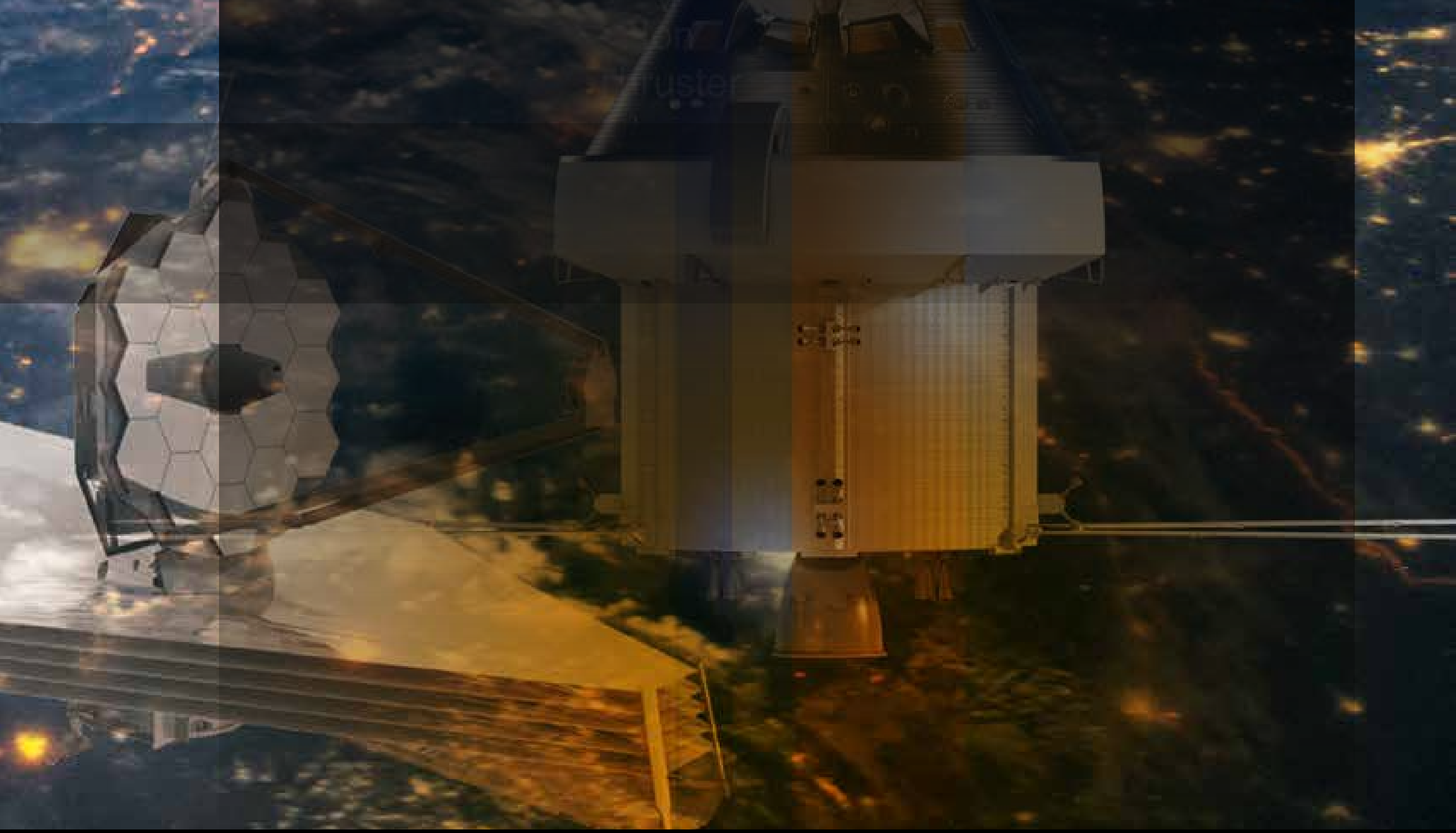
8.3.2
Atomic and Molecular Species Assessment

8.3.3
Sample Handling

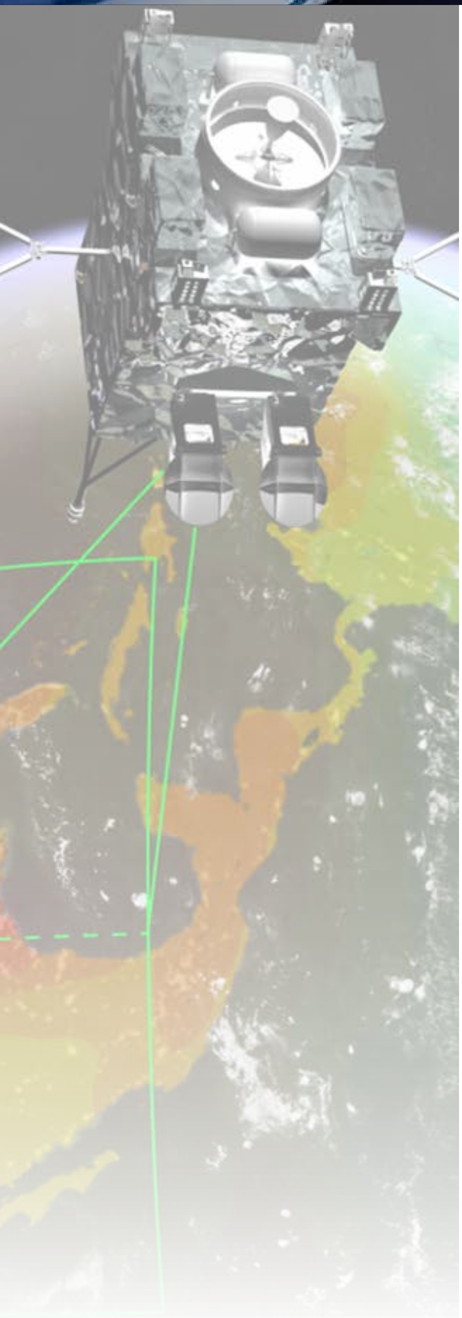
8.3.4
Environment Sensors

8.3.5
Electromagnetic Wave Based Sensors

8.3.6
Extreme Environments Related to Critical System Health Management



TX08 Sensors and Instruments



Artist's illustration of a concept for NASA's GeoCarb mission, which will map concentrations of key carbon gases above the Americas from geostationary orbit. (NASA)

TX08.1 Remote Sensing Instruments and Sensors

Remote sensing instruments and sensors include components, sensors, and instruments sensitive to electromagnetic radiation; particles (charged, neutral, dust); electromagnetic fields, both direct current (DC) and alternating current (AC); acoustic energy; seismic energy; or whatever physical phenomenology the science requires. These instruments and sensors can be either active or passive devices in practice, depending upon the measurement regime and detection technology.

TX08.1.1 Detectors and Focal Planes

Detectors, focal planes and readout integrated circuits provide large-format array technologies that require high quantum efficiency (QE); low noise, high resolution, uniform, and stable response; low power and cost; and high reliability. These technologies include low-noise, high-speed, low-power and radiation hardened readout integrated circuit (ROIC) electronics; superconducting sensors; spectral detectors; polarization-sensitive detectors; radiation-hardened detectors; and micro-Kelvin and sub-Kelvin high sensitivity detectors that cover the spectrum from submillimeter wave (Far-IR) to X-ray.

Example Technologies

- Backshort Undergrid bolometer arrays
- Mercury Cadmium Telluride and Strained Superlattice Arrays
- Charge coupled devices
- Sidecar readout integrated circuits
- Radiometric calibration and abnormality correction algorithms (e.g. non-uniformity)

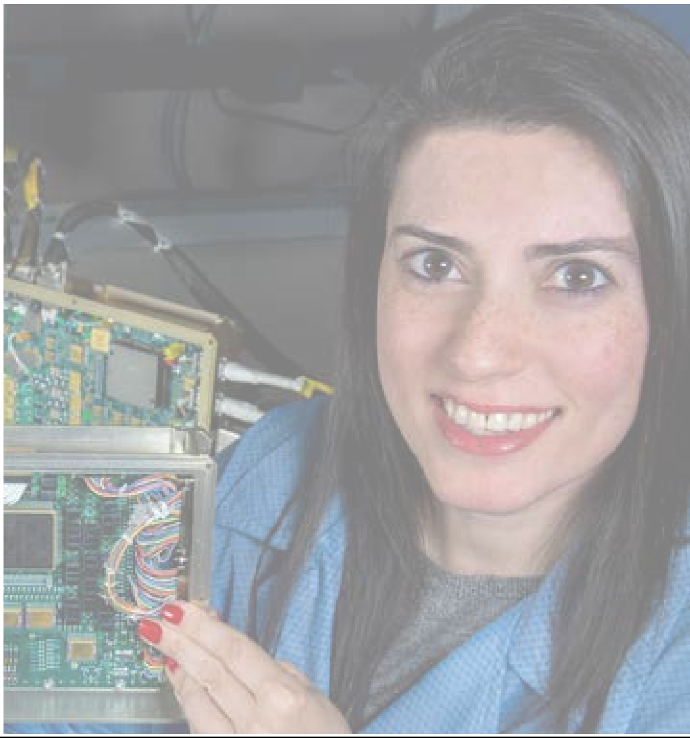
TX08.1.2 Electronics

Electronics includes analog and mixed signal instrument electronics and the associated packaging technology, designed for reuse and/or extensibility, with reduced volume, mass, and power that can operate over a wide temperature range and other extreme environments such as high radiation. This includes detector support electronics such as digital back ends, high-voltage power supplies, wireless networking techniques, and integrated electronic, photonic, and sensor readouts that enable significant signal processing and data compression.

Example Technologies

- Analog and mixed-signal instrument front end electronics application-specific integrated circuits (ASICs), Field Programmable Gate Arrays (FPGAs) and discrete components (e.g., radio frequency (RF) System on Chip, Multi-Channel Digitizer (MCD)
- Control and bias voltage electronics
- Low noise amplifiers
- Multi-channel A/D and D/A Converters
- Trans-impedance amplifiers and bias generators
- Space cube
- Onboard Synthetic Aperture Radar (SAR) processor
- Modular Unified Space Technology Avionics for Next Generation missions (MUSTANG)
- Nanoelectronics

Goddard technologist Noosha Haghani holds one of many electronics cards, which she and her team designed for a new avionics system called MUSTANG. MUSTANG has been baselined for two upcoming NASA missions. (NASA/W. Hrybyk)



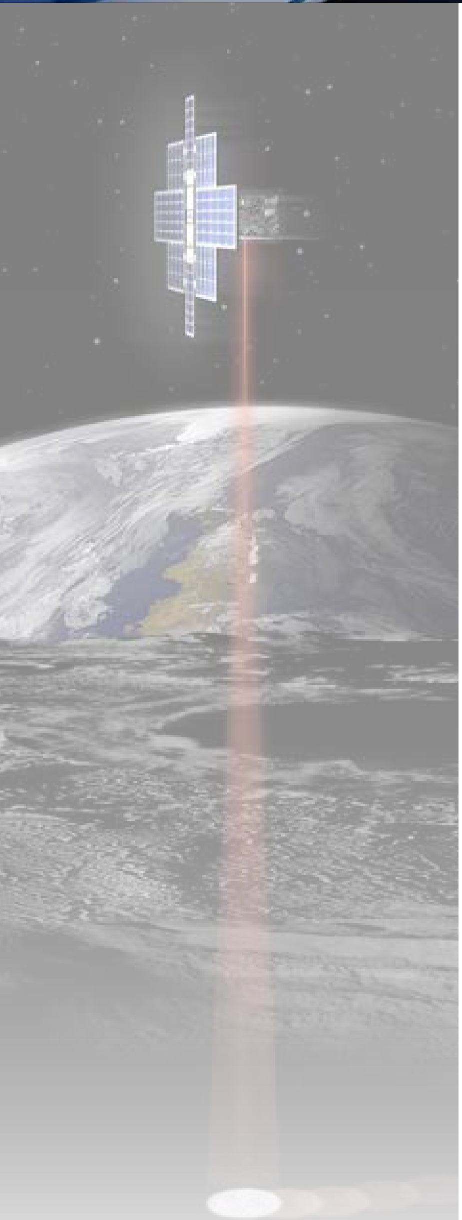
TX08.1.3 Optical Components

Optical component technologies are ultimately aimed at finding breakthrough technologies that can enable entirely new instrument or observatory architectures. Optical component technologies are grouped in the following categories: ultraviolet imaging, wide field of view imaging for near-Earth asteroids, and instruments for quantum interferometry. These improvements in optical components must omplement improvements in associated detectors.

Example Technologies

- Mirrors, lenses, interferometers, gratings, prisms, and fibers
- Dynamic pointing components (e.g. field steering mirrors)
- Active optical elements
- Advanced surface technologies (e.g. frequency selective surfaces and composites)
- Ground metrology and systems

TX08 Sensors and Instruments



This artist's concept shows the Lunar Flashlight spacecraft, a six-unit CubeSat designed to search for ice on the Moon's surface using special lasers. The spacecraft will use its near-infrared lasers to shine light into shaded polar regions on the Moon, while an onboard reflectometer will measure surface reflection and composition. (NASA-JPL-CalTech)

TX08.1.4 Microwave, Millimeter-, and Submillimeter-Waves

Microwave and radio transmitter and receiver component technologies for the 30 kHz to 10 THz range include integrated radar transmitter/ receiver (T/R) modules and integrated radiometer receivers, active microwave instruments (radar), passive radiometers (microwave and infrared), and crosscutting technologies such as radiation-hardened electronics.

Example Technologies

- Laser heterodyne and gas correlation radiometers
- Low noise receivers
- Transmit/receive modules
- Couplers/combiners, isolators, amplifiers, filters, antennas, and waveguide components

TX08.1.5 Lasers

Passive laser technologies, such as laser heterodyne radiometry, can involve low-power elements such as distributive feedback (DFB) lasers; active laser systems that pass through the atmosphere to make a measurement, such as light detecting and ranging (LIDAR) require higher powered laser elements.

Example Technologies

- Pulsed lasers and the electro-optical components that support them like fibers, gratings, crystals, laser diodes, electro-optical modulators, nanolasers

TX08.1.6 Cryogenic/Thermal

Space-qualified cryogenic and thermal systems include both passive and active technologies used to cool instruments and focal planes, sensors, and large optical systems. Cryogenic and thermal system component technologies are grouped in the following categories: micro-Kelvin, sub-Kelvin (K), 4 to 20 K, and low-cost cryocoolers; all have requirements for low power, low mass, and low exported vibration during operation.

Example Technologies

- Adiabatic demagnetization refrigerators
- Dilution refrigerators
- Sorption coolers and supporting components
- Cryocoolers, like Stirling refrigerators, Brayton Cycle refrigerators, pulse tube refrigerators, Joule-Thomson coolers
- Supporting cryogenic thermal control components like heat straps, heat pipes, cryogenic radiators

TX08.2 Observatories

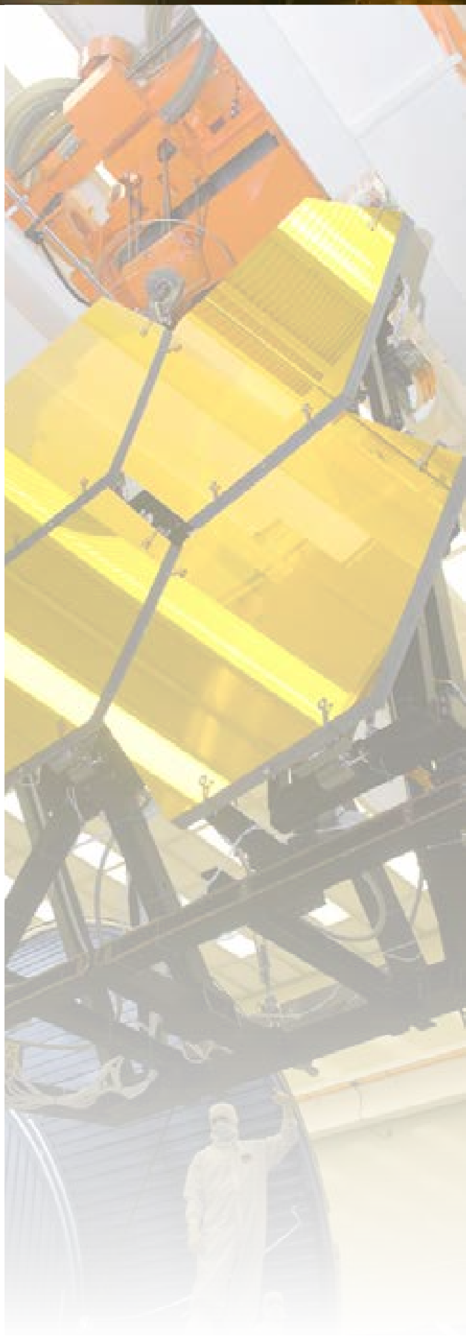
Observatory technologies are necessary to design, manufacture, test, and operate space telescopes and antennas that collect, concentrate, or transmit photons. Observatory technologies enable or enhance large-aperture monolithic and segmented single apertures as well as structurally connected or free-flying sparse and interferometric apertures. Applications span the electromagnetic spectrum.

TX08.2.1 Mirror Systems

Mirror systems development aims to provide increased sensitivity and resolution, such as improved resolution of X-ray grazing incidence optics and reduced areal costs for aperture systems > 10 m in diameter.

Example Technologies

- Ground metrology and systems
- Integrated electronic, integrated photonic, sensor readouts that enable significant data compression
- Low-noise, low-power, high-performance analog and mixed signal electronic components
- Electronics packaging technology capable of operating in and surviving extreme temperatures
- Sensor electronics designs to accommodate reduced size, weight, and power (SWaP), including wireless networking techniques
- Analog and Mixed-Signal Instrument front end electronics ASICs
- FPGAs and discrete components
- Space cube
- Onboard Synthetic Aperture Radar (SAR) processor
- Modular Unified Space Technology Avionics for Next Generation missions (MUSTANG)
- Nanoelectronics
- Supporting high-voltage power supplies



The James Webb Space Telescope mirrors have completed deep-freeze tests and are removed from the X-ray and Cryogenic test Facility at Marshall Space Flight Center. (NASA)

TX08.2.2 Structures and Antennas

Structure and antenna development aims to provide lightweight, space compatible metering structures that can be efficiently packaged for launch, precisely deployed or erected on orbit, and maintain stability for instrument operation by including adaptive control of the deployed shape, wavefront control, and materials. The systems include phased arrays and reflectors and may be either static or scanning.

Example Technologies

- James Webb Space telescope (JWST) deployment system and the JWST sunshade
- Soil Moisture Active Passive (SMAP) and NASA-ISRO Synthetic Aperture Radar (NISAR) deployable mesh antenna and boom system
- Metering system for the Nuclear Spectroscopic Telescope Array (NUSTAR) X-ray optics

TX08.2.3 Distributed Aperture

Distributed aperture technologies aim to provide a robust, reliable capability for precise in-space positioning of multiple spacecraft over both small (50m for an exoplanet interferometer or X-ray telescope) and large (50mm for a starshade and a telescope) inter-spacecraft distances, and to implement long-baseline instrumentation and distributed sensors.

Example Technologies

- Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)
- Laser interferometer space antenna

TX08.3 In-Situ Instruments and Sensors

In-situ instruments and sensors include components, sensors, and instruments sensitive to fields and particles able to perform in-situ characterization of Earth and planetary atmospheres and the space environment, as well as vehicle and habitat monitoring.

TX08.3.1 Field and Particle Detectors

Field detectors include millimeter wave through X-ray sensors, magnetic and electric field sensors, gravity-wave sensors, magnetometers, and imaging radiometers and spectrometers. Particle detectors include neutral particle sensors, ionic particle sensors, and plasma detectors. Supporting electronic technologies for power, mitigating environmental effects such as temperature drift or background radiation contamination, and calibration are included.

Example Technologies

- Fast Plasma Instrument (FPI)
- Dual Ion Sensors (DIS)
- Dual Electron Sensors (DES)
- Analog Fluxgate Magnetometer (AFG)

TX08.3.2 Atomic and Molecular Species Assessment

Sensors for atomic and molecular species identification include mass spectrometers, such as Ion trap, Orbitrap, Quadrupole mass filters, and time-of-flight; microscopes and optical spectrometers for chemical analysis such as femtosecond lasers; Raman laser systems or passive optical chemical sensors, Fourier Transform spectrometers; grating spectrometers; laser heterodyne radiometers; X-ray diffraction; tunable diode laser absorption instruments; LIDARs; and gas correlation radiometers.

Example Technologies

- Sample Analysis at Mars (SAM)
- Mars Organic Molecule Analyser (MOMA)
- Gas chromatographs
- Microfluidic systems
- Absorption spectrometers

This is a close-up view of the "spectrometer-on-a-chip" technology that could dramatically reduce the size of spectrometers in the future. (Credit: NASA Goddard/Chris Gunn)

TX08.3.3 Sample Handling

Sample handling technologies accept samples from the devices gathering them and deliver them to the appropriate instrument for analysis, seal and store samples to maintain the local environment, and separate and prepare samples for chemical analysis while maintaining sample and environmental integrity.

Example Technologies

- The rock abrasion tool (RAT)
- Drills
- Sample return storage units
- Sample preparation tools

TX08.3.4 Environment Sensors

Environment sensors provide the local environmental measures such as vehicle health and habitation health and include sensors such as seismometers, weather sensors (temp, wind speed, atmospheric pressure, humidity), static electric field, chemical species, structural measures (pressure, strain, etc.), particle detectors.

Example Technologies

- Temperature, humidity, wind speed and direction, atmospheric pressure, seismic sensors

TX08.3.5 Electromagnetic Wave-Based Sensors

Electromagnetic wave-based sensors are sensor systems utilizing Ultra Violet, millimeter wave, and fiber-optic based detectors for discrete measurements, and for system monitoring and control.

Example Technologies

- Strain, temperature, pressure, structure/materials, sensors

TX08.3.6 Extreme Environments Related to Critical System Health Management

Extreme environment sensors are those capable of operating in extreme environments including high temperatures or extreme temperature ranges, high pressures, highly reactive flows, high vibration and acceleration levels, cryogenic environments, high vacuum, reduced or near-zero gravity, exposures to abrasive particulate impacts.

Example Technologies

- Sensors of temperature, pressure, vibration, electrical current and voltage, torque, mechanical stress and strain, chemicals, and optical or electromagnetic characteristics

TX08.X Other Sensors and Instruments

This area covers sensors and instruments technologies that are not otherwise covered by the sub-paragraphs outlined in TX08 of the 2020 NASA Technology Taxonomy.

NASA's OSIRIS-REx spacecraft is revealed after its protective cover is removed inside the Payload Hazardous Servicing Facility at Kennedy Space Center. (NASA/Dimitri Gerondidakis)

TX09

Entry, Descent, and Landing

Overview

This area covers entry, descent, and landing (EDL) technology developments, conducted in a coordinated and sustained manner, to enable not only the current planned set of missions, but also the mission sets and science goals that may not be realizable based on current and near-term evolving technologies, nor by heritage technologies that are no longer available.

TX09 Entry, Descent, and Landing

TX09.1 Aeroassist and Atmospheric Entry

9.1.1
Thermal Protection Systems

9.1.2
Hypersonic Decelerators

9.1.3
Passive Reentry Systems for SmallSats

TX09.2 Descent

9.2.1
Aerodynamic Decelerators

9.2.2
Supersonic Retropropulsion

TX09.3 Landing

9.3.1
Touchdown Systems

9.3.2
Propulsion Systems for Landing

TX09.4 Vehicle Systems

9.4.1
Architecture Design and Analysis

9.4.2
Separation Systems

9.4.3
System Integration and Analysis for EDL

9.4.4
Atmosphere and Surface Characterization

9.4.5
Modeling and Simulation for EDL

9.4.6
Instrumentation and Health Monitoring for EDL

9.4.7
Guidance, Navigation and Control (GN&C) for EDL

TX09 Entry, Descent, and Landing

NASA's Orion spacecraft floats in the Pacific Ocean after splashdown from its first flight test in Earth orbit. (NASA)

TX09.1 Aeroassist and Atmospheric Entry

Aeroassist and Atmospheric Entry (AAE) is a mission segment where a spacecraft transits a planetary atmosphere from direct entry or orbit. Key functions of the spacecraft during the entry segment are aerodynamic stability, thermal management, guidance and control, and structural integrity.

TX09.1.1 Thermal Protection Systems

Thermal Protection System (TPS) is the set of thermal and structural materials, integration techniques, and manufacturing methods that protect the entry system from the extreme heating and aerodynamic forces experienced by a spacecraft during hypersonic atmospheric transit.

Example Technologies

- Extreme environment ablative TPS
- High-reliability TPS
- Conformal ablative TPS
- Multifunctional, shock layer radiation-reflective material
- Multifunctional, Micrometeoroid Orbital Debris (MMOD)-tolerant materials
- Solar and space radiation attenuating materials
- Multifunctional thermo-structural materials
- Non-Destructive Evaluation (NDE)

TX09.1.2 Hypersonic Decelerators

Hypersonic decelerators are entry system components that generate and manage aerodynamic forces on the transiting spacecraft during AAE, principally drag for deceleration and lift for guidance and control. Traditionally, the decelerator is an enveloping rigid aeroshell that surrounds the payload. Other concepts include inflatable or mechanically deployed aerosurfaces either on the fore-facing spacecraft or trailing tethered devices. Hypersonic decelerators may be largely passive or actively controlled to achieve a desired trajectory while maintaining operational constraints on heating, deceleration rate, or other parameters.

Example Technologies

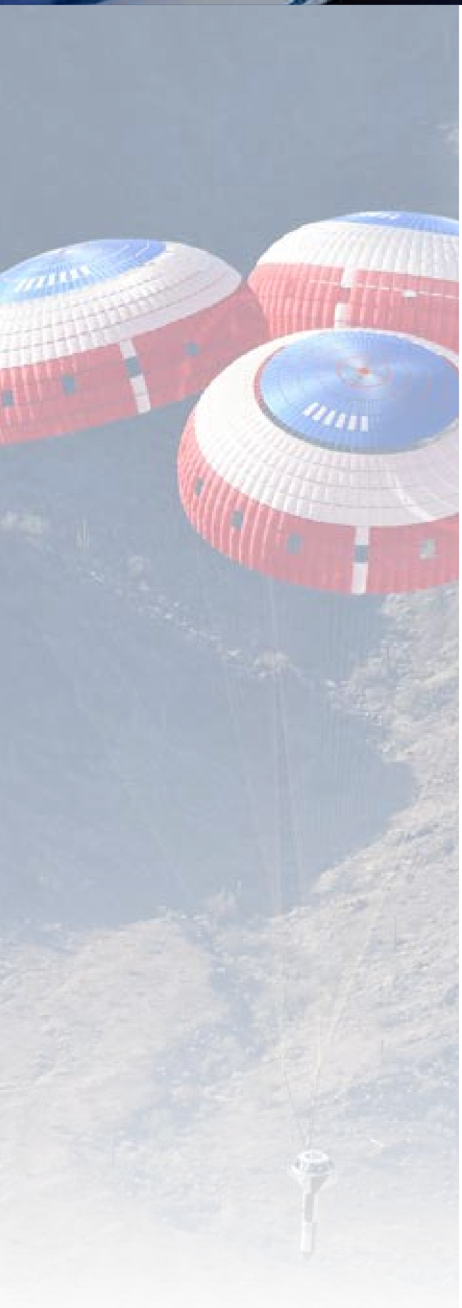
- Sample return capsules
- Entry vehicles with lift/drag (l/d) 0.4 to < 2.0
- Enhanced aerodynamics for slender vehicles
- Entry vehicles with lift/drag (l/d) > 2.0
- Aerodynamics modulation hardware
- Control modulation software
- Entry guidance software

TX09.1.3 Passive Reentry Systems for SmallSats

Passive reentry systems facilitate deorbit and reentry without attitude control and propulsion systems, making them very attractive for small satellite missions for which the mass, cost and complexity of an active deorbit system would be prohibitive.

Example Technologies

- Drag sails
- Composite booms
- Lightweight, foldable aerobrakes



Boeing conducted the first in a series of reliability tests of its CST-100 Starliner flight drogue and main parachute system by releasing a long, dart-shaped test vehicle from a C-17 aircraft over Yuma, Arizona. (NASA/Boeing)

TX09.2 Descent

Descent is a mission phase of EDL that bridges the entry and terminal descent and landing phases, with initiation typically in the low supersonic to high subsonic speed regime, after the entry heat pulse is complete. The primary technical objective is to further decelerate the spacecraft and position it accurately for staging to terminal descent and landing. This deceleration can be obtained via aerodynamic forces with systems such as inflatables or parachutes, or via a propulsion system.

TX09.2.1 Aerodynamic Decelerators

Aerodynamic decelerators are deployable descent system components that generate aerodynamic forces on the spacecraft, principally drag for deceleration, and lift for guidance and control. Parachutes or parafoils are traditionally employed for this purpose, but other deployable or inflatable devices, attached or trailing, may scale more effectively to higher mass missions.

Example Technologies

- Supersonic Inflatable Aerodynamic Decelerator (SIAD)
- Mechanically deployed decelerators and methods of active control
- Steerable and guided deployable decelerators
- Dual-mode attached decelerator systems
- Ballutes

TX09.2.2 Supersonic Retropropulsion

Supersonic Retropropulsion (SRP) is a propulsive descent technology that initiates in the supersonic flow regime, augmenting or largely replacing aerodynamic drag for deceleration while also providing an effective means of trajectory control.

Example Technologies

- Advanced algorithms and sensors for SRP
- Deep-throttling, high-thrust engines for Mars descent

TX09.3 Landing

Landing is a mission phase of EDL that encompasses the terminal descent and touchdown elements, with initiation typically in the low subsonic speed regime after completion of descent. The primary objective is to facilitate safe touchdown of the spacecraft on the planetary surface with prescribed accuracy and landing loads, while not causing unacceptable risk from landing system elements such as rocket plume impingement.

TX09.3.1 Touchdown Systems

Touchdown systems enable safe and robust landing in conditions ranging from water to relatively uncharacterized terrain to controlled ground space.

Example Technologies

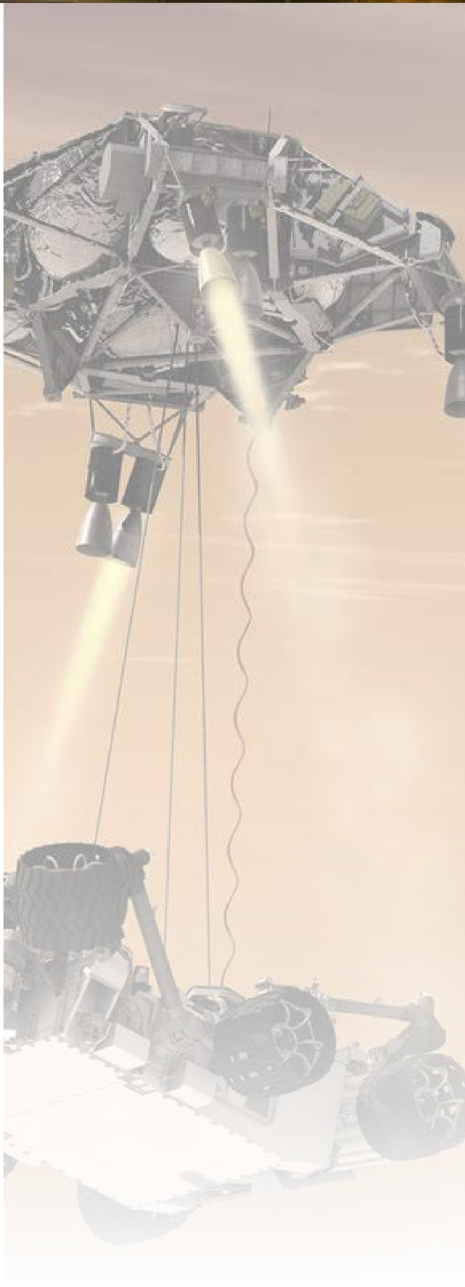
- Penetrators and spike anchors
- Mid-air retrieval (MAR)
- Active landing gear
- Energy modulators (e.g., crushables, airbags)
- Skids or runners

TX09.3.2 Propulsion Systems for Landing

Propulsion systems for landing enable elimination of the vertical velocity component while providing for hazard avoidance and/or divert maneuvers with the goal of fuel efficient and safe touchdown.

Example Technologies

- High efficiency propulsion
- Propulsive descent systems
- Deep throttling capabilities for fuel efficient and safe touchdowns



An artist's impression capturing the moments before Mars 2020 lands on the surface of the Red Planet. (NASA)

This artist concept shows thrusters firing during the entry, descent and landing phase for NASA Mars Science Laboratory mission to Mars. (NASA)

TX09.4 Vehicle Systems

Vehicle Systems enables a thorough understanding of overall design space, requirements, constraints, and available technologies. A key component of vehicle systems is the development of accurate tools for analyzing the end-to-end vehicle performance for EDL.

TX09.4.1 Architecture Design and Analysis

Architecture analysis provides top-level analysis capabilities enabling informed architecture trades and technology development decisions to reduce analysis cycle time, minimize life cycle cost, maximize performance and reduce risk.

Example Technologies

- High-fidelity, integrated performance models
- Dynamic behavior modeling
- Model-based systems engineering

TX09.4.2 Separation Systems

Separation systems enable transition between EDL mission segments, including separation from cruise stage prior to entry as well as all staged events during the atmospheric transit.

Example Technologies

- Mechanical or inflatable deployment of staged systems
- Rigidizable aeroshell sub-systems
- Propulsive-based hypersonic stage separation

TX09.4.3 System Integration and Analysis for EDL

EDL system integration and analysis implements and maintains a flexible simulation structure that evolves with the EDL system definition to enable performance, design, and risk decisions throughout the life cycle.

Example Technologies

- Event-driven environment simulation

TX09.4.4 Atmosphere and Surface Characterization

Atmosphere and surface characterization includes modeling of atmospheric and surface conditions with sufficient engineering fidelity to ensure robust atmospheric transit in the presence of uncertainties as well as precision landing and appropriate hazard avoidance.

Example Technologies

- Descent sensors to detect the surface and determine altitude and velocity
- Automated systems to convert orbital data to onboard maps
- Advanced sensors for real-time three dimensional (3D) terrain mapping
- Advanced sensors for terrain imaging and surface and subsurface characterization

TX09.4.5 Modeling and Simulation for EDL

Modeling and simulation for EDL refers to the computer codes, underlying physical models, and processes that enable configuration definition and design verification and validation for systems that—short of a full scale flight test—cannot be tested exactly in the configuration and environment for which it is intended to operate. The models cover both the environmental response to the presence of the system in operation, and the operational performance of the system in the environment. A key concern is understanding and modeling of interactions between rocket plumes and the ground.

Example Technologies

- Multi-disciplinary coupled analysis tools
- Aerothermodynamics modeling
- Ablative material response models
- Non-ablative material response models
- TPS quantification models and processes
- Numerical methodologies and techniques
- Autonomous aerobraking
- Orbital debris entry and breakup modeling
- Meteor entry and breakup modeling
- Fluid Structure Interaction (FSI) tools
- SRP modeling tools
- Aerodynamic modeling tools
- Plume-surface interaction
- Multi-scale simulation tools

TX09.4.6 Instrumentation and Health Monitoring for EDL

EDL instrumentation serves two primary purposes: First, by providing data on system performance during EDL, instrumentation allows engineers to validate the overall design, assess margin, validate design simulations, and target future modeling improvements to those areas where disagreement is largest. Second, health monitoring instrumentation ensures that the EDL system components are undamaged and capable of performing their function.

Example Technologies

- TPS instrumentation
- Radiometers and spectrometers for entry vehicle heat shields
- Distributed instrumentation
- Miniaturized, micro electro mechanical systems (MEMS)-based sensors for entry vehicles
- Semi- or non-intrusive instrumentation concepts
- Remote observation platforms for Earth entries

TX09.4.7 Guidance, Navigation and Control (GN&C) for EDL

Guidance, navigation and control (GN&C) includes software and hardware required to execute de-orbit through landing phases of EDL with accuracy and robustness. Guidance algorithms are needed to find constrained, optimal paths for entry targeting, entry flight, and surface targeting. Control systems and algorithms are required to effectively steer vehicles to follow guided trajectories with minimum propellant, power, and mass requirements. Navigation systems and algorithms are needed to accurately determine vehicle state and attitude relative to environment and targets. Environment modeling includes technology that generates models or maps of terrain from images or other measurements.

Example Technologies

- Advanced guidance algorithms for safe precision landing
- Advanced sensors for spacecraft velocimetry and altimetry
- Terrain digital elevation map or 3D model generation (offline)
- Terrain digital elevation map or 3D model generation (onboard)
- Synthetic terrain model generation/simulation

TX09.X Other Entry, Descent, and Landing

This area covers EDL technologies that are not otherwise covered by the sub-paragraphs outlined in TX09 of the 2020 NASA Technology Taxonomy.

The heat shield of Orion undergoing inspection. (NASA)

TX10 Autonomous Systems

Overview

Autonomous systems (in the context of robotics, spacecraft, or aircraft) are a cross-domain capability that enables the system to operate in a dynamic environment independent of external control.

TX10 Autonomous Systems

TX10.1 Situational and Self Awareness

10.1.1
Sensing and Perception for Autonomous Systems

10.1.2
State Estimation and Monitoring

10.1.3
Knowledge and Model Building

10.1.4
Hazard Assessment

10.1.5
Event and Trend Identification

10.1.6
Anomaly Detection

TX10.2 Reasoning and Acting

10.2.1
Mission Planning and Scheduling

10.2.2
Activity and Resource Planning and Scheduling

10.2.3
Motion Planning

10.2.4
Execution and Control

10.2.5
Fault Diagnosis and Prognosis

10.2.6
Fault Response

10.2.7
Learning and Adapting

TX10.3 Collaboration and Interaction

10.3.1
Joint Knowledge and Understanding

10.3.2
Behavior and Intent Prediction

10.3.3
Goal and Task Negotiation

10.3.4
Operational Trust Building

TX10.4 Engineering and Integrity

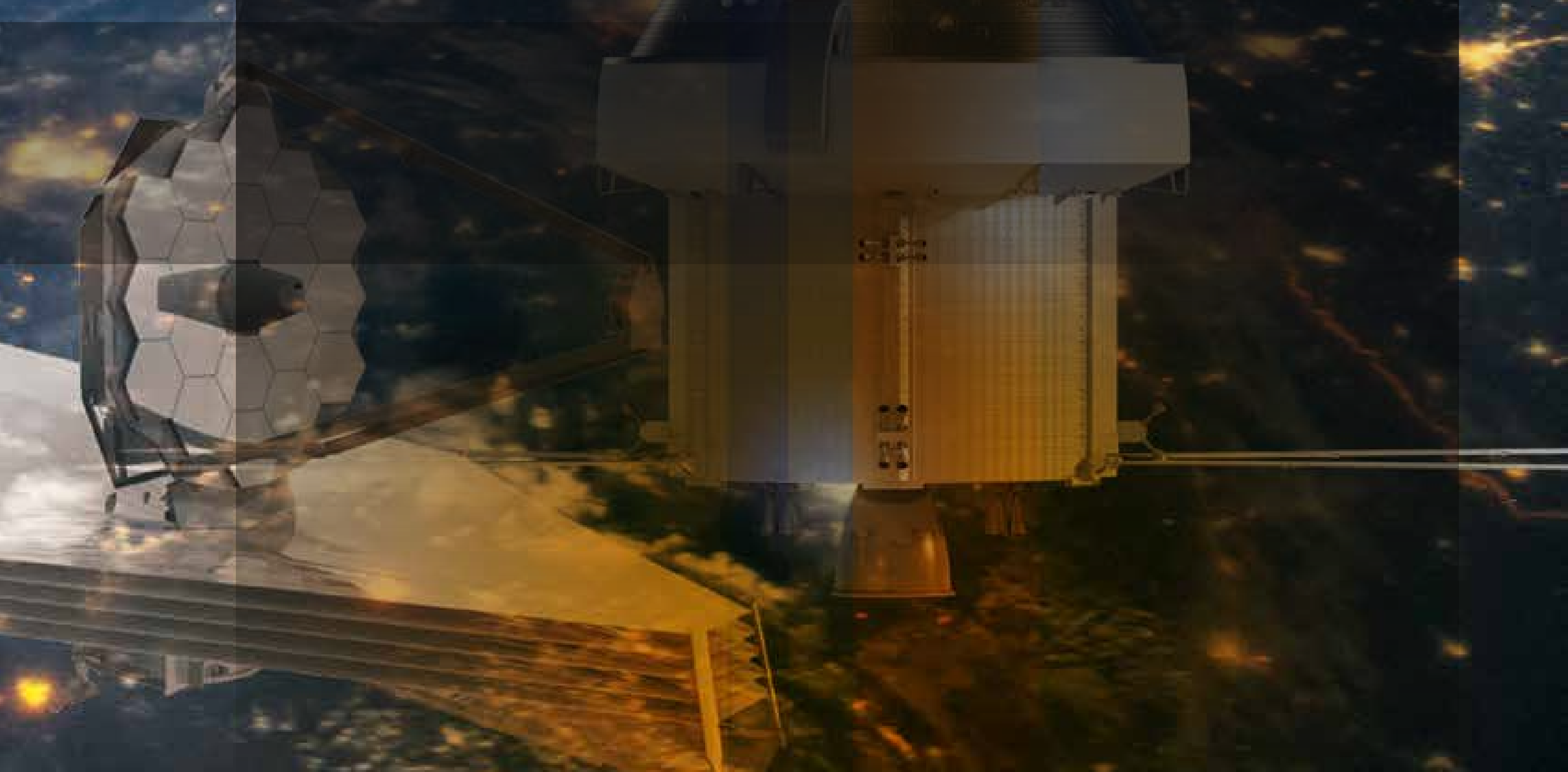
10.4.1
Verification and Validation of Autonomous Systems

10.4.2
Test and Evaluation of Autonomous Systems

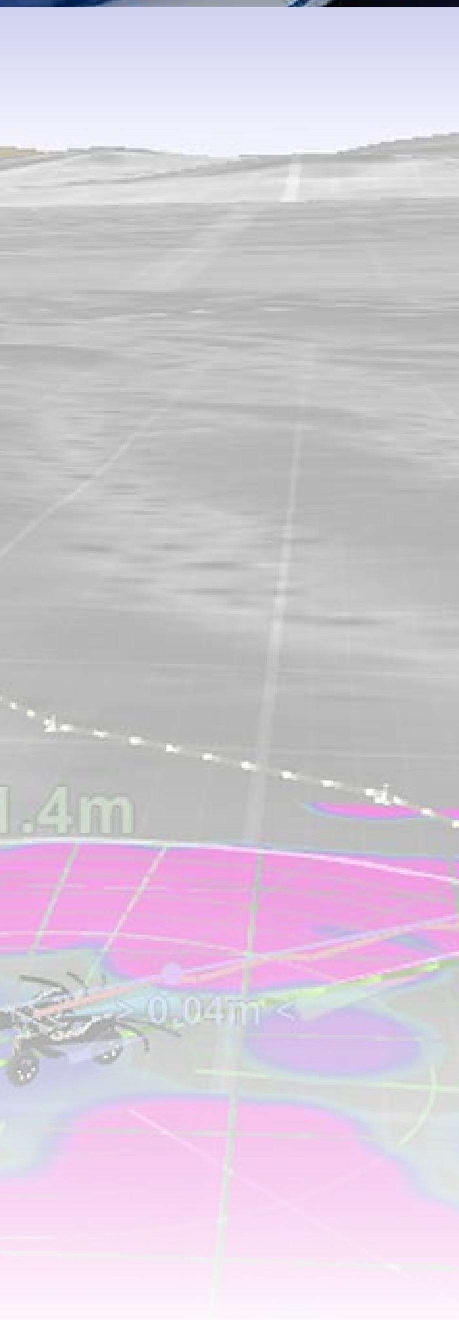
10.4.3
Operational Assurance of Autonomous Systems

10.4.4
Modeling and Simulation of Autonomous Systems

10.4.5
Architecture and Design of Autonomous Systems



TX10 Autonomous Systems



Visualization of a planetary rover and spectrometer measurements during a lunar analog robotic prospecting mission in the Mojave Desert. (NASA)

TX10.1 Situational and Self-Awareness

Situational and self-awareness technologies interrogate, identify, and evaluate both the state of the environment and the state of the system. Examples include artificial neural networks (including deep learning), unsupervised learning, supervised learning, reinforcement learning, feature learning, and support vector machine.

TX10.1.1 Sensing and Perception for Autonomous Systems

Sensing and perception technologies for autonomous systems collect and process information internal and external to the system from sensors and instruments.

Example Technologies

- Three dimensional (3D) sensing and perception from stereo vision or light detection and ranging (LIDAR)
- Force and tactile sensing
- Science-instrument sensing (e.g. spectrometers) that is eventually used in decision-making
- Tools that assess data validity and manage uncertainty
- System-health and housekeeping sensors
- Space-suit sensors that track astronauts' motions

TX10.1.2 State Estimation and Monitoring

State estimation and monitoring technologies estimate internal and external states from raw or processed inputs generated by multiple sensors/instruments, ascertainment, and continual comparison to expected states.

Example Technologies

- Pose estimation for a rover
- Pose estimation for an in-space robotic-assembly arm
- Velocity estimation for an aerial vehicle
- Oxygen-level estimation and monitoring
- Battery health-state estimation
- Wind-speed estimation for a balloon explorer
- Tools that assess data validity and manage uncertainty

TX10.1.3 Knowledge and Model Building

Knowledge and model building technologies create information sources about the environment or the system from sensing, perception, and human interaction that can be queried.

Example Technologies

- Fusion of multi-sensor data over time to generate physical or dynamical models of the system or environment
- Topographic mapping of a planetary surface from multiple surface and/or near-surface assets
- Atmospheric modeling for aerial mobility
- Ontologies for natural-language processing
- Ontologies for object manipulation
- Vehicle habitability status from integrated physics based models of life support, power, thermal, and environmental sensors

TX10.1.4 Hazard Assessment

Hazard assessment technologies evaluate whether the state of the environment, the state of the system, and/or their interaction pose a threat to the safety of actions (or inactions) that are contemplated, which could compromise the system or mission.

Example Technologies

- Terrain hazard assessment for spacecraft planetary landing
- Traversability analysis for surface mobility
- Collision-risk assessment of aerial mobility
- Safety-assessment for a life-support system

TX10.1.5 Event and Trend Identification

Event and trend identification technologies analyze data (about environment or system) to identify events and trends that may affect future state, operations, or decision-making.

Example Technologies

- Characterization of system performance
- Prediction of weather events
- Prediction of air traffic
- Science data analytics for decision making

TX10.1.6 Anomaly Detection

Anomaly detection technologies determine that the environment or system does not exhibit expected characteristics.

Example Technologies

- Detection of abnormal behavior in a component or subsystem
- Identification of a weather anomaly
- Identification of excessive rover sinkage in loose sandy terrain

TX10.2 Reasoning and Acting

Reasoning and acting technologies analyze and evaluate situations (present, future or past) for decision making and for directing actions to achieve a goal or a mission.

TX10.2.1 Mission Planning and Scheduling

Mission planning and scheduling technologies select goals, objectives, and activities to achieve a mission, subject to the situation and constraints.

Example Technologies

- Selection of science observations (e.g. for satellites and unmanned aerial vehicle (UAVs))
- Replanning/rescheduling after unexpected event (e.g. opportunistic science, responding to changing weather conditions)
- Rescheduling after system fault (e.g. choosing new observation after instrument fails, choosing new objectives after mechanical system fault limits motion, etc.)
- Mixed initiative planning/scheduling of human spacecraft activities
- Autonomous habitat recovery and survivability planning

The Robot Sequencing and Visualization Program (RSVP) for the Mars Science Laboratory Mission (MSL) is built upon prior Mars Pathfinder and Mars Exploration Rover mission operations software. (NASA)

TX10.2.2 Activity and Resource Planning and Scheduling

Activity and resource planning and scheduling technologies select and order activities to be performed while managing system resources to achieve mission goals.

Example Technologies

- Power/energy consumption and production planning/scheduling
- Planning/scheduling given constraints, such as fuel, life support system consumables (air, water), spacecraft memory, communication link (availability, bandwidth, latency), etc.
- Planning/scheduling given consumables for science ops (e.g. number of sample containers)
- Mixed initiative planning/scheduling of human spacecraft activities
- Piloted aircraft decision support

TX10.2.3 Motion Planning

Motion planning technologies generate or modify a path or trajectory to reach a desired target physical location or configuration subject to system and environment constraints.

Example Technologies

- Robotic arm/manipulator kinematics/dynamic planning
- Robot surface motion planning
- Spacecraft attitude/trajectory planning
- Aircraft path planning

TX10.2.4 Execution and Control

Execution and control technologies change the system state to meet mission goals and objectives, according to a plan or schedule, subject to control authority and permission, and based on mission phase, environment or system state.

Example Technologies

- Reactive control (e.g. aircraft see-and-avoid, rover hazard avoidance, fault response)
- Discrete control/scripting/mode control, contingent control (e.g. integration of fault management and planning/scheduling)
- Subsystem procedure and automation control and situational awareness for human operator

TX10.2.5 Fault Diagnosis and Prognosis

Fault diagnosis and prognosis technologies identify faults, prediction of future faults, and assessment of system capability as a consequence of those faults.

Example Technologies

- UAV/spacecraft battery prognostics
- Structural health monitoring
- Spacecraft control moment gyro monitoring
- Cryogenic storage leak detection (internal/external)
- Aircraft engine health monitoring
- Dynamic behavior modeling

TX10.2.6 Fault Response

Fault response technologies restore nominal or best possible system configuration and operations after a fault.

Example Technologies

- Spacecraft fault impacts reasoning
- Power system reconfiguration
- Life support system reconfiguration
- Robot arm reconfiguration
- Aircraft emergency landing planner

TX10.2.7 Learning and Adapting

Learning and adapting technologies adapt to changing environments and conditions without explicit re-programming using knowledge collected from the past, or from other systems' experiences.

Example Technologies

- Learning planning/scheduling models
- Learning fault models
- Learning anomalies
- Learning for system degradation
- Learning models for state estimation and control

TX10.3 Collaboration and Interaction

Collaboration and interaction technologies support two or more elements or systems working together to achieve a defined outcome.

TX10.3.1 Joint Knowledge and Understanding

Joint knowledge and understanding technologies support collection, assembly, sharing, and interpretation of information and intent among elements to solve problems and plan actions/responses.

Example Technologies

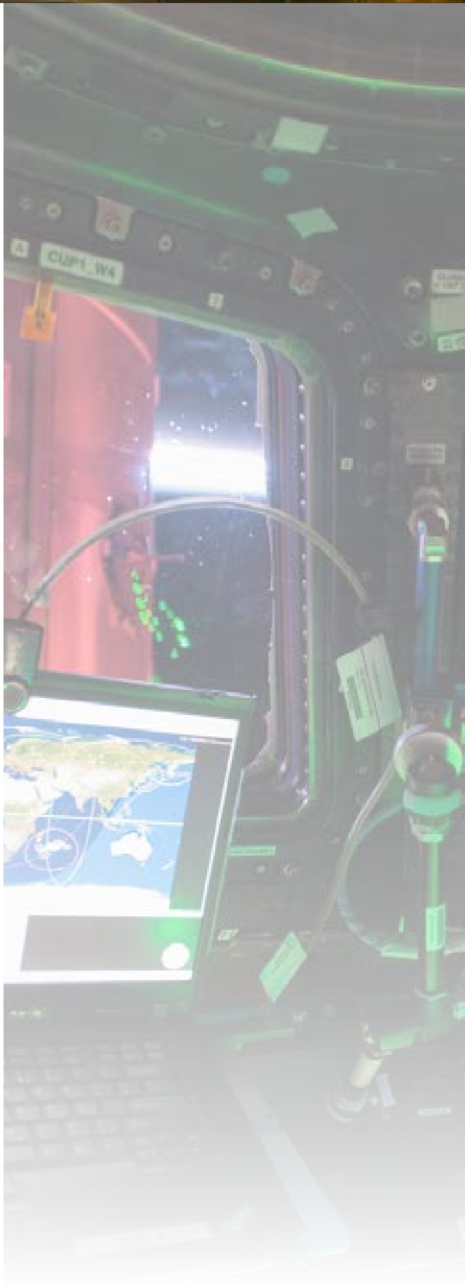
- Management of aircraft and spacecraft fault diagnostic and prognostics
- Speech recognition interfaces (including non-verbal attributes such as prosody) for aircraft flight management
- Integration of information across activities and systems

TX10.3.2 Behavior and Intent Prediction

Behavior and intent prediction technologies forecast the actions of other elements or systems to support collaboration and interaction.

Example Technologies

- Workload estimation across mixed initiative systems
- Integration of information for prognostic system prediction
- Response prediction and limitations for alerting and interaction (e.g. aircraft “detect and avoid” alerting)
- Confidence estimation for predictions across activities and elements (e.g. weather events)
- Prediction for precursors for rare events
- Prediction of human response to critical autonomy functions



Sharing data from the cupola aboard the International Space Station (ISS). (NASA)

A view of the mockup arm, end effector, and lander top deck of Insight during a simulation. (NASA)

TX10.3.3 Goal and Task Negotiation

Goal and task negotiation technologies support agreement on current and future activities, their priorities, and their disposition among elements or systems.

Example Technologies

- Space mission planning systems
- Airline Operations Center (also known as Airline Operations Control Center)
- Context-based function allocation between humans, robotic agents, and habitat

TX10.3.4 Operational Trust Building

Operational trust building technologies assure that the system is operating in a manner consistent with expectations of all elements.

Example Technologies

- Aircraft Flight Mode Annunciators (FMA)
- Aircraft navigation performance monitoring
- Transition of autonomy levels between crewed and uncrewed habitats

TX10.4 Engineering and Integrity

This area covers design considerations, processes, and properties necessary to implement autonomy.

TX10.4.1 Verification and Validation of Autonomous Systems

Verification and validation (V&V) technologies determine that an autonomous system meets the requirements (verification) and fulfills its intended purpose (validation).

Example Technologies

- Scalable formal methods for adaptive and uncertain systems (i.e., model checking, theorem proving, static analysis)
- Model validation frameworks
- Work analysis and operations concepts for autonomous behaviors
- Uncertainty propagation analysis

TX10.4.2 Test and Evaluation of Autonomous Systems

Test and evaluation technologies characterize the functionality and capabilities of the autonomous system.

Example Technologies

- Automated systems testing
- Model-based testing and accreditation
- Statistical edge-case testing approaches
- Non-destructive testing
- Testbeds for assessment of autonomous systems in laboratory and operational settings

TX10.4.3 Operational Assurance of Autonomous Systems

Operational assurance confirms, before or during operations, that an autonomous system is operating safely, efficiently, and in a manner that does not adversely affect the operation of other systems.

Example Technologies

- Runtime monitoring
- Certifications for adaptive systems
- Model invalidation
- Operational approval method for complex integrated systems
- Risk management approaches

TX10.4.4 Modeling and Simulation of Autonomous Systems

Modeling and simulation technologies represent an autonomous system and/or its operation for use in system design, evaluation, or operational assessment.

Example Technologies

- Monte Carlo techniques
- Immersive environments
- Standardized simulation infrastructure and frameworks
- Model-based systems engineering

TX10.4.5 Architecture and Design of Autonomous Systems

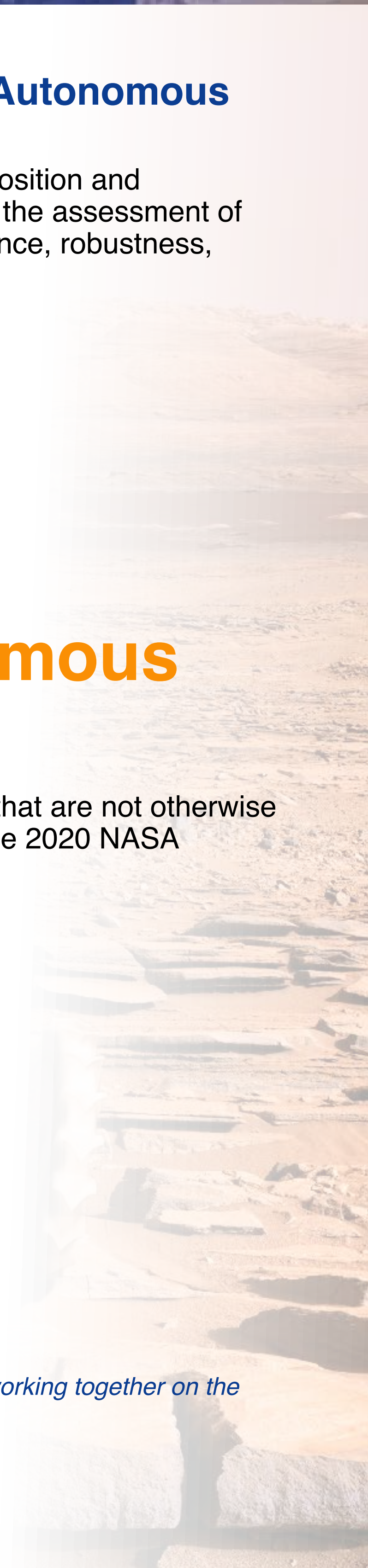
This area covers methods and tools for system composition and development that promote the existence and support the assessment of attributes of the system, such as performance, resilience, robustness, scalability, safety, and reliability.

Example Technologies

- Correct-by-design controller synthesis
- Scalable frameworks
- Contract-based design
- Fault-tolerant design
- Distributed communications infrastructure

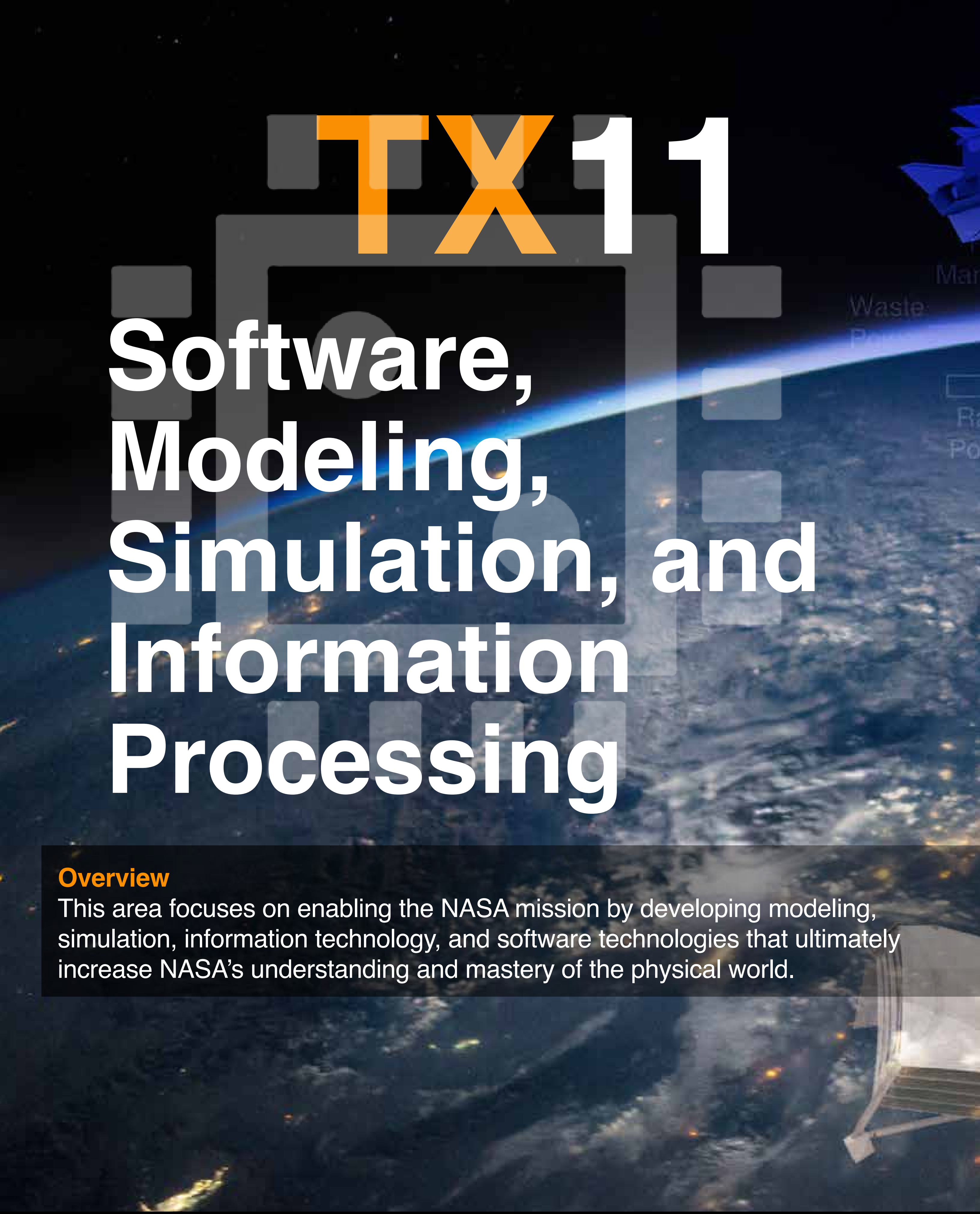
TX10.X Other Autonomous Systems

This area covers autonomous systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX10 of the 2020 NASA Technology Taxonomy.



An artist's rendering of a series of mobile, autonomous robots working together on the surface of Mars. (NASA/Phil Smith)

TX10 Autonomous Systems



TX11

Software, Modeling, Simulation, and Information Processing

Overview

This area focuses on enabling the NASA mission by developing modeling, simulation, information technology, and software technologies that ultimately increase NASA’s understanding and mastery of the physical world.

TX11 Software, Modeling, Simulation, and Information Processing

TX11.1 Software Development, Engineering, and Integrity

11.1.1 Tools and Methodologies for Software Design and Development

11.1.2 Verification and Validation of Software Systems

11.1.3 Test and Evaluation

11.1.4 Operational Assurance

11.1.5 Architecture and Design of Software Systems

11.1.6 Real-Time Software

11.1.7 Frameworks, Languages, Tools, and Standards

11.1.8 Software Analysis and Design Tools

11.1.9 Software Cyber Security

TX11.2 Modeling

11.2.1 Software Modeling and Model Checking

11.2.2 Integrated Hardware and Software Modeling

11.2.3 Human-System Performance Modeling

11.2.4 Science Modeling

TX11.3 Simulation

11.3.1 Distributed Simulation

11.3.2 Integrated System Lifecycle Simulation

11.3.3 Model-Based Systems Engineering (MBSE)

11.3.4 Simulation-Based Training and Decision Support Systems

11.3.5 Exascale Simulation

11.3.6 Uncertainty Quantification and Non-deterministic Simulation Methods

11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation

TX11.4 Information Processing

11.4.1 Science, Engineering, and Mission Data Lifecycle

11.4.2 Intelligent Data Understanding

11.4.3 Semantic Technologies

11.4.4 Collaborative Science and Engineering

11.4.5 Cyber Infrastructure

11.4.6 Cyber Security

11.4.7 Digital Assistant

11.4.8 Edge Computing

TX11.5 Mission Architecture, Systems Analysis and Concept Development

11.5.1 Tools and Methodologies for Defining Mission Architectures or Mission Design

11.5.2 Tools and Methodologies for Performing Systems Analysis

11.5.3 Tools and Methodologies for Vehicle or Concept Definition Activities

TX11.6 Ground Computing

11.6.1 Exascale Supercomputer

11.6.2 Automated Exascale Software Development Toolset

11.6.3 Exascale Supercomputer File System

11.6.4 Quantum Computer

11.6.5 Public Cloud Supercomputer

11.6.6 Cognitive Computer

11.6.7 High Performance Data Analytics Platform

11.6.8 Cloud Computing

TX11 Software, Modeling, Simulation, and Information Processing

Boeing's Structural Test Article of its CST-100 Starliner spacecraft arrives at the company's Huntington Beach, California, facilities for evaluations. Built to the specifications of an operational spacecraft, the STA is intended to be evaluated through a series of thorough testing conditions. (NASA)

TX11.1 Software Development, Engineering, and Integrity

This area covers technologies for the design, development, testing and verification of software systems.

TX11.1.1 Tools and Methodologies for Software Design and Development

Tools and methodologies for software design and development provides frameworks, languages, tools, processes, and standards that will enable the management of both short- and long-term complexity in the development and test of flight, ground, and model software.

Example Technologies

- Software Development Model Based and Auto Code Generation Techniques
- Metrics useful for engineering and management for determining software quality, safety, and security
- Formal methods verification of software requirements and design
- Compiler directive languages for portable high-performance and hybrid computing
- Static code analyzers
- System Level Modeling

TX11.1.2 Verification and Validation of Software Systems

The procedures and testing used to determine that a software system meets the requirements (verification) and fulfills its intended purpose (validation).

Example Technologies

- Model-based testing
- Payloads and Components Real-Time Automated Test System (PACRATS)
- Code coverage testing techniques
- Continuous automated software analysis and testing techniques
- SysML Model Based Systems Engineering (MBSE)

TX11.1.3 Test and Evaluation

This area covers the testing environment, simulations, models, and procedures used to evaluate software system functionality and capabilities in software-only and integrated software-hardware testbeds.

Example Technologies

- Real-time and non-real-time test environments
- Mechanism models
- Command and control simulation
- Non-integrated subsystem testing
- Extended testability analysis tools
- Payloads and components

TX11.1.4 Operational Assurance

This area covers the procedures, processes, and standards used to assure that a software system while operating is executing in a manner that does not affect the operation of other systems and protects safety and efficiency during operations.

Example Technologies

- Software partitioning technologies
- Fault tolerance techniques
- Common mode failure techniques
- Software fault detection approaches
- Systems and methods for active diagnosis and self-healing of software systems

TX11.1.5 Architecture and Design of Software Systems

This area covers the development of conceptual / behavioral models and the development of system specifications including resilience and the human roles in a system.

Example Technologies

- Software development methodologies that emphasize modeling and/or human interaction
- Human/machine interfaces and interactions
- Astronaut programming and fault management interfaces

TX11.1.6 Real-Time Software

Real-time software is designed for use onboard spacecraft or aircraft to control or manage the vehicle where timing is critical, providing a level of guarantee that a task can complete or an action will be taken by their specified timing requirements.

Example Technologies

- Fault detection response
- Mechanism control, engine/thruster control
- Science data sampling
- Image exposure control; guidance, navigation, and control (GN&C)

TX11.1.7 Frameworks, Languages, Tools, and Standards

A common set of frameworks, languages, tools, and standards will enable the management of both short- and long-term complexity in sharing, exchanging, and integrating software solutions from diverse sources. These technologies will reduce the costs associated with software development.

Example Technologies

- Reusable software libraries
- Common simulation frameworks
- Common ground system architectures
- Common communication protocols
- Common standards for trajectory parameterization/models
- Common command and data handling architectures

TX11.1.8 Software Analysis and Design Tools

A software analysis and design tool is a computer program that software developers use to create, debug, maintain, or otherwise support other software programs and applications. A collection of software tools provides programming support capabilities throughout the software life cycle.

Example Technologies

- Software development, test, and load testing tools
- Defect tracking tools
- Static analysis tools
- Software configuration management tools
- Security testing tools
- Data management tools; compilers; and multi-core and distributed processing

TX11.1.9 Software Cyber Security

Software cyber security prevents, detects, and responds to attacks on mission systems by applying secure coding and development practices. Software cyber security requires IT technologies for assurance of full-lifecycle information integrity, cybersecurity situational awareness, and software developer security analysis for space, ground and aeronautical software.

Example Technologies

- Secure development environments to control authorized access
- Secure coding practices and tools for mission systems
- Security verification of externally developed software

TX11.2 Modeling

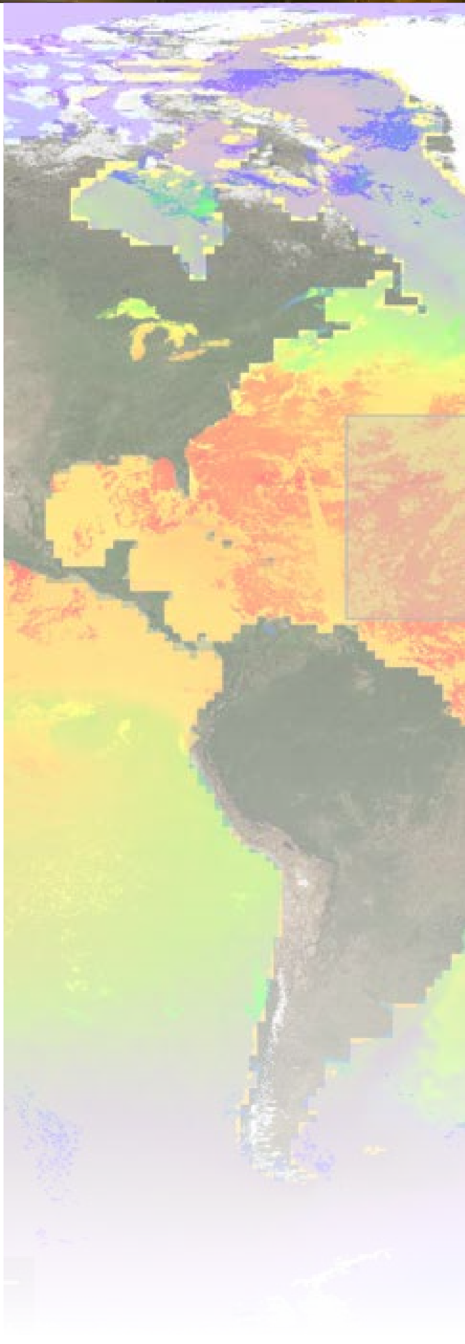
Modeling technologies support autonomous, integrated, and interoperable modeling capabilities throughout NASA's mission portfolios.

TX11.2.1 Software Modeling and Model Checking

Software modeling and modeling checking (also known as Defect Identification and Mitigation) technologies utilize or create models of the software logic and data flows within the larger system context in order to analyze cyber-physical interactions, generate semantically well-formed source code, or generate tests for full code coverage.

Example Technologies

- Hybrid model checking
- Automated software testing environment
- Software development environment with program synthesis



The NASA Sea Level Change Data Analysis Tool (DAT) has been designed to allow for quick-look comparisons and analysis of NASA datasets of sea level change. The datasets range from sea level observations, to ice observations, to model output to quickly study anomalies and get immediate results on potential relations between different datasets. (NASA)

TX11.2.2 Integrated Hardware and Software Modeling

Integrated hardware and software modeling technologies provide the ability to evaluate hardware and software systems early in the design process; expose the complex and unintended interactions between the hardware and software; transform designs into models that can be assessed and analyzed for integrated system performance; ensure verification of interface requirements; and identify possible failure modes early in the design process and continuously use the model throughout the development, testing, and operation of the system.

Example Technologies

- Hardware/software (HW/SW) interface modeling specification language
- Intelligent hardware and software interface reasoning framework
- Automated design specification knowledge capture system
- Dynamic behavior modeling

TX11.2.3 Human-System Performance Modeling

Human-system performance modeling ensures that new and relevant human-related technologies are infused into all vehicle and habitat designs and associated operational concepts. Digital human models have their greatest impact on mission design if the validated models can be seamlessly integrated within mission models.

Example Technologies

- Integrated human-systems models
- Human digital twin
- Toolset for automated task generation for human-system modeling
- Augmented reality and virtual reality (AR/VR)

TX11.2.4 Science Modeling

Science modeling uses mathematical models to quantify the physical processes as a function of underlying variables.

Example Technologies

- Fortran compatible and interoperable parallel libraries
- High performance processor toolset for science modeling
- Quality metrics for science data
- Toolset for concurrent data diagnostics and acquisition for science modeling
- Software infrastructure for sensor webs
- Planetary contaminant modeling

TX11.3 Simulation

Simulation technologies provide engineering data and insight into the level of risk across the entire lifecycle of NASA's distributed, heterogeneous, and long-lived mission systems.

TX11.3.1 Distributed Simulation

Distributed simulation provides the ability to model the sequential (time- and state-based) behavior of a defined system across a geographically-distributed and network-connected collection of heterogeneous computer systems.

Example Technologies

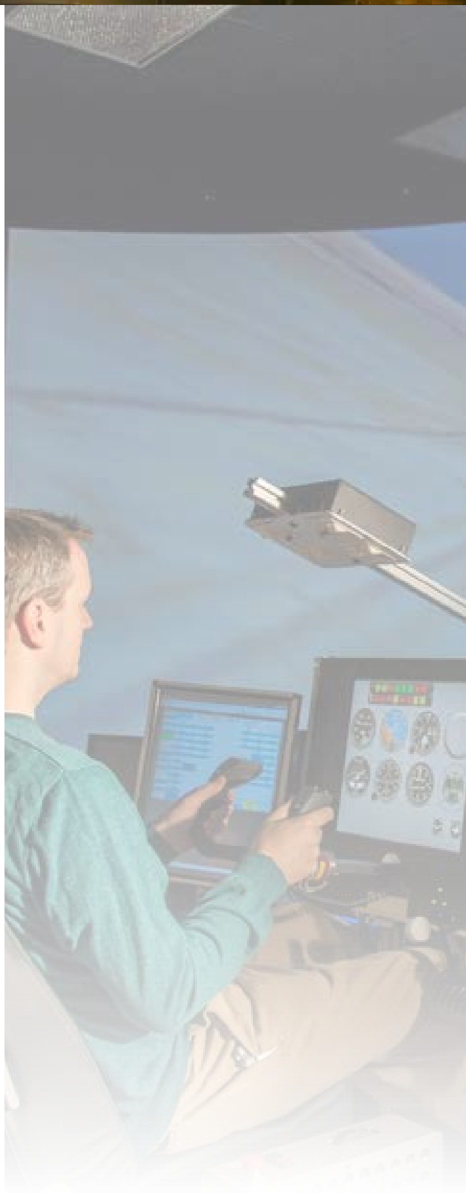
- Immersive environments for distributed simulation of NASA systems
- High-speed computer networks
- Standardized NASA simulation interoperability infrastructure
- Standardized NASA simulation data exchange standard
- Cross-domain simulation toolset and integration framework

TX11.3.2 Integrated System Lifecycle Simulation

Integrated system lifecycle simulation enables the interfaces, algorithms, and collaborative, networked platforms necessary for development of large, complex, multi-decadal, systems of systems.

Example Technologies

- Model and simulation interface specifications
- Federated simulations
- Enterprise-level modeling and simulation repositories
- Digital thread
- SysML MBSE tool/data base driven digital platform technology



X-57 principal investigator Sean Clarke flies the X-57 simulator at NASA's Armstrong Flight Research Center, examining ideal maneuvers and reaction times for flight. (NASA/ Lauren Hughes)

TX11.3.3 Model-Based Systems Engineering (MBSE)

Simulation-based systems engineering employs computational modeling and simulation methods to aid in design, development, certification, and sustainment of complex aerospace vehicles and systems throughout their lifecycles. These technologies support critical decision-making by mitigating the effects of variability and uncertainty for missions and mission environments where testing and measurement systems alone are insufficient or cost-prohibitive.

Example Technologies

- Multi-Domain Modeling (MDM) Frameworks
- High-Performance Simulations (HPS)
- Adaptive Model Updating (ADU) Toolset
- Advanced Diagnostics and Prognostics (ADP) Toolset
- Robust Decision-Making (RDM) Framework
- Onboard predictive physics-based vehicle simulation
- Digital twin

TX11.3.4 Simulation-Based Training and Decision Support Systems

Simulation-based training and decision support systems provide new approaches for the development of human-in-the-loop full mission testing and training simulations that are needed to reduce time and costs and ensure mission success and safety.

Example Technologies

- Onboard simulation-based trainers
- Integrated mission human-in-the-loop simulation system
- Digital-human-in-the-loop simulation system

TX11.3.5 Exascale Simulation

Physics-based exascale environments are needed to support the emerging requirements of multifaceted mathematics in complex systems, such as algorithms and analysis of methodologies for multi-scale and multi-physics simulation. These environments extend simulation performance and capability, the ability to seamlessly generate representative meshes, and the ability to numerically validate exascale data from various sources in near-real time.

Example Technologies

- Extreme-scale software for modeling and simulation
- Extreme-scale geometry and grid generation environments
- Extreme-scale numerical validation environment

TX11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods

Uncertainty quantification and nondeterministic simulation methods identify, classify, model, and propagate all forms of uncertainty present in a system to enable understanding and management of their impact on system performance, resources, robustness, reliability, and safety.

Example Technologies

- Robust System Uncertainty Modeling Toolset
- Probabilistic Risk Assessment (PRA) Toolset
- Discrete Event Simulation (DES)
- Aleatory and Epistemic Uncertainty Assessment Toolset
- Toolset for Global Sensitivity Analysis of Uncertain Systems
- Software Toolset for Robust Design in the Presence of Uncertainty
- Surrogate Models for Uncertainty Quantification
- Six sigma analysis and optimization
- First and second order reliability methods
- Importance sampling
- Mean value methods
- Monte Carlo Sobol and descriptive sampling

The center of the Milky Way galaxy imaged by NASA Spitzer Space Telescope is displayed on a quarter-of-a-billion-pixel, high-definition 23-foot-wide 7-meter LCD science visualization screen at NASA Ames Research Center. (NASA)

TX11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation

Multiscale, multiphysics, and multifidelity simulation develops methods needed to represent physical processes at operative length and time scales and unify best-physics representations across multiple disciplines.

Example Technologies

- Sequential Multiscale Analysis Toolset
- Concurrent Multiscale Analysis Toolset
- Energetic Extreme Flux Analysis Toolset
- Chemically Extreme Environment Analysis Toolset
- Thermomechanically Extreme Environment Analysis Toolset
- Electro-Magnetic Extreme Analysis Toolset
- Lattice-Boltzmann computational fluid dynamics (CFD)
- Coupled Eulerian Lagrangian Method
- Smooth Particle Hydrodynamics
- Discrete Element Method
- Parametric and Topological Optimization
- Low to high frequency electromagnetic simulation
- High accuracy acoustic modeling
- Dynamic Behavior modeling/Multiscale Simulation tool

TX11.4 Information Processing

This area covers technologies for triaging data with intelligent onboard algorithms and thoroughly analyzing the data using ground-based systems. These technologies include data lifecycles, intelligent data understanding, semantic technologies, collaborative science and engineering, cyber infrastructure and security, digital assistant, and edge computing.

TX11.4.1 Science, Engineering, and Mission Data Lifecycle

Science, engineering, and mission data lifecycle technologies support the increasingly data-intensive nature of NASA science and exploration missions including the need to consider the data lifecycle from the point of collection to the application and use of the data.

Example Technologies

- Reference information system architecture frameworks
- Distributed information architecture frameworks
- Information modeling frameworks
- Onboard data capture and triage methodologies
- Real-time data triage and data reduction methodologies
- Scalable data processing frameworks
- Massive engineering and science data analysis methodologies
- Remote data access framework
- Massive data movement services
- Large-scale data dissemination environments
- Toolset for massive model data

TX11.4.2 Intelligent Data Understanding

Intelligent data understanding technologies provide the ability to automatically mine and analyze datasets that are large, noisy, and of varying modalities, including discrete, continuous, text, and graphics, and extract or discover information that can be used for further analysis or decision making.

Example Technologies

- Intelligent data collection and prioritization toolset
- Event detection and intelligent action toolset
- Data on demand toolset
- Intelligent data search and mining toolset
- Data fusion toolset
- Information representation standards for persistent data
- Artificial intelligence (AI)
- Robot-automated cross-program standardization

TX11.4.3 Semantic Technologies

Technologies that utilize natural language processing to combine disparate data sets and mine large data sets for new insights. These technologies ingest textual (and mixed text/numeric/graphical) documentation, metadata, and data to automate data assimilation, data mining, and data characterization tasks.

Example Technologies

- Semantic Enabler for Data (Text, Binary, and Databases)
- Ultra Large-Scale Visualization and Incremental Toolset
- Semantic Bridge Framework, Analysis of Competing Hypotheses (ACH) Framework
- Shape similarity search
- Three Dimensional (3D) shape and semantic comparison

TX11.4.4 Collaborative Science and Engineering

Collaborative science and engineering technologies allow distributed teams with disparate expertise and resources, including those of partner agencies and contractors, to work in a unified manner.

Example Technologies

- Immersive Data Explorer
- Distributed Collaborative Engineering Frameworks
- Distributed Collaborative Science Data Analysis Frameworks

TX11.4.5 Cyber Infrastructure

Cyber infrastructure includes storage, computation, network communications, data management services (including data archiving), distributed computing, and cross-cutting software services.

Example Technologies

- On-demand, multi-mission data storage and computation
- Scalable data management frameworks
- Scalable data archives systems
- High performance networking
- Block chain

TX11.4.6 Cyber Security

Cyber security involves protecting information systems and data from attack, damage, or unauthorized access, and requires technologies for assurance of full-lifecycle information integrity and cyber security situational awareness and analysis.

Example Technologies

- Cyber security and information assurance framework
- Cyber security situational assessment environment
- User/asset geographic tracking system
- Anomaly detection system
- Secure cloud bursting infrastructure
- Cyber security situational assessment of environment for mission operations
- Security analysis and verification tools
- Techniques for verifying security requirements

TX11.4.7 Digital Assistant

A digital assistant is a set of artificial intelligence applications with a natural language interface that perform information processing or low-level cognitive tasks on behalf of the user.

Example Technologies

- Pilot or astronaut advisor (e.g. CIMON)

TX11.4.8 Edge Computing

Edge computing is a combination of hardware and software technologies that enable information processing at the edge of network where the information is acquired.

Example Technologies

- In-situ data analysis
- In-situ data triage
- Autonomous sensor targeting
- Autonomous event detection

A close up shot of the Playbook mission planning interface. Astronaut Andreas Mogensen, from the European Space Agency, using Playbook during the NASA Extreme Environments Mission Operations (NEEMO) 19 Mission. (NASA)

TX11.5 Mission Architecture, Systems Analysis, and Concept Development

This area covers technologies to support the definition of mission architectures, performing systems analysis and vehicle or concept development activities.

TX11.5.1 Tools and Methodologies for Defining Mission Architectures or Mission Design

This area covers high level or generic tools, methodologies, and practices used to support the definition of mission architecture concepts, mission designs, and architecture strategies.

Example Technologies

- Mission planner/monitor
- Adaptive systems framework
- Multi-agent master framework
- Non-smooth optimization methods
- Operational research
- Combinatorial optimization

TX11.5.2 Tools and Methodologies for Performing Systems Analysis

This area covers technologies that enable systems analyses that yield meaningful insights into novel, complex, and highly coupled systems ranging from rapid turnaround impact assessments to variable order and fidelity models and non-deterministic methods.

Example Technologies

- Trade space analysis tools
- Design and data visualization
- Automated system-level performance evaluation and characterization tool
- Dynamic behavior modeling/SysML MBSE tool
- Coupled trajectory/spacecraft/system design

TX11.5.3 Tools and Methodologies for Vehicle or Concept Definition Activities

This area covers tools and methodologies for conceptual-level exploration of vehicle systems including vehicle definition studies.

Example Technologies

- High fidelity vehicle simulator

TX11.6 Ground Computing

This area covers advanced computing and data storage technologies for big data analysis and high-fidelity physics-based simulations for Earth and space science, as well as aerospace research and engineering.

TX11.6.1 Exascale Supercomputer

Exascale supercomputers provides peak computational capability of ≥1 exaFLOPS,1018 floating point operations per second, for exascale performance of NASA computations, with excellent energy efficiency and reliability, to support NASA's exponentially growing high-end computational needs.

Example Technologies

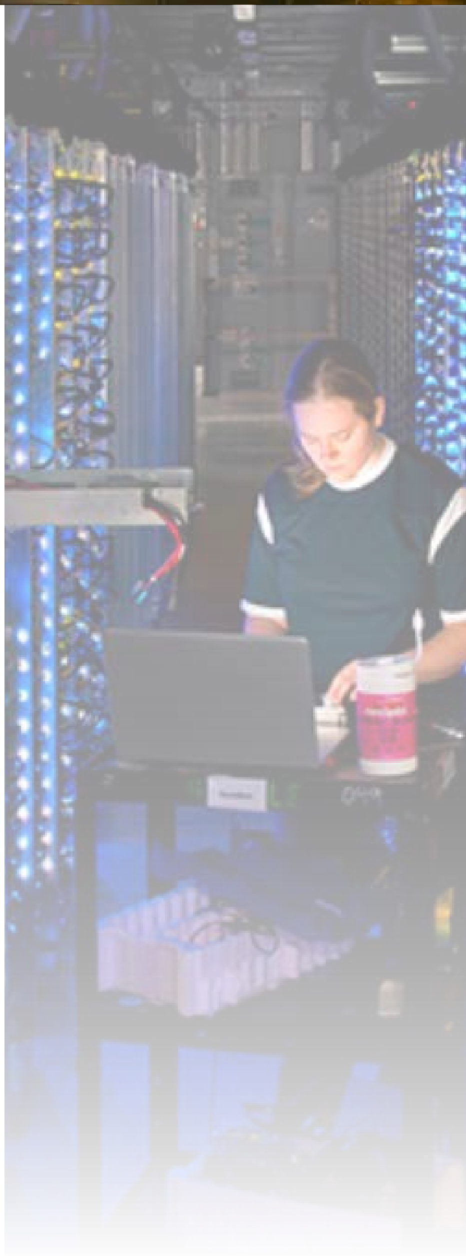
- Commercial sector supplied supercomputer at another government agency sustained 14.4 petaFLOPS (PFLOPS = 10^15 floating point operations per second) on a fluid dynamics simulation

TX11.6.2 Automated Exascale Software Development Toolset

The Automated Exascale Software Development Toolset provides automated, exascale application performance monitoring, analysis, tuning, and scaling.

Example Technologies

- Auto parallelizing compiler for shared-memory computers



The U.S. Geological Survey's Earth Resources Observation and Science (EROS) Center holds petabytes of data gathered from Earth observation satellites. (USGS/NASA)

TX11.6.3 Exascale Supercomputer File System

The Exascale Supercomputer File System provides online data storage capacity of ≥ 1 exabyte, enabling data storage for exascale modeling and simulation (M&S) and data analysis, with sufficient performance and reliability to maintain productivity for a broad array of NASA applications.

Example Technologies

- 20 petabyte parallel distributed file system for the Pleiades supercomputer

TX11.6.4 Quantum Computer

Quantum computers utilize quantum effects such as superposition and entanglement to enable the solution of certain computational problems, such as optimization or pattern recognition, where an exhaustive search of all possibilities or computations by a conventional computer would be infeasible.

Example Technologies

- 7-qubit quantum computer

TX11.6.5 Public Cloud Supercomputer

Public cloud supercomputers provide additional resources for NASA supercomputer users, such as for mission-critical computing in an emergency.

Example Technologies

- Huge public clouds exist, such as those operated by the commercial sector, which can do computing on demand

TX11.6.6 Cognitive Computer

Cognitive computers provide efficient, adaptable brain-like computing, using synthetic neurons and synapses, programmed by learning from instances, to sense, predict, and reason.

Example Technologies

- Brain-inspired chip architecture based on a scalable, interconnected, configurable network of “neurosynaptic cores”

TX11.6.7 High Performance Data Analytics Platform

High performance data analytics platforms provide a computing and storage environment optimized for high-performance data analytics, supporting interactive exploration and analysis with petabyte-scale observational and computed data sets.

Example Technologies

- Data is downloaded from various sources to the local computer, where commercial and custom software perform interactive data analysis

TX11.6.8 Cloud Computing

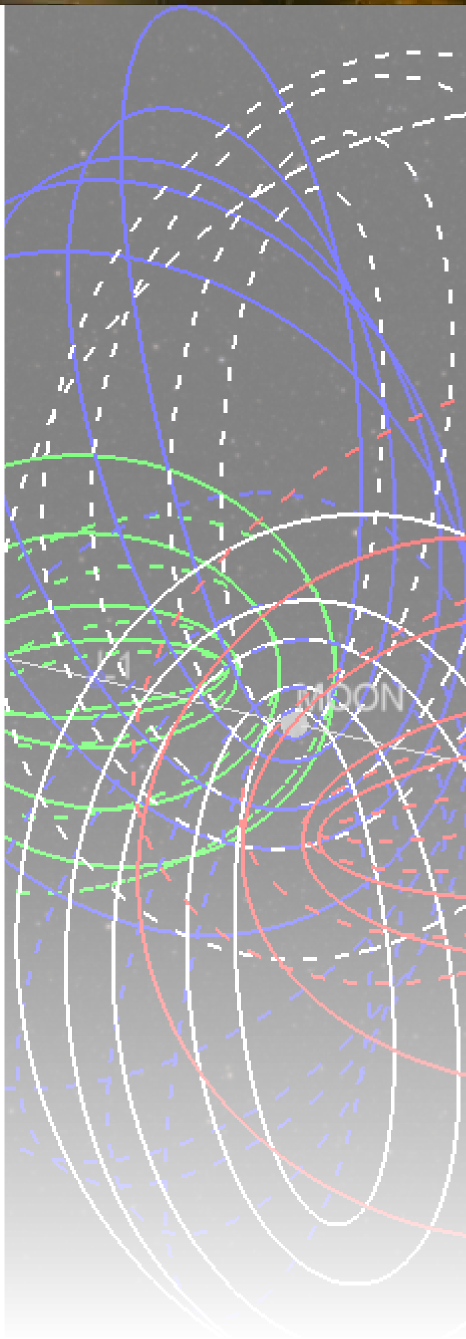
Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.

Example Technologies

- Cloud-based data archive centers for science data

TX11.X Other Software, Modeling, Simulation, and Information Processing

This area covers software, modeling, simulation, and information processing technologies that are not otherwise covered by the sub-paragraphs outlined in TX11 of the 2020 NASA Technology Taxonomy.



Copernicus, a generalized spacecraft trajectory design and optimization system, is capable of solving a wide range of trajectory problems such as planet or moon centered trajectories, libration point trajectories, planet-moon transfers and tours, and all types of interplanetary and asteroid/comet missions. (NASA)

TX12

Materials, Structures, Mechanical Systems, and Manufacturing

Overview

This section covers technologies for developing new materials with improved or combined properties, structures that use materials to meet system performance requirements, and innovative manufacturing processes.

TX12 Materials, Structures, Mechanical Systems, and Manufacturing

TX12.1 Materials

12.1.1 Lightweight Structural Materials

12.1.2 Computational Materials

12.1.3 Flexible Material Systems

12.1.4 Materials for Extreme Environments

12.1.5 Coatings

12.1.6 Materials for Electrical Power Generation, Energy Storage, Power Distribution and Electrical Machines

12.1.7 Special Materials

12.1.8 Smart Materials

TX12.2 Structures

12.2.1 Lightweight Concepts

12.2.2 Design and Certification Methods

12.2.3 Reliability and Sustainment

12.2.4 Tests, Tools and Methods

12.2.5 Innovative, Multifunctional Concepts

TX12.3 Mechanical Systems

12.3.1 Deployables, Docking, and Interfaces

12.3.2 Electro-Mechanical, Mechanical, and Micromechanisms

12.3.3 Design and Analysis Tools and Methods

12.3.4 Reliability, Life Assessment, and Health Monitoring

12.3.5 Certification Methods

12.3.6 Mechanical Drive Systems

12.3.7 Mechanism Life Extension Systems

12.3.8 Docking and Berthing Mechanisms and Fixtures

TX12.4 Manufacturing

12.4.1 Manufacturing Processes

12.4.2 Intelligent Integrated Manufacturing

12.4.3 Electronics and Optics Manufacturing Process

12.4.4 Sustainable Manufacturing

12.4.5 Nondestructive Evaluation and Sensors

12.4.6 Repurpose Processes

TX12.5 Structural Dynamics

12.5.1 Loads and Vibration

12.5.2 Vibroacoustics

12.5.3 Shock and Impact

12.5.4 Test, Tools, and Methods

TX12 Materials, Structures, Mechanical Systems, and Manufacturing

NASA's Space Launch System (SLS) core stage is installed in Test Stand 4697 at NASA's Marshall Space Flight Center in Huntsville, Alabama in July 2019. (NASA/Boeing)

TX12.1 Materials

This area covers synthesized and tailored materials that have multiple functions to meet specific mission needs.

TX12.1.1 Lightweight Structural Materials

Lightweight structural materials reduce the mass and increase the efficiency of structures and structure components including advanced metallics, nanomaterials, polymers, matrix composites, multifunctional materials, damage detecting/damage tolerant materials, and self-repairing/self-healing materials.

Example Technologies

- Nanofibers, fibers, resins and adhesives that enable the tailoring of large monolithic structures
- Materials that perform multiple functions, materials that include mechanisms for fast, in-situ repairs
- Topology optimized structures; architectured foams
- Novel low density metal
- Composite alloys

TX12.1.2 Computational Materials

Computational materials predict life, tailor or improve properties, and guide experimental validation.

Example Technologies

- Multiscale modeling, linking atomistic to continuum scale for life prediction modelling and tailoring of structural, thermal, functional materials
- Characterization techniques to validate the models
- Integrated computational materials engineering (ICME), a product design technique
- Materials Genome Initiative (MGI) which includes the infrastructure (e.g. materials databases) to discover, manufacture, and deploy advanced materials

TX12.1.3 Flexible Material Systems

Flexible material systems are textiles and other materials that can be easily bent without breaking, including materials for soft robotics, flexible sensors and electronics, and flexible structural materials. Flexible material systems also encompass metal structures that use interconnected rigid connections and compliant metal structures that can deform through elastic deformation.

Example Technologies

- Applications to habitats and deployable structures, balloons, parachutes, space suits, metalized films and solar sails, tethers, multifunctional materials that include materials that enable the morphing or deployment of aerospace structures, compliant mechanisms based on elastic deformation of thin sections, flexible metal cloth created through additive manufacturing, biobarrier fabrics for planetary protection

TX12.1.4 Materials for Extreme Environments

Materials for extreme environments protect against harsh environments and operating conditions. These hot structures are designed to deliver component capabilities that sustain loads and pressures, provide stiffness and stability, or provide support or containment at operating conditions typically thousands of degrees above room temperature.

Example Technologies

- Materials used for radiation environments, heat shields, cryo-insulators, high-temperature materials including nanomaterials, metallic, ceramic matrix composites, ultrahigh temperature ceramics, advanced alloys, insulators, materials that resist abrasive wear, materials with high wear resistance in vacuum, controllable Composite Technology for Exploration (CTE) materials, and materials for ultra-low temperatures including amorphous metals

TX12.1.5 Coatings

Coatings are materials, nanomaterials, and amorphous materials that provide thin, lightweight barrier protection from environmental hazards that include light, dust, fouling, temperature, harsh gases, chemical attack icing, putative microbial life forms, and atomic oxygen.

Example Technologies

- Includes films, optical blacks, nanofibers, nanocomposites, thermal barrier coatings, environmental coatings

TX12.1.6 Materials for Electrical Power Generation, Energy Storage, Power Distribution and Electrical Machines

This area covers materials for energy generation, harvesting, storage and distribution with application to fuel cells, batteries, capacitors, energy harvesting devices, motors and generators, and thermal management of power electronics.

Example Technologies

- Solid oxide, advanced anodes, advanced cathodes, polymer electrolyte membranes, graphene sheets, piezoelectric and thermoelectric materials, phase change materials, magnetostrictive materials, high strength magnetic materials, superconducting materials, amorphous and nanocrystalline coatings, diamond-like coatings, thermally sprayed materials, cold sprayed materials, hydrophobic and hydrophilic surfaces, nano-patterned surfaces, coatings that provide sensing

TX12.1.7 Special Materials

This area covers materials with specialized functions.

Example Technologies

- Adhesive materials concepts, nanofiltering and fluid barrier materials, porous/non-porous materials, optically transparent window materials, materials with negative refractive index, aerogels, metamaterials, topological materials, functionally graded materials, metallic glasses, nanocrystalline metals, materials with controllable CTE, multifunctional laminates, shape memory alloys, high entropy alloys, multi-functional materials

TX12.1.8 Smart Materials

Smart materials enable actuation of systems such as morphing wings, thermal/mechanical actuators, and superelasticity.

Example Technologies

- Shape memory alloys
- Piezoelectrics

TX12.2 Structures

This area covers lightweight, robust, multifunctional, smart structures that are reliable and predictable.

TX12.2.1 Lightweight Concepts

Lightweight concepts are efficient structures and structural systems using new and innovative approaches to develop beyond-state-of-the-art mass reductions for affordable, enhanced performance, reliable, and environmentally responsible aerospace applications.

Example Technologies

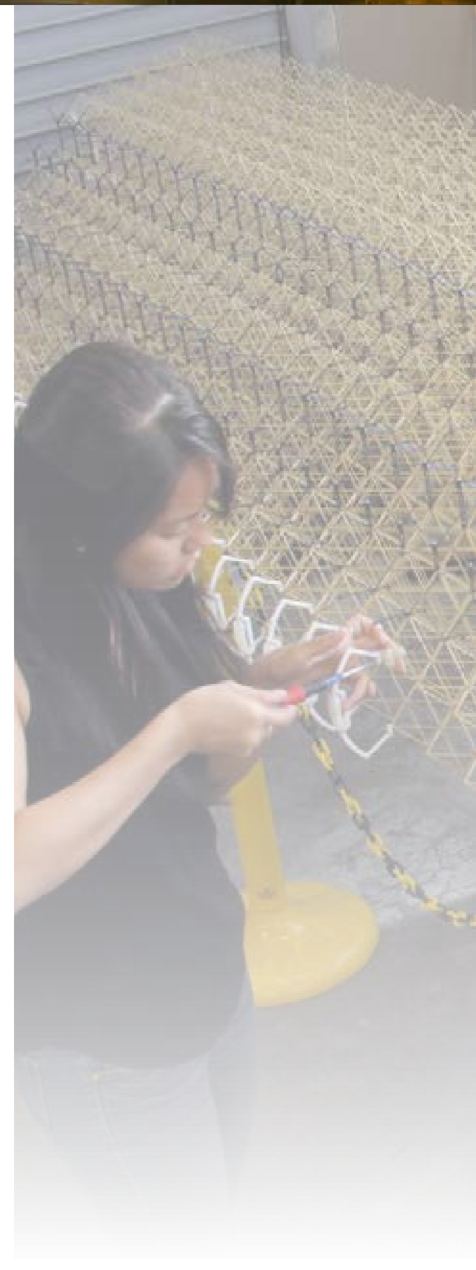
- Components for space vehicles and surface habitats, in-space depots and landers, solar or antenna arrays, complex precision deployables, propulsion systems, and terrestrial airframes and engines which function either as primary load bearing or as secondary structures
- Technologies used for these components may include either rigid construction (e.g., shell or truss structures) or expandable configurations (e.g., inflatable structures) having efficient structural geometries (e.g., hat-stiffened shells) constructed from advanced materials (e.g., polymer matrix composites) using advanced fabrication methods (e.g., additive manufacturing)

TX12.2.2 Design and Certification Methods

Design and certification methods balance a mixture of high-fidelity analytical, deterministic and probabilistic tools, failure prediction capabilities, and validation of the tools with test data to create a model-based design, development, test, and evaluation process that provides for “Virtual Digital Certification.”

Example Technologies

- High-fidelity, integrated, verified tools and processes for analysis, design, manufacturing, certification and sustainment of structures under all loading and environmental conditions
- Improved methods for allowable predictions and models for predictive failure (especially composites)



An initial, hand-assembled version of the wing, illustrating the lattice pattern used in its design. (NASA/Kenny Cheung)

TX12.2.3 Reliability and Sustainment

Reliability and sustainment aims to develop and include statistically based designs, tools and methods for dependable determination of the participation of structural reliability into the overall flight vehicle reliability concomitant with the needed autonomy for complex missions.

Example Technologies

- Predictive damage/life extension prediction methods
- Structural/thermal health monitoring
- Virtual digital fleet leader/digital twin sustainment

TX12.2.4 Tests, Tools, and Methods

An integrated package of hardware and software allows high-fidelity model correlation at the vehicle level to better understand vehicle response to flight environments and to better incorporate this information to advance certification, reliability, and sustainment for aerospace applications.

Example Technologies

- Integrated flight test data identification model
- Full field data acquisition system and model verification and validation
- Virtual digital certification method and system
- Virtual digital fleet leader testing

TX12.2.5 Innovative, Multifunctional Concepts

Innovative and multifunctional technologies combine subsystems/capabilities into the structure for mass and volume savings beyond state of the art, include reconfigurable, adaptive and smart structures.

Example Technologies

- Multifunctional pressurized/non-pressurized structures including multi-use structures
- Actively controlled and adaptive structures
- Integrated windows
- Four dimensional (4D) printed parts
- Advanced heat exchangers with load-bearing capacity
- Excavating tools with integrated sensing
- Radiation and debris shielding with integrated sensing

TX12.3 Mechanical Systems

Mechanical systems improve life and reliability of mechanisms to extend mission life. These systems improve the precision alignment capability of mechanisms to extend the capability of deployable structures.

TX12.3.1 Deployables, Docking, and Interfaces

Deployables, docking, and interfaces combine and/or separate aerospace vehicles and aerospace vehicle systems either remotely or with humans in the loop.

Example Technologies

- Interfaces that streamline connectivity
- Precision hinges, latches, grappling mechanisms, low-shock releasing and deploying mechanisms
- Reliable packaging techniques for deployables
- Applications to all ranges of structure sizes
- Provisions for operation in harsh environment
- Integrated Docking and Automated Rendezvous Systems Design, Docking Systems for Exploration
- Deployables such as solar arrays, antennae, booms, reflectors, and solar sails

TX12.3.2 Electro-Mechanical, Mechanical, and Micromechanisms

This area covers the development and testing of tools and interfaces for electro-mechanical, mechanical, and micromechanisms.

Example Technologies

- Robotic tools and interfaces that will allow robotic assembly, manipulation, and servicing of aerospace vehicles and components as well as interfaces
- Fluid transfer and refueling
- Provisions for operation in harsh environment

Recently, engineers at Northrop Grumman Corporation in Redondo Beach, California were testing the Deployable Tower Assembly (DTA) for the James Webb Space Telescope (JWST) to ensure it worked properly. (NASA/Northrop Grumman)

TX12.3.3 Design and Analysis Tools and Methods

This area covers the combination of numerical analysis methods of different disciplines to enable creation of a single model of aerospace vehicle mechanical systems, reducing overall stack-up of margins.

Example Technologies

- Dynamic behavior modeling

TX12.3.4 Reliability, Life Assessment, and Health Monitoring

This area covers technologies for timely anomaly detection, prognosis, and life assessment prediction for vehicles or mechanical systems.

Example Technologies

- Integrated health monitoring systems including embedded sensors
- Damage and remaining life prediction techniques

TX12.3.5 Certification Methods

Certification methods provide the ability to model complex or integrated system failure modes with high confidence.

Example Technologies

- Digital probabilistic representation and virtual evaluation of the flight system—including incorporation of testing results—with comprehensive diagnostic and prognostic capabilities to enable efficient development and certification and safe, autonomous operation throughout the service life of system

TX12.3.6 Mechanical Drive Systems

This area covers materials to enable advanced mechanical and magnetic gears for power transmission, and high strength materials for advanced flywheel mechanical energy storage.

Example Technologies

- High capacity, high efficiency magnetic materials
- Materials that maintain elasticity under cryogenic conditions

TX12.3.7 Mechanism Life Extension Systems

Mechanism life extension involves the limitations of mechanism life in extreme and harsh environments, particularly overcoming the life-limiting properties of current lubrication and components in harsh environments of dust and cryogenics.

Example Technologies

- Long-life bearing/lube system
- Cryo long-life actuator

TX12.3.8 Docking and Berthing Mechanisms and Fixtures

Technologies that enable a spacecraft to affect docking and berthing of another spacecraft or natural space object (small body) include robotic manipulators and tools for docking systems, berthing systems, and any other system used to affect docking and berthing of an object. Additionally, these technologies can include those that are specifically designed to facilitate docking and berthing, such as passive berthing and docking fixtures. Note: The robotic manipulator and tools for capture are captured in TX04.5.5 Capture mechanisms and fixtures.

Example Technologies

- Dexterous/long reach robotics
- Other grippers
- Marman ring & other berthing mechanism
- Stinger/LAE docking mechanism
- Lunar/Mars surface robotic docking mechanism
- Electromagnetic docking
- Crew docking mechanism
- Deep space crew docking system (deep space, Lunar surface, Mars surface)
- Touch and go sampling mechanism
- Harpoon
- berthing and docking fixtures

TX12 Materials, Structures, Mechanical Systems, and Manufacturing

TX12.4 Manufacturing

This area covers innovative physical manufacturing processes and integrate with analysis and design through a ‘digital thread.’

TX12.4.1 Manufacturing Processes

Deployables, docking, and interfaces combine and/or separate aerospace vehicles and aerospace vehicle systems either remotely or with humans in the loop.

Example Technologies

- Additive manufacturing of metallics and nanofiber/fiber/ceramic matrix based composites, especially for large structures
- In-space fabrication, assembly and repair
- Advanced casting and injection molding of metal components, including amorphous metals, metal matrix composites and high-strength aluminum alloys
- Advanced subtractive manufacturing processes including wire-Electrical Discharge Machining (EDM), water jetting and surface finishing
- Advanced laminate or sheet metal fabrication

TX12.4.2 Intelligent Integrated Manufacturing

Intelligent integrated manufacturing technologies comprise the “digital thread” model-based manufacturing environment.

Example Technologies

- Integration of smart sensors, controls, and measurement, analysis, decision support, and communication software tools for process control
- Model-based, digital implementation that integrates design, manufacturing and product support processes

This rocket engine fuel pump has hundreds of parts including a turbine that spins at over 90,000 rpm. This turbopump was made with additive manufacturing and had 45 percent fewer parts than pumps made with traditional manufacturing. (NASA)

TX12.4.3 Electronics and Optics Manufacturing Process

Electronics and optics manufacturing process produces logic, electrical, electronic components of increased efficiency, for extreme environments and precision optics component manufacturing.

Example Technologies

- Optical materials, components, structures
- Precision optics for large scale applications
- Advanced architecture nanoelectronics
- One dimension/two dimension (1D/2D) nanoelectronics
- Vacuum-tube nanoelectronics
- Flexible electronics

TX12.4.4 Sustainable Manufacturing

Sustainable manufacturing reduces (or eliminates) hazardous materials in production processes.

Example Technologies

- Removing hazardous materials from by-product of manufacturing processes, using green energetic compounds

TX12.4.5 Nondestructive Evaluation and Sensors

Non-destructive devices and nanodevices deployment and embedding rapidly and autonomously interrogate large structure areas, understand as-build conditions, accurately characterize structural integrity and environment, and detect and assess anomalies.

Example Technologies

- Special focus on increased sensitivity and selectivity, with reduced mass, power consumption and a smaller overall footprint
- Sensors, sensor networks, processing software for data reduction and damage location and life prediction

ESA's European Service Module arrived in Cleveland in November and was transported to NASA Glenn's Plum Brook Station for testing in the Space Power Facility in 2016. (NASA)

TX12.4.6 Repurpose Processes

Repurpose processes support the recycling and reuse of spent material and structures at destinations, for repair or new application.

Example Technologies

- Reuse vehicle tanks for habitats and storage
- Packaging for building material
- Metals components as additive manufacturing feedstock

TX12.5 Structural Dynamics

Loads and Structural Dynamics is a specialty branch of structural and mechanical engineering that deals with the determination of the vibration response of a structure subjected to dynamic (time varying) forces in its operational environment. It involves the interaction of aerodynamic, dynamic, elastic, damping, inertia, and control forces acting on vehicles and structures. Included are response and stability investigations of linear and nonlinear systems using analytical, empirical, and experimental techniques.

Structural dynamics technologies support effective and efficient deterministic and stochastic predictions of the mechanical (global and local static and dynamic) environments and associated structural dynamic behavior for the structural and system capabilities for future aerospace missions. Included are test technologies and techniques used in the verification and validation of structural and mechanical systems and associated numerical models for critical loads and environments.

TX12.5.1 Loads and Vibration

This area covers advanced loads and dynamics analysis capabilities with a focus on non-linear modeling and analysis and uncertainty quantification. This area includes novel vibration control techniques applicable to systems such as on-orbit docking and capture and advanced aero propulsion systems (e.g. electromagnetic loading of structures for electric aircraft propulsion).

Example Technologies

- Development of variational coupled loads analysis techniques
- Advanced fast coupled loads analysis tools
- Enhanced structural nonlinear joint dynamics modeling
- Turbomachinery response analysis tools

TX12.5.2 Vibroacoustics

This area covers modeling and analysis techniques for high/mid-frequency range (e.g., Boundary Element Method based techniques).

Example Technologies

- Enhanced internal payload fairing acoustic environment modeling approaches
- Advanced vibroacoustic model correlation techniques
- Structural damping integration methods (active/adaptive strategies to mitigate fatigue, failure, control-structures interactions, structural vibration and acoustics)

TX12.5.3 Shock and Impact

This area covers enhanced modeling and correlation tools and techniques with test validation.

Example Technologies

- Shock analysis methods and tools
- Impact blast and fragmentation assessment tools

TX12.5.4 Test, Tools, and Methods

This area covers operational modal analysis for large space flight hardware structural systems and multi-dimensional test techniques.

Example Technologies

- Large structures operational modal analysis test techniques
- Smart dynamic testing approaches inclusive of multi-input/multi-output techniques

TX12.X Other Manufacturing, Materials, and Structures

This area covers manufacturing, materials, and structures technologies that are not otherwise covered by the sub-paragraphs outlined in TX12 of the 2020 NASA Technology Taxonomy.

TX13

Ground, Test, and Surface Systems

Overview

The Ground, Test, and Surface Systems taxonomy includes technological innovations in capabilities, infrastructure, and processes to prepare, assemble, validate, execute, support, and maintain aeronautics & space activities and operations, on Earth and on other planetary surfaces to address risk, decrease operations and maintenance costs, and increase safety and mission availability.

TX13 Ground, Test, and Surface Systems

TX13.1 Infrastructure Optimization

13.1.1
Natural and Induced Environment Characterization and Mitigation

13.1.2
Launch/Test/Ops Site Management

13.1.3
Commodity Recovery

13.1.4
Propellant Production, Storage and Transfer

13.1.5
Ground and Surface Logistics

13.1.6
Test, Operations, and Systems Safety

13.1.7
Impact/Damage/Radiation-Resistant Systems

TX13.2 Test and Qualification

13.2.1
Mechanical/Structural Integrity Testing

13.2.2
Propulsion, Exhaust, and Propellant Management

13.2.3
Non-Destructive Inspection, Evaluation, and Root Cause Analysis

13.2.4
Verification and Validation of Ground, Test, and Surface Systems

13.2.5
Flight and Ground Testing Methodologies

13.2.6
Advanced Life-Cycle Testing Techniques

13.2.7
Test Instruments and Sensors

13.2.8
Environment Testing

TX13.3 Assembly, Integration and Launch

13.3.1
Offline Element Processing

13.3.2
Vehicle and Payload Assembly and Integration

13.3.3
Launch, Recovery and Reutilization

TX13.4 Mission Success Technologies

13.4.1
Mission Planning

13.4.2
Team Preparedness and Training

13.4.3
High-Fidelity Simulation and Visualization

13.4.4
Autonomous, Real-Time Command and Control

13.4.5
Operations, Health and Maintenance for Ground and Surface Systems

13.4.6
Ground Analogs for Space/Surface Systems

TX13 Ground, Test, and Surface Systems

The completed spacecraft that will carry the Mars 2020 rover to the Red Planet next year hangs suspended by cables inside the Space Simulator Facility at NASA's Jet Propulsion Laboratory in Pasadena, California. (NASA/JPL-Caltech)

TX13.1 Infrastructure Optimization

Optimization of infrastructure (the facilities, resources, commodities, and support systems necessary to perform NASA missions) focuses on technologies to decrease infrastructure complexity, reduce operations and maintenance (O&M) costs, increase safety and reliability, and enable multi-customer utilization. Optimization should provide the best balance between required functionality, efficiency, flexibility and life-cycle costs.

TX13.1.1 Natural and Induced Environment Characterization and Mitigation

Natural environments are defined as the naturally occurring conditions (temperature, rain, corrosion, humidity, salt, lightning, dust, wind, electrostatic charges, solar radiation, icing, etc.) to which mission infrastructure will be subjected. Induced environments are defined as the environments and conditions generated during the performance of activities by the infrastructure during assembly, disassembly, reversible assembly, testing, and processing on Earth or in space; and launch and recovery operations. (e.g., vibration, shock, Electromagnetic Interference (EMI), plume exhaust, hydrogen embrittlement, environmental impacts, etc.).

Example Technologies

- Active and passive means to reduce acoustic energy associated with launch
- Electrostatic charge build-up resistant materials and coatings
- Advanced flame trench surface materials
- Automated deep-deployment sediment analysis
- Materials compatible with advanced propulsion systems/commodities
- Corrosion detection under coatings, lightning-induced effects assessment tools
- Acoustic noise cancellation system
- Environmental remediation technologies
- New ground processing methods that reduce waste and pollution

TX13.1.2 Launch/Test/Ops Site Management

Launch/Test/Ops Site Management provides the facilities, servicing equipment, methodologies, and an experienced support team needed for safe processing, testing and launch of NASA's flight vehicles.

Example Technologies

- Collision avoidance and prognostics for cranes
- Variable geometry flame trenches
- Mobile launch pad kit
- Advanced flame trench surface materials
- Field repair through predictive and reconfigurable components
- Prognostics and diagnostics tools for ground operations

TX13.1.3 Commodity Recovery

Commodity conservation and recovery technologies are needed to optimize use of mission consumables and recover unused commodities in systems, commodities used to condition systems (such as purging), or commodities that are mixed with other constituents as a part of a process.

Example Technologies

- Helium waste stream recovery
- Hydrogen pooling mitigation
- Purge systems optimization
- Water recovery
- Helium purge instrumentation
- Helium capture, storage, and re-purification systems

TX13.1.4 Propellant Production, Storage and Transfer

Technology development for propellant production, storage, and transfer aims to increase on-site production and improve storage capability, verify quality, enhance distribution and conservation of fluids to reduce commodity costs and losses (from boil off and non-optimal usage), eliminate waste (from lack of commodity management and combustion products), mitigate hazards exposure to personnel, and reduce servicing durations and frequencies.

Example Technologies

- On-demand production of propellants
- Zero boil-off storage
- Toxic/green propellant storage and distribution
- Smart materials for leak detection
- Active/passive transfer technologies
- Production of propellants and other fluids from fresh/salt water, biomass or landfill
- Propellant loading and transfer technologies for reduced gravity environments
- Thermal insulation systems

TX13.1.5 Ground and Surface Logistics

Ground and surface logistics technologies reduce the size of the logistics footprint; ensure timely availability of logistical support; ensure resilience of the supply chain across programs; and ensure integrity of component pedigrees through on-demand manufacturing, modeling supply chain resilience, secure manufacturing technologies, and emerging parts planning and location systems.

Example Technologies

- Counterfeit part countermeasures
- Supply chain and supplier economic resilience modeling
- Digital product lifecycle management
- Service life prediction methods
- Built-in test enhanced life forecasting
- Calibration methods for surfaces systems
- Additive manufacturing of spare parts using in-situ surface materials
- Thermal insulation systems

TX13.1.6 Test, Operations, and Systems Safety

Test, operations, and systems safety technological advancements for monitoring and controlling the safety and performance requirements of flight vehicles are aimed towards evolving situational awareness and providing real-time insight into hazards, technical risk and performance margin.

Example Technologies

- Non-traditional sensors for fault isolation
- Precision lightning strike locator system
- Virtual hazardous operations modeling
- On-demand, custom-fitted and lighter-weight Personnel Protective Equipment (PPE)
- Ground safety tools for radioactive payload processing robotic caretakers for hazardous operations/locations, automated alignment and coupling systems
- Probabilistic risk modeling
- Risk-based assessments
- Multiphysics coupled therma-hydraulic and neutronics criticality models

TX13.1.7 Impact/Damage/Radiation-Resistant Systems

Impact, damage, radiation-tolerant systems include approaches to enhance system robustness in extreme environments and can range from very low to high temperatures, pressures, etc. Robustness of systems can include nanomaterials systems, metamaterials, radiation resistant materials, self-repairing systems, improved interlaminar interfaces, multifunctional systems, in-situ health monitoring, and repair mechanisms.

Example Technologies

- Flexible structures
- Refractory materials hardened for foreign-object debris
- Self-healing systems
- Impact damage resistant ceramic nanocomposites
- Radiation hardened or resistant and shielding materials
- Carbon nanotube and graphene materials
- Nanosensors and embedded sensors for in-situ health monitoring

Test technicians at Northrop Grumman's (formerly (Orbital ATK) facility in Promontory, Utah, examine the Space Launch System (SLS) booster aft skirt, which is set up for final validation testing of its avionics command and control system. (NASA/Orbital ATK)

TX13.2 Test and Qualification

This area covers the test and qualification environments necessary to validate the performance of flight vehicles, components, and ground/surface systems, including the methodologies and capabilities associated with test and qualification performance.

TX13.2.1 Mechanical/Structural Integrity Testing

Mechanical/structural integrity testing characterizes material properties, performance, and integrity to ensure reliable and safe structural components and verifies component performance under dynamic conditions and in cyclic processes.

Example Technologies

- Advanced non-conventional Schlieren techniques
- Temperature/pressure sensitive paint
- Advanced force measurement system
- Quick demate and remate T-0 couplers
- Composite materials repair
- Accelerated corrosion and material degradation testing
- Smart materials for damage detection
- Dynamic impact photogrammetry
- High volume and high flow testing at high (6000psi) and ultra-high (>7500 psi) complex and high thrust propulsion systems testing

TX13.2.2 Propulsion, Exhaust, and Propellant Management

Propulsion, exhaust, and propellant management provides commodity loading, rocket engine acoustic energy abatement, and propellant servicing capabilities to increase safety of operations.

Example Technologies

- Hyperspectral Imaging for cryogenic/toxic/non-hazardous fluids leak
- Fire detection and mitigation including propellant fire/flame detection
- Advanced techniques to scale up to a launch pad or engine test stand environment
- Detonation/conflagration effects
- Modular flame trench
- Universal propellant servicing system
- Small robots for repairs and mitigation actions
- Automated umbilicals
- Rocket exhaust capture and filtration

TX13.2.3 Non-Destructive Inspection, Evaluation, and Root Cause Analysis

Technologies and techniques are needed to perform “in-place” non-destructive inspection and evaluation testing before and during the critical path operations to ensure component performance during processing and launch activities and enable testing to determine the root cause of component failure.

Example Technologies

- Miniaturized robotic inspection devices
- Radiography; integrated, multi-parameter, ground-powered sensors for non-destructive evaluation
- Molecular agents for predictive health of fluid systems
- Composite Overwrap Pressure Vessel (COPV) analysis technologies

TX13.2.4 Verification and Validation of Ground, Test, and Surface Systems

Verification and validation technologies enhance the ability to determine the degree to which a ground, test, and surface systems design implementation matches intended usage and meets life-cycle mission concepts and critical performance requirements.

Example Technologies

- Standardized wireless data acquisition systems
- Advanced high-speed photography
- Augmented reality for design, process engineering, and test support

TX13.2.5 Flight and Ground Testing Methodologies

This area covers technologies specific to enabling flight systems testing for aeronautics and aerospace applications.

Example Technologies

- Runway surface movement detection system
- Advanced overrun runway materials
- Formation flying
- Advanced antenna systems for flight operations
- Aerospace traffic control system
- Adaptive flight instrumentation
- Arc jet test capabilities for flight qualification
- Weather prediction models/aeroscience ground test facilities

TX13.2.6 Advanced Life-Cycle Testing Techniques

This area covers technologies for high fidelity, useful life testing of components and systems (fatigue, stress, thermal, fault recovery, performance automation).

Example Technologies

- Built-in test enhanced life forecasting
- Rapid test reconfigurability
- Accelerated life testing
- Adaptive systems
- Test autogeneration and execution
- Models and approaches for remaining useful life prognostics
- Fault detection, isolation and diagnosis; modeling, engineering and analysis tools

TX13.2.7 Test Instruments and Sensors

This area covers sensor, instrumentation, and data acquisition technologies to enable specialized, repeatable, adaptive and highly specialized verification and operational testing required for NASA missions.

Example Technologies

- Integrated, multi-parameter, ground-powered sensors for continuous monitoring
- Radio frequency identification (RFID) wireless instrumentation systems
- Hyperspectral imaging
- Non-traditional sensors for fault isolation
- Ablation spectroscopy

TX13.2.8 Environment Testing

Environment testing technologies verify and ensure that aeronautics, aerospace and space systems can perform in the stringent environments that define NASA missions, including natural/induced environments of shock, vibration, temperature, thermal cycling, vacuum, humidity, radiation, dust, corrosion, weather, acoustics, cryogenics, and micrometeoroid orbital debris.

Example Technologies

- Multi-parameter testing, extreme environment characterization and prediction
- Corrosion real-time and accelerated testing
- Precision and small-scale data acquisition systems
- Outgassing and off gassing
- Material compatibility with optics
- Health monitoring
- Weather analysis
- Dust tolerant systems
- Passive and active systems to mitigate cryogenics losses
- In-situ health monitoring

Exploration Ground Systems' mobile launcher is seen atop crawler-transporter 2 at Kennedy Space Center's Launch Complex 39B in Florida on June 27, 2019. (NASA)

TX13.3 Assembly, Integration, and Launch

Assembly, integration, and launch is comprised of facilities, equipment, processes, and skills that move components through the receiving and inspection process, the assembly and test of subsystems, the integration into the final launch configuration, and the final launch sequence activities. New technologies and concepts can realize dramatic increases in responsiveness and mission availability.

TX13.3.1 Offline Element Processing

Offline element processing is heavily tied to 'factory' support systems and specific vehicle configuration information; transformational technologies and future servicing capabilities aim to provide greater flexibility, better management of critical path activities, and the ability to merge offline and launch site infrastructure and support systems.

Example Technologies

- Automated alignment, coupling, assembly, and transportation systems
- Portable heads-up display for maintenance work instructions
- Intelligent crane controls

TX13.3.2 Vehicle and Payload Assembly and Integration

The assembly of flight hardware in final flight configuration requires a set of facilities, equipment, and processes unique to that vehicle and payload. Transformational technologies and future servicing capabilities can provide greater mission flexibility, enable a greater number of simultaneous activities, and provide the ability to share infrastructure and support systems between multiple NASA activities.

Example Technologies

- Robotic assistants for assembly
- Self-cleaning couplers
- Automated umbilicals
- Common ground test systems (i.e., between elements and integration levels)
- Wireless power for prelaunch servicing (e.g., payload power and testing) and for umbilicals

TX13.3.3 Launch, Recovery and Reutilization

At the end of a mission, payloads and samples are recovered and the launch infrastructure is repaired, refurbished, or revalidated as needed before the next launch. Technology development focuses on rapid fueling and de-fueling, staging, payload insertion, mission execution, and assessment of infrastructure readiness.

Example Technologies

- Wireless power interfaces for ground systems at pad
- Sounding rocket ground systems
- Anti-icing cryogenic couplers
- Deployable sensor networks for launch monitoring
- Extraterrestrial sample return containment
- Unmanned aerial vehicles for payload recovery

In this view looking up inside the Vehicle Assembly Building at NASA's Kennedy Space Center in Florida, a crane lowers the Space Launch System (SLS) Core Stage pathfinder into High Bay 3 on Oct. 16, 2019. The pathfinder is being used by Exploration Ground Systems and its contractor, Jacobs, to practice offloading, moving and stacking maneuvers, using important ground support equipment to train employees and certify all the equipment works properly. (NASA/Ben Smegelsky)

TX13.4 Mission Success Technologies

This area covers technologies that collectively enhance mission success and reduce long-term risk to NASA Programs.

TX13.4.1 Mission Planning

Planning and scheduling technologies aim to optimize the use of resources during NASA missions, from the execution of daily work tasks, to working within all constraints and requirements to plan long-range activities such as launch manifests and facility utilization.

Example Technologies

- Intelligent planning and scheduling
- Multi-dimensional integration of mission plans with closed-loop activity scheduling

TX13.4.2 Team Preparedness and Training

Team preparedness and training technologies help flight crews and ground support personnel maintain proficiency and preparedness for making critical decisions as they address the complex operating states and failure modes of NASA systems. Heads-up displays, three dimensional (3D) immersive systems, augmented reality, and the ability to draw on high-fidelity information learning systems and training aids on demand are examples of emerging technologies that will be needed as missions become longer and more complex.

Example Technologies

- Immersive training
- Virtual training
- Advanced ground crew work instructions and procedures display
- Personal/biometric confirmation technology
- Integrated, just-in-time training management technology

Engineers at NASA's Johnson Space Center in Houston are evaluating how crews inside a mockup of the Orion spacecraft interact with the rotational hand controller and cursor control device while inside their Modified Advanced Crew Escape spacesuits. (NASA)

TX13.4.3 High-Fidelity Simulation and Visualization

High-fidelity simulation and visualization technologies provide situational awareness to flight crews, test engineers, and mission operations teams by seamlessly mining, visualizing, and sharing high-fidelity engineering models of ground and surface systems, related support systems, and operational states in real time, which reduces mission risk and allows for adaptive decision making.

Example Technologies

- Concurrent multi-user multi-dimensional situational information environment
- Automatic model-based configuration of control systems

TX13.4.4 Autonomous, Real-Time Command and Control

Autonomous, real-time command and control technologies aim to provide the capability to perform closed-loop command and control for high-energy systems in extreme environments.

Example Technologies

- Automatic generation of control software and test algorithms
- Real time data and voice loops to mobile devices
- State aware monitor and control
- Highly secure and access-controlled flexible data networking
- Intelligent procedures for operations sequencing and system troubleshooting

TX13.4.5 Operations, Health and Maintenance for Ground and Surface Systems

Technologies for operations, health and maintenance for ground and surface systems aim to reduce the mean-time-between-failure and mean-time-to-repair of supporting ground systems and enable capabilities for pre-staging and operation of unattended commodity production, logistics, support systems, and other surface infrastructure.

Example Technologies

- Anomaly and fault detection, isolation and diagnosis
- Prediction and prognosis algorithms for components and systems; autonomous inspection, maintenance, and repair (IMR) support systems
- Test, verification, and calibration methods for surface systems
- Commodity management
- Nuclear material handling and testing
- In-situ servicing
- Dust mitigation
- Robotic caretakers for IMR operations
- System data and performance trending/characterization

TX13.4.6 Ground Analogs for Space/Surface Systems

Ground Analogs for space/surface Systems aim to simplify launch and surface operations and expand operational and architectural options, enable efficient handling of consumable commodities in space, decrease reliance on terrestrial support, reduce mass and volume of replacement parts required to sustain long-duration human exploration missions, increase the operational availability of spacecraft systems with little or no increase in logistics spares mass and volume, and reduce crew time required for performance of maintenance operations.

Example Technologies

- Portable gravity offload system for ground checkout
- Autonomous commodities (e.g., LOX, helium, water, air) storage and transfer operations
- Launch and landing pad materials
- Excavation tools, prospecting free flyers, regolith operations technologies for mining and excavation
- Common interfaces for small launchers and payloads
- Zero power reactor

TX13.X Other Ground, Test, and Surface Systems

This area covers ground, test, and surface systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX13 of the 2020 NASA Technology Taxonomy.

NASA's Exploration Ground Systems conducts a water flow test with the mobile launcher at Kennedy Space Center's Pad 39B in Florida on July 2, 2019. It is the first of nine tests to verify the sound suppression system is ready for launch of NASA's Space Launch System for the first Artemis mission. During launch, 400,000 gallons of water will rush onto the pad to help protect the rocket, NASA's Orion Spacecraft, mobile launcher, and launch pad from the extreme acoustic and temperature environment. (NASA/Kim Shiflett)

TX13 Ground, Test, and Surface Systems

TX14

Thermal Management Systems

Overview

Thermal management systems acquire, transport, and reject heat, as well as insulate and control the flow of heat to maintain temperatures within the specified limits. Virtually all vehicles and related equipment require some level of thermal control, some much more tightly controlled than others, and the design approach and technologies employed vary widely depending on application.

TX14 Thermal Management Systems

TX14.1 Cryogenic Systems

14.1.1
In-Space Propellant Storage and Utilization

14.1.2
Launch Vehicle Propellant

14.1.3
Thermal Conditioning for Sensors, Instruments, and High Efficiency Electric Motors

14.1.4
Ground Testing and Operations

14.1.5
Cryogenic Analysis, Safety, and Properties

TX14.2 Thermal Control Components and Systems

14.2.1
Heat Acquisition

14.2.2
Heat Transport

14.2.3
Heat Rejection and Storage

14.2.4
Insulation and Interfaces

14.2.5
Thermal Control Analysis

14.2.6
Heating Systems

14.2.7
Verification and Validation of Thermal Management Systems

14.2.8
Measurement and Control

TX14.3 Thermal Protection Components and Systems

14.3.1
Thermal Protection Materials

14.3.2
Thermal Protection Systems

14.3.3
Thermal Protection Analysis

14.3.4
Thermal Protection System Testing

14.3.5
Thermal Protection System Instrumentation

TX14 Thermal Management Systems

A robot places composite fibers on the tank's inner wall structure. Engineers at Boeing Research & Technology formed the composite cryogenic tank using automated fiber placement at the Boeing Developmental Center in Tukwila, Washington. (NASA)

TX14.1 Cryogenic Systems

Cryogenics is the art, science, and engineering of achieving extremely low temperatures below 150 C and involves research, technology development, design, analysis, characterization, and testing of components through ground/flight evaluations supporting qualification and use of cryogenic fluids/temperatures for flight. Cryogenics employs unique skills, facilities, and expertise as the thermodynamics, fluid dynamics, material behaviors, and component/system responses vary significantly at low temperatures. Applications include all aspects of propulsion, science, ground operations, other unique applications, supporting analysis, safety and test.

TX14.1.1 In-space Propellant Storage and Utilization

In-space propellant storage and utilization technologies aim to extend cryogenic storage duration from hours to years and develop fluid management technologies to control, transfer, and utilize cryogenic propellants. These technologies enable a broad range of missions including but not limited to landers, ascent stages, in-space transfer vehicles, habitats, and in-situ resource utilization (ISRU) operations and encompasses both in-space or extraterrestrial destination surface environments.

Example Technologies

- Vacuum and partial vacuum insulation systems
- Low conductive heat-load structure
- Solar shields applications to limit insulation exposure
- Cryocoolers and integration for reduced/zero boil-off of propellants and provide liquefaction
- Micro-g fluid dynamics (2-phase transport, surface wetting, surface tension, evaporation condensation)
- Propellant acquisition/management devices (surface tension devices)
- Instrumentation/mass gauging in micro-g conditions; pressurization and pressure control (passive/active) and propellant mixing/destratification
- Propellant systems/hardware chill-down
- Low leakage, multi-use isolation valves
- Propellant transfer for stages, ISRU, other applications
- Propellant slosh dynamics
- Liquefaction for ISRU and other applications
- Heat rejection (cryocoolers or thermodynamic vents, other systems)
- Valves, actuators, and components

TX14.1.2 Launch Vehicle Propellant

Launch vehicle propellant technologies include all propellant handling aspects for both the vehicle and its payload while on the pad and during the ascent and on-orbit deployment phases. This subcategory includes technologies relevant to commercial launch industry enabling growth to support NASA Earth-to-orbit needs for cargo, science, and crew.

Example Technologies

- Tank/line insulation suitable for atmospheric conditions/survive ascent environment
- Composite structures and components and lines for cryogenic application
- Propellant stratification and management
- Ascent/staging slosh/ullage collapse/geysering management
- Vehicle feedline chill and operation
- Instrumentation/mass gauging to track propellant inventory
- Autogenous and helium pressurization systems for cryogenic propellants
- Settled cryogenic fluid operations
- Quick disconnects (vehicle and payloads)

TX14.1.3 Thermal Conditioning for Sensors, Instruments, and High Efficiency Electric Motors

This area includes cost-effective, high-efficiency, low-weight/vibration cryocoolers and advanced sub-Kelvin cooling technology; technologies for thermal management for cryogenic applications to unique flight science sensors and instrumentation; and technologies to integrate cryocoolers into superconduction machines and power electronics for electrified aircraft. This area also includes technologies relevant to NASA's unique wide-ranging science mission and research activities as well.

Example Technologies

- Integrated thermal control/parasitics
- Cryocooler refrigeration above and below 10 K
- Magnetic refrigeration, dilution coolers, multi-stage mechanical coolers, multi-stage passive coolers and Turbo-Brayton cryocoolers
- Joule-Thomson effect
- Solid cryogens heat sink
- Liquid hydrogen spacecraft dewars
- Vapor cooling for instruments and storage hardware
- Solar shields/baffles for spacecraft cryogenic systems
- Coatings to limit thermal load on spacecraft cryogenic systems
- Heat rejection and thermal switches
- Thermal parasitics for cryogenic fluids/ cryocooler systems
- Emerging applications for cryogenic environments such as low-temperature mechanisms (e.g. planetary exploration)
- Integrated cryocoolers for superconducting motors

TX14.1.4 Ground Testing and Operations

This area includes technologies to increase efficiency, reduce cost, and improve capability for cryogenic propellant usage in on-Earth operations and testing, including safe autonomous operations, densification, and point-of-use liquefaction and storage.

Example Technologies

- Advanced thermal insulation systems and concepts
- Densification of propellants/fluids at small and large scale (cooling below the normal boiling point (NBP))
- NBP fluids for propellant loading and conditioning
- Large scale refrigeration systems and technology
- Quick disconnects
- Cryogenic pumps
- Automation/fault detection
- Leak/fire detection for cryogenic systems
- Instrumentation for ground cryogenic systems (temperature, pressure, gauging, flow, etc.)

TX14.1.5 Cryogenic Analysis, Safety and Properties

This area includes technologies to develop, improve, and validate detailed thermal and fluid analysis techniques for cryogenic components and hardware as well as cryogenic safety approaches, methodology and application for ground and flight environments. This subcategory also includes improved and expanded expertise and knowledge in materials applications for unique cryogenic environments spanning data, manufacturing, and specialized design and testing to meet mission needs.

Example Technologies

- Integrated thermal modeling
- Cryogenic systems
- Computational fluid dynamics (CFD) (gravity and micro-gravity environments)
- Cryogenic propellant/fluid safety oxygen
- Fuels (e.g., H2, CH4) and inerts (e.g., N2)
- Cryogenic hardware systems safety
- Cryogenic properties (solid, liquid, vapor, and mixture)
- Other materials of construction at cryogenic temperatures (strength, thermal/electrical conductivity, emissivity, magnetism, and superconductivity)
- Material properties testing apparatus (strength, thermal/electrical conductivity, and emissivity)
- Additively manufactured materials for cryogenic applications
- Superconductive magnets/motors

TX14.2 Thermal Control Components and Systems

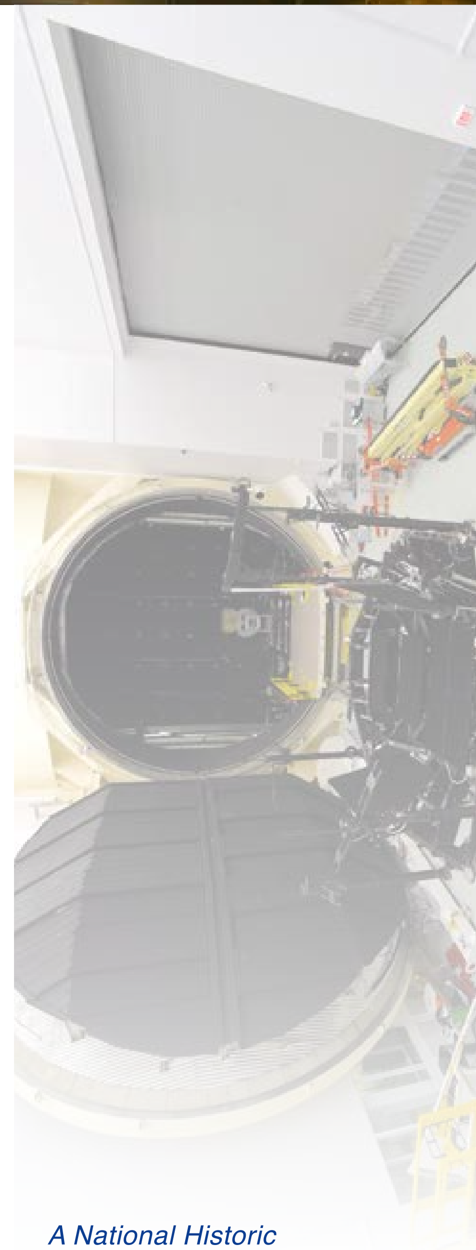
Thermal control components and systems provide capabilities that enable a vehicle to maintain operational temperature limits. A vehicle utilizes various components to achieve the primary functions of waste energy acquisition, transport, rejection/storage/reclamation, and temperature control within hardware limits through various mission environments. These functions are enabled through core capabilities of analysis, performance monitoring via sensors, and verification and validation to ensure mission success.

TX14.2.1 Heat Acquisition

Heat acquisition is the function within a vehicle that captures energy from a heat source. This function can be achieved through active and passive heat transfer within a thermal control system. The primary function of heat acquisition is to ensure the rate of waste energy transfer to a thermal control system either maintains a component within operational temperature limits or is sufficient for useful reapplication elsewhere (heat reclamation/harvesting). This area includes technologies to more effectively capture heat on a flight and a surface mission including cold plates, evaporators, and heat exchangers, as well as methods to advance robustness, life, efficiency, and temperature range of operability.

Example Technologies

- Cold plates and evaporators
- Liquid/liquid heat exchangers and air/liquid heat exchangers
- Boiling heat transfer
- Evaporation heat transfer
- Condensation heat transfer
- Crew cabin/avionics temperature and cabin humidity controls
- Hydrophilic coatings and surfaces
- Condensing heat exchangers
- High heat load collection (500 kW - 1 MW)
- Freezer and refrigerator



A National Historic Landmark, Chamber A at Johnson Space Center is famous for being used to test Apollo moon mission hardware, including suited astronauts inside the chamber on occasion. The chamber was used to conducted tests on the James Webb Space Telescope (JWST). (NASA/ Chris Gunn)

TX14.2.2 Heat Transport

Heat transport enables moving waste energy from a vehicle component and/or system for either rejection to the environment or re-use elsewhere within the vehicle. This area includes technologies for both spacecraft and electrified aircraft propulsion thermal management. The transport of energy is accomplished using active and/or passive capabilities within a thermal control system. Technologies include those items that can more effectively transfer heat, as well as methods to advance robustness, life, efficiency, and temperature range of operability.

Example Technologies

- Heat pipes (e.g. constant conductance, variable conductance, diode)
- Capillary pumped fluid loops and loop heat pipes
- Mechanically pumped fluid loops (e.g., single phase and two phase)
- Thermal straps
- Forced air cooling (heating, ventilation, and air conditioning (HVAC))
- Fans
- Heat pumps (e.g., thermoelectric coolers, vapor compression systems)
- Vapor cooling
- Heat switches (e.g. paraffin, coefficient of thermal expansion, shape memory alloys)
- Solid state conduction bars/doublers (e.g. high thermal conductivity composites)
- Loop heat pipe and high heat load transport (500 kW - 1 MW)
- Two phase heat transport and pool boiling

TX14.2.3 Heat Rejection and Storage

This area includes technologies to more effectively reject heat on a flight. Technologies are needed to make these methods more reliable and standardized and increase the capability for effective ground testing. This area includes technologies that manage system heat primarily through the use of the thermal and/or optical properties of a given material. This area includes in-space and ground applications.

Example Technologies

- Radiators and radiator turn-down devices (e.g. louvers, heat switches, variable conductance heat pipes)
- Phase change materials
- Transpiration cooling
- Heat sinks, optical coatings, variable coatings, sunshades, molten salts, cryogens, evaporation, boiling, and condensation
- Autonomous radiator maintenance
- Dust tolerant radiators
- High heat load 500 - 500 kW rejection

TX14.2.4 Insulation and Interfaces

This area includes technologies associated with insulations, including technologies to enhance interface conductance and also to reduce heat transfer across interfaces. This area also includes technologies for the prevention of heat intrusion to undesired locations, such as cryogenic propellant tanks, ground equipment, and certain spacecraft components as well as prevention of heat loss from given systems (e.g. crewed vehicles and maintenance of avionics operating temperatures).

Example Technologies

- Multi-layer insulations
- Foam insulations
- Aerogels
- Thermal gap fillers

TX14.2.5 Thermal Control Analysis

Thermal control analysis software is used to analyze the full thermal performance of a system, including orbital analysis, radiation analysis, thermal and fluid solvers, and optimization of design parameters through simulation. Technologies can include methods to more effectively link these functions, allow the analysis to be faster and more automated, perform uncertainty analysis, and decrease the time needed for thermal model development.

Example Technologies

- Thermal solvers
- Orbit analysis
- Radiation analysis
- Optimization
- Fluid flow analysis
- Layered composite insulation systems
- Coupled, multi-physics simulations for temperature induced phenomena affecting system performance
- Structural-thermal-optical (STOP) analysis
- Detailed thermal network analysis to evaluate the thermal performance of a given system

TX14.2.6 Heating Systems

Heating systems provide energy to maintain temperatures, either electrically or through radioactive decay using technologies such as thin-film heater, ceramic heaters.

Example Technologies

- Electric heaters
- Nuclear-based heating source (e.g. radioisotope heater units, general-purpose heat source)
- Chemical/combustion-based heating source

TX14.2.7 Verification and Validation of Thermal Management Systems

Verification and validation technologies support thermal testing of vehicle thermal systems and/or components, thermal model correlation, and the inspection of thermal control systems or hardware.

Example Technologies

- Testing, correlation, and inspection

TX14.2.8 Measurement and Control

This area includes technologies to improve measurement and control of thermal systems.

Example Technologies

- Sensors
- Mechanical thermostats
- Temperature control software and algorithms

TX14.3 Thermal Protection Components and Systems

Thermal protection components and systems is the set of thermal and structural materials, integration techniques, and manufacturing methods that protect the entry system from the extreme heating and aerodynamic forces experienced by a spacecraft during hypersonic atmospheric transit. Key challenges include increased thermal performance, high reliability, damage tolerance, and integration methods that do not create vulnerabilities in the spacecraft. For many exploration missions, thermal and structural load bearing capability are often required, with multifunctional material solutions offering overall system mass efficiency.

TX14.3.1 Thermal Protection Materials

Thermal protection materials (TPM) are the materials and coatings designed to tolerate high temperatures while insulating the spacecraft from the incident heating. Materials are often generally classified as single or multi-use, with application dependent on operations. This category also includes fundamental research and development of new material concepts, as well as materials testing used to determine underlying properties.

Example Technologies

- Tiles and blankets
- Rigid and conformal ablators
- Flexible materials
- Foams (i.e., ascent Thermal Protection Systems (TPSs))
- Coatings
- Materials research, development and testing
- Multi-functional materials (MMOD resistance, radiation reflective, etc.)

NASA's 3-Dimensional Multifunctional Ablative Thermal (3D-MAT) Protection System project designed and developed a game changing woven thermal protection system (TPS) technology tailored to the needs of the Orion Multi-Purpose Crew Vehicle (MPCV) compression pad for the lunar return mission, EM-1, and beyond. (NASA)

TX14.3.2 Thermal Protection Systems

TPSs encompass the integration of thermal protection materials, structure, bonding agents and gap fillers along with the manufacturing techniques and processes to enable the construction of an entire aeroshell. Included in this area are active and passive systems as well as hot structures for which the same material carries both thermal and structural loads for the aeroshell.

Example Technologies

- Active, passive, semi-passive, ablative, insulative, heat pipes, transpiration cooled thermal protection concept development
- Multilayer flexible (e.g., Hypersonic Inflatable Aerodynamic Decelerator (HIAD) thermal protection system)
- Ceramic matrix composite hot structures
- Carbon-carbon hot structures, attachment/integration

TX14.3.3 Thermal Protection Analysis

Thermal protection analysis encompasses the numerical approaches to simulate the incident environments as well as the material thermal and structural response to those environments. Such analyses can be performed via a range of approaches from fully uncoupled to fully coupled depending on mission requirements.

Example Technologies

- Aeroheating (convective and radiative)
- Ablation, thermal, thermo-structural, coupled, and margin policy development
- Reliability assessment and failure analysis
- Computational materials design

TX14.3.4 Thermal Protection Systems Testing

TPS testing encompasses experimental methods used to characterize the performance of TPS and TPM when subjected to relevant environments. Such testing can explore a single aspect of the flight environment (e.g. heat flux), or combinations of several aspects. Also included in this area are techniques for characterizing the test facilities, ranging from instrumentation to improved simulation capability.

Example Technologies

- Arc jet, laser-based, wind tunnel, solar tower, radiant, thermo-mechanical, pressurized elevated temperature, and combined (e.g., Laser Enhanced Arc-jet Facility (LEAF) Lite) flight testing
- Facility characterization (e.g. modeling, instrumentation)

TX14.3.5 Thermal Protection System Instrumentation

TPS instrumentation encompasses in-situ or remote techniques to measure the incident environment and/or the response of the TPS to that environment during flight.

Example Technologies

- Thermocouples
- Heat flux gauges
- Recession sensors
- Strain sensors
- Radiometer/spectrometers
- Sensor networks
- Integrated Structural Health Monitoring (ISHM)
- Remote observation platforms
- Pressure sensors

TX14.X Other Thermal Management Systems

This area covers thermal management systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX14 of the 2020 NASA Technology Taxonomy.

TX15

Flight Vehicle Systems

Overview

Flight Vehicle Systems is composed of the disciplines of Aerosciences and Flight Mechanics. Aerosciences is the prediction of vehicle and component atmospheric flight performance and flow qualities to enable robust and efficient flight vehicle development, achieving performance requirements while minimizing environmental impacts. Flight Mechanics provides the analysis, prediction, measurement, and test of vehicle dynamics, trajectories, and performance, and enables mission success for a wide range of vehicles.

TX15 Flight Vehicle Systems

TX15.1 Aerosciences

15.1.1
Aerodynamics

15.1.2
Aerothermodynamics

15.1.3
Aeroelasticity

15.1.4
Aeroacoustics

15.1.5
Propulsion Flowpath and Interactions

15.1.6
Advanced Atmospheric Flight Vehicles

15.1.7
Computational Fluid Dynamics (CFD) Technologies

15.1.8
Ground and Flight Test Technologies

TX15.2 Flight Mechanics

15.2.1
Trajectory Design and Analysis

15.2.2
Flight Performance and Analysis

15.2.3
Flight Mechanics Testing and Flight Operations

15.2.4
Modeling and Simulation for Flight

Key aerosciences technologies are enabling the development of advanced supersonic transports with reduced sonic boom signatures, allowing them to overfly the Continental United States and other populated regions. (NASA)

TX15.1 Aerosciences

Aerosciences is the prediction of vehicle and component atmospheric flight performance and flow qualities to enable robust and efficient flight vehicle development, achieving performance requirements while minimizing environmental impacts. The technologies involved in aerosciences require development of analytical and empirical systems; computational analysis; ground testing technologies in wind tunnels, arc jets, ballistic ranges, water channels; and flight technologies in specific technical areas.

TX15.1.1 Aerodynamics

Aerodynamics uses computational analysis, ground test, and flight to predict vehicle and component atmospheric flight performance and flow qualities (e.g. six-component aerodynamic forces and moments, detailed pressure distributions, qualitative and quantitative off-body flow characteristics).

Example Technologies

- Flow characterization through analysis and testing, with prediction and characterization of unsteady separated flow being a primary technology challenge
- Target vehicles include aircraft, launch vehicles, entry, descent, and landing (EDL) systems, abort systems, parachutes, and inflatable decelerators across all speed regimes from subsonic to hypersonic; characterization of subsonic, transonic, supersonic, and hypersonic flows, junction flows, landing gear, high lift systems, and innovative control effectors
- New technologies to predict and analyze the underlying unsteady flow characteristics driving buffet and aeroacoustics for aircraft, launch vehicles and spacecraft
- Advanced aerodynamic predictive capability required to enable efficient atmospheric flight vehicle designs

TX15.1.2 Aerothermodynamics

Aerothermodynamics uses computational analysis, ground test, and flight to predict vehicle and component aeroheating environments and flow qualities (e.g. convective and radiative heating, surface temperature, heat flux, interactions with vehicle components like thermal protection systems).

Example Technologies

- Forebody and afterbody heating characteristics with heating prediction on capsule afterbodies in separated flow
- Shock layer radiation prediction and characterization; advanced predictive technology

TX15.1.3 Aeroelasticity

Aeroelasticity is the coupled interaction of vehicle aerodynamics with vehicle structures and control systems, including static aeroelastic deformation, flutter, buffet, control surface buzz, aeroservoelasticity, and limit cycle oscillations.

Example Technologies

- Computational aeroelastic tools coupling Computational Fluid Dynamics (CFD) with structural dynamics methodologies to predict flutter, buffet, limit cycle oscillations and aeroservoelastic interactions
- Advanced unsteady CFD techniques to predict nonlinear fluctuating pressure fields for launch vehicle and aircraft buffet, control surface buzz and other nonlinear aero structural interactions
- Advanced ground test techniques and strategies to simulate and predict the performance of coupled aero/structural systems as well as complex unsteady flows and loads
- Advanced aircraft systems such as truss-braced wing and other concepts based on high aspect ratio wing configurations enabled by advanced static and dynamic aeroelastic prediction methodology
- Active flutter suppression; aeroelastic tailoring; active static/buffet/gust load alleviation

TX15.1.4 Aeroacoustics

Aeroacoustics is a branch of acoustics that studies noise generation via either turbulent fluid motion or aerodynamic forces interacting with surfaces, including periodically varying flows such as shock waves and noise generated by landing gears and deflected aero surfaces; and non-periodic unsteady flows such as those encountered during ascent of launch vehicles and spacecraft. These technologies are applied to fixed-wing, vertical lift, Unmanned Aerial Systems/Urban Air Mobility vehicles, launch vehicles, abort vehicles, and spacecraft.

Example Technologies

- Integrated approach to computational predictive methods, sensors, and test techniques to study aeroacoustic effects generated by shock motion, flow separation and reattachment, exhaust plumes and plume impingement, and sonic booms
- Prediction of aeroacoustic effects on vehicle structure, vehicle subsystems (such as electronics), the community, and methods to mitigate these effects for operations including buffet and aeroacoustic load reduction, noise reduction, sonic boom mitigation, and efficient airframe-engine integration

TX15.1.5 Propulsion Flowpath and Interactions

Propulsion flowpath and interactions looks at the details of flow into, through and out of the propulsion system and how these flows interact and/or are impacted by the vehicle. This is a broad area including rocket plumes, reaction control systems, inlet flows, nozzle and exhaust flows, combustion, distributed electric propulsion, hypersonic propulsion flow, and tightly integrated/coupled propulsion systems.

Example Technologies

- Technology challenges include prediction and characterization of flow-related performance for integrated propulsion systems
- Applications include distributed electronic propulsion, propulsion integration for sustained hypersonic flight, highly integrated efficient propulsion systems for aviation, Reaction Control Systems (RCS) during spacecraft entry, supersonic retro propulsion, launch abort vehicles, launch vehicle ascent, and stage separation

TX15.1.6 Advanced Atmospheric Flight Vehicles

This area covers unconventional vehicle concept designs enabled by advancements in understanding of flow and fluid phenomena.

Example Technologies

- Concept flow-related technologies supporting development of subsonic transports, supersonic transports, hybrid electric concepts, advanced spacecraft, launch vehicle and abort vehicles, planetary EDL and ascent vehicles, and urban air vehicles

TX15.1.7 Computational Fluid Dynamics (CFD) Technologies

This area covers Advanced CFD algorithms, strategies, and tools leading toward a vehicle Certification by Analysis capability.

Example Technologies

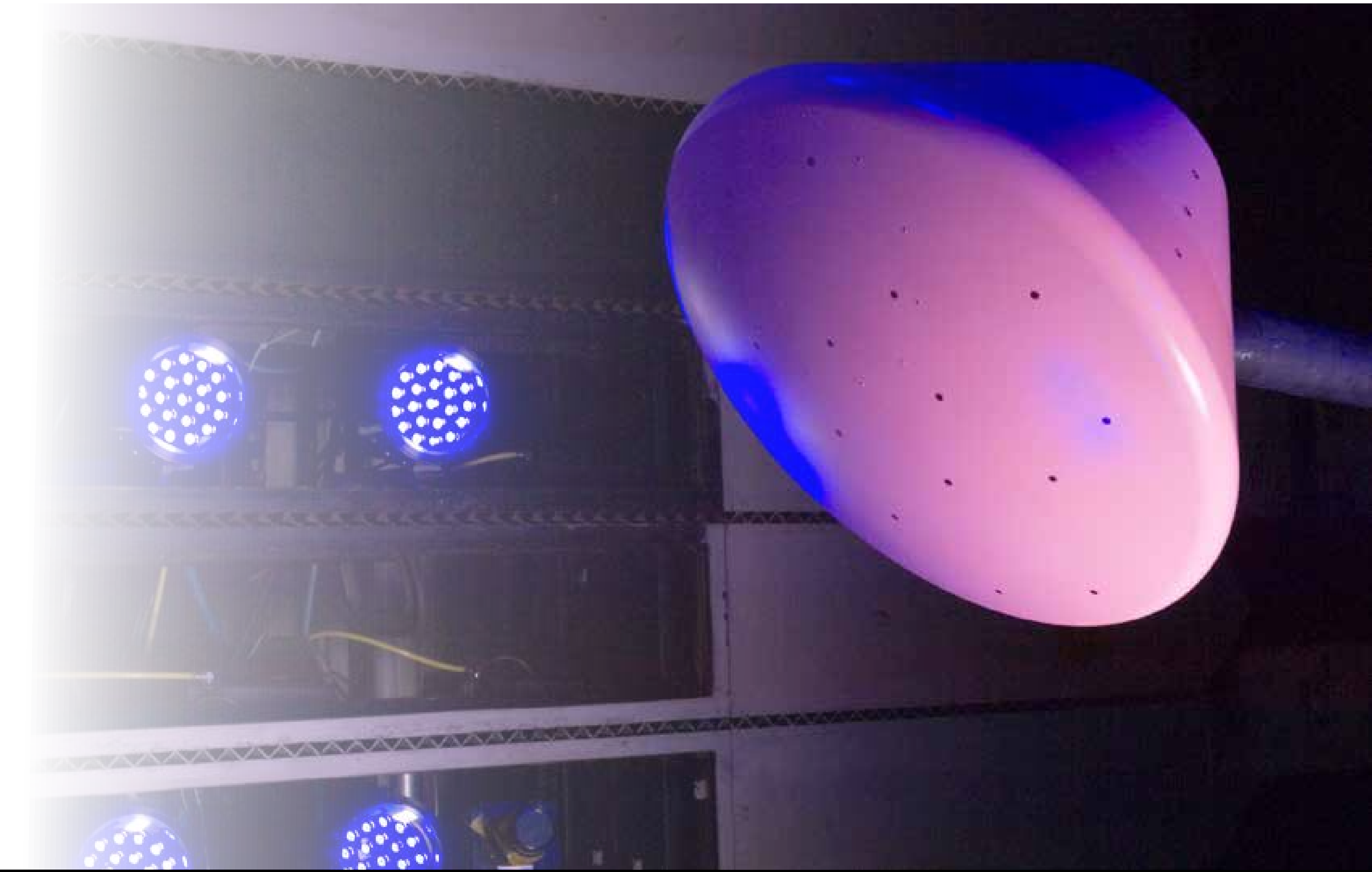
- Advanced algorithms and computational strategies allowing predictive and design tools to operate efficiently on emerging high performance computing architectures
- Advanced algorithms and tools to predict smooth-body, separated flows, chemically reacting flows, forced and naturally occurring unsteady flows
- Direct numerical simulation, large eddy simulation, and detached eddy simulation
- Particle methods like Lattice Boltzmann
- Geometry modeling
- Grid generation
- Large-data post processing technologies adapted to and integrated in CFD tools, methods, and strategies

TX15.1.8 Ground and Flight Test Technologies

This area covers advanced ground test capabilities, techniques, and strategies to enable development and validation of atmospheric flight vehicle concepts, validation of new CFD technology, and vehicle and flow research.

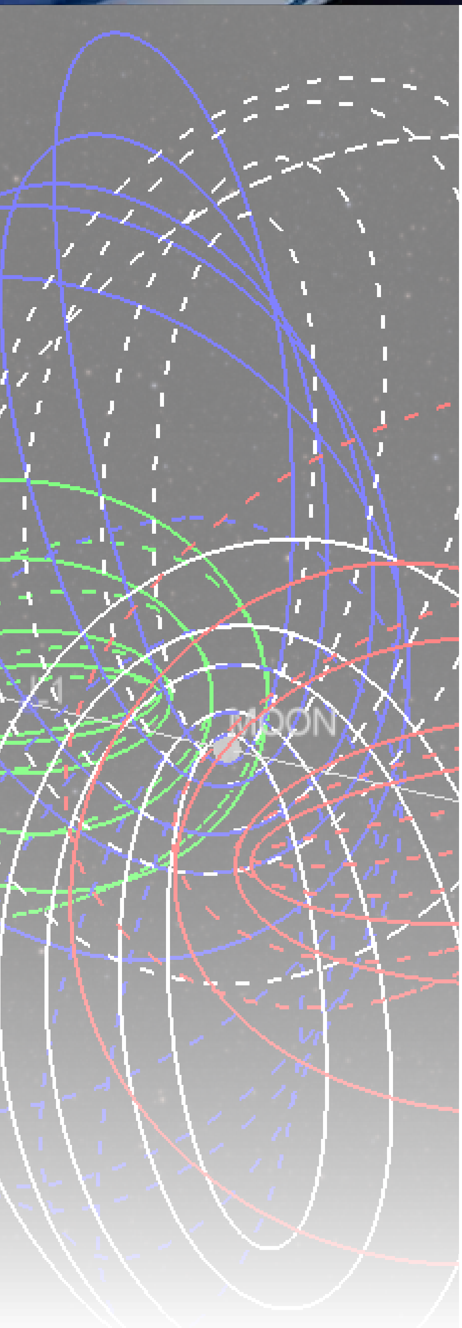
Example Technologies

- Technologies that incorporate advanced sensors, measurement techniques, and processes into ground testing in wind tunnels, ballistic ranges, water channels, arc jets and other ground test facilities as well as similar technologies for flight testing
- Advanced pressure and temperature measurement, qualitative and quantitative off-body measurement techniques, advanced static and dynamic pressure sensitive paint, advanced load balances, including flow-through balances for powered testing, and model deformation measurement systems for aeroelastic test
- Flight testing leverages similar technology and extends into remote thermal imaging techniques for direct aerothermodynamic measurements of flight vehicles and technologies like background oriented Schlieren techniques for off-body flow measurement, visualization and interaction



Emerging ground and flight test techniques and strategies are used to provide critical data to the development of advanced flight vehicles and validation of the tools used to predict their performance. (NASA)

TX15 Flight Vehicle Systems



Halo orbits in the Earth-Moon system designed using the Copernicus Trajectory Design and Optimization Program. (NASA)

TX15.2 Flight Mechanics

Flight mechanics provides the analysis, prediction, measurement, and test of vehicle dynamics, trajectories, and performance throughout the project life cycle, from mission definition, vehicle sizing and requirements, end-to-end modeling and simulation, refining the vehicle design, verification that design requirements are met, flight test, and mission operations.

TX15.2.1 Trajectory Design and Analysis

Trajectory design and analysis technologies support the design, optimization, analysis, and reconstruction of space vehicle and air vehicle flight trajectories.

Example Technologies

- Trajectory Design and Optimization. Includes design and optimization of space vehicle and air vehicle trajectories. Includes definition of the envelope of acceptable trajectories given the capabilities of the vehicle, and determination of the optimal trajectory. For space vehicles, includes ascent; orbital targeting, orbital maintenance, and on-orbit rendezvous; interplanetary trajectories; theoretical astrodynamics; low-thrust design and optimization; planetary moon tour design; three-body orbit modeling and design; and entry through landing. For air vehicles, includes takeoff, mission execution or cruise, and approach/landing
- Trajectory Reconstruction. Technologies that enhance post-flight and on-board procedures that use real-time, telemetered or recorded flight data to determine as-flown estimates of vehicle performance (propulsion, aerodynamics, GN&C, etc.) and encountered environment characteristics (atmosphere, and gravity
- End-to-end mission design and optimization of space vehicles and air vehicles. Involves integrating trajectory solutions from the various phases of flight to optimize the overall mission in terms of duration, mass, propellant, flexibilities, and requirements for associated subsystems, such as lighting, communications, power, propulsion, etc. Helps evaluate interactions and trades between other disciplines (aero, propulsion, structures, GN&C, etc.) and identifies/establishes subsystem performance and requirements

TX15.2.2 Flight Performance and Analysis

Flight performance and analysis supports the analysis and prediction of (open and closed-loop) vehicle performance and dynamics (including flying/handling qualities, system identification, and performance requirements, certification and model validation) during a maneuver, mission phase, or end-to-end mission for all current and advanced vehicle concepts, and for all phases of flight.

Example Technologies

- Technologies and techniques for the analysis, design, and prediction of vehicle performance parameters and evaluation against vehicle and mission requirements and constraints, such as 3DOF analyses for preliminary designs and trade studies followed by high fidelity 6-DOF evaluations with GN&C in the loop
- Technologies to aid in the analysis and evaluation and prediction of vehicle dynamics effects, and their impact on overall vehicle performance and stability/control, including the study, estimation, and analysis of open-loop (bare airframe) vehicle stability and controllability characteristics and the effects of the flight control system on these characteristics
- Technologies that enhance the analysis and prediction of vehicle flying and/or handling qualities, and evaluation of vehicle and/or pilot ability to adequately perform desired mission profile, including pilot-in-the-loop handling qualities (vehicle performance and workload) methods, analysis, and testing
- Technologies for system identification including the use of statistical methods to extract vehicle models from flight data through the use of planned maneuvers or effector commands, which allows comparison of flight-derived vehicle models with ground-based predictions and allows updating of ground-based flight simulations to more closely represent observed flight characteristics
- Research into methods, application and analysis of system identification methods, test techniques and flight test data; development, refinement and verification and validation of vehicle performance requirements
- Technologies that help with model validation includes evaluation and comparison against truth models of measured environmental conditions or measured system and sub-system characteristics and responses

NASA pilot Nils Larson evaluates software in the X-59 simulator that could predict where sonic booms would be felt on the ground and the intensity. (NASA/Lauren Hughes)

TX15.2.3 Flight Mechanics Testing and Flight Operations

Flight mechanics testing and flight operations supports the designing, planning, and conducting flight and ground-based tests (experimental and computational) focused on vehicle flight mechanics using flight dynamic test facilities, CFD tailored to flight-dynamic prediction, and/or pilot-in-the-loop ground-based simulators and in-flight full-scale and sub-scale test beds.

Example Technologies

- Technologies to aid in-flight and post-flight assessments of vehicle performance and handling such as trajectories and environments
- Technology development of sensors and systems to gather relevant flight data during flight tests and operational flights
- Technologies to aid in the planning and conducting flight tests and functional flights using ground-, air, and space-based assets
- Technologies and techniques for the analysis of requirements to create safe flight trajectories and observational assets for test personnel, crew, and public
- Technologies aimed in the planning and conducting tests and experiments using sub-scale to full-scale test articles (e.g. wind tunnel tests across the Mach range) to obtain aerodynamic and other data for assessing flight-dynamic behavior of vehicles, for simulation models, and stability and control analyses
- Use of existing measurement techniques, and development of new and novel techniques when state-of-the-art systems are not adequate, including use of piloted simulators for evaluation of aircraft and space vehicle flying and handling qualities

Synthetic vision cockpit display in Research Flight Deck simulator at NASA Langley Research Center in Hampton, Virginia. (NASA)

TX15.2.4 Modeling and Simulation for Flight

Modeling and simulation for flight supports the design, development, and implementation of vehicle flight dynamic simulations (simulation architecture, coordinate systems, equations of motion, etc.) and subsystem models (aerodynamic, aerothermal, propulsion, power, thermal, mass property, slosh, aero-servo-elastic structural, natural environment, geodesy, gravity, and uncertainty models) to enable accurate analysis and predictions of vehicle dynamics, trajectories, and performance.

Example Technologies

- Development of technologies that simulate the physics of flight vehicles, including GN&C, natural environment models, and vehicle subsystem (plant) models that affect vehicle performance and dynamics
- Development of visualizations of the flight vehicle to better communicate and determine operational performance
- Integration of visualization tools with trajectory design, reconstruction, and end-to-end mission design
- Math models of vehicle subsystems (aerodynamic, aerothermal, propulsion, power, thermal, mass property, slosh, aero-servo-elastic, structural, sensors, effectors, separation systems etc.) and environments (atmosphere, gravity, geodesy, etc.) that can be included as a software component in flight mechanics tools such as 6-DOF flight simulation
- Uncertainty modeling
- Simulation and trajectory visualization

TX15.X Other Flight Vehicle Systems

This area covers flight vehicle systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX15 of the 2020 NASA Technology Taxonomy.

TX16

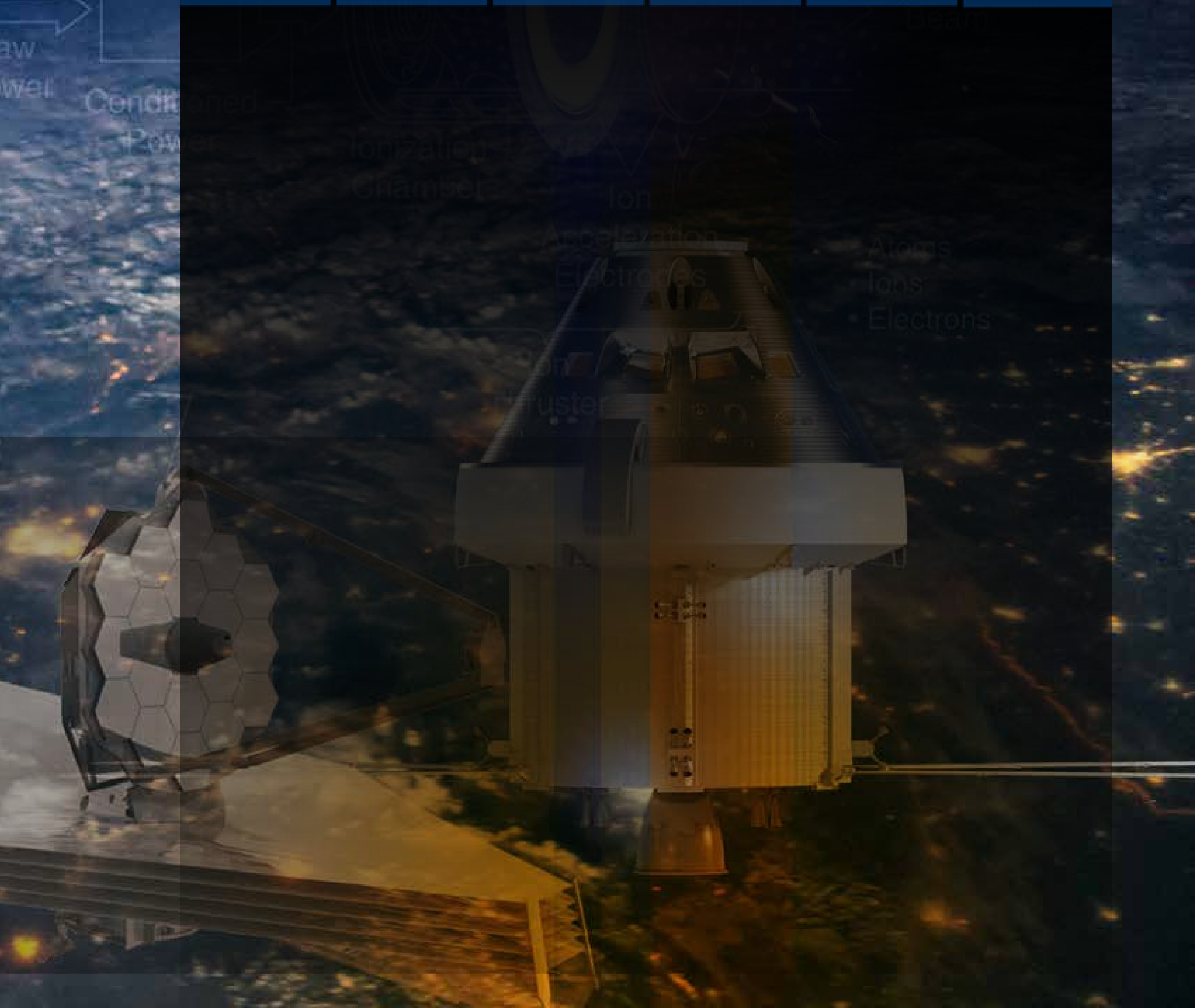
Air Traffic Management and Range Tracking Systems

Overview

Air Traffic Management and Range Tracking Systems are composed of technology disciplines associated with a modernized Air Traffic Management (ATM) system and range operations. The Next Generation Air Transportation System (NextGen) is the Nation's plan for a modernized ATM system that will achieve much higher levels of operational capacity and efficiency while maintaining or improving safety and other performance measures. The areas for NASA include safety and automation technologies which include far reaching concepts and technologies for future planning and operations and safely extend the capabilities and range of uses of the National Airspace System (NAS) for air transportation and commercial space integration. Air Traffic Management and Range Tracking Systems are unique technology areas within NASA and with the increasing amount of commercial space providers, and the regulatory oversight of the Federal Aviation Administration for Commercial Crew Program missions, there is a drive toward converging Range safety into general flight safety.

TX16 Air Traffic Management and Range Tracking Systems

TX16.1	TX16.2	TX16.3	TX16.4	TX16.5	TX16.6
Safe All Vehicle Access	Weather/ Environment	Traffic Management Concepts	Architectures and Infrastructure	Range Tracking, Surveillance, and Flight Safety Technologies	Integrated Modeling, Simulation, and Testing



TX16 Air Traffic Management and Range Tracking Systems

TX16.1 Safe All Vehicle Access

This area aims to enable safe scalable, routine, high-tempo airspace access for all users. Representative vehicle examples include but are not limited to general aviation, urban air mobility (UAM), commercial aircraft operations, unmanned vehicles, supersonic aircraft, rotorcraft, balloons, and commercial space vehicles.

Example Technologies

- Develop concepts and procedures that enable the safe integration of all vehicle types in the NAS, with examples such as Unmanned Aircraft Systems Traffic Management (UTM) Prototype for user services
- UAM viability demonstrations
- Safety technologies for new vehicle concepts
- Multi-domain situational awareness and prognostic safety awareness, prediction and alerting tools
- Technologies for safe global operations with resilient degradation; virtual airspace visualization concepts and technologies

TX16.2 Weather/Environment

This area aims to develop tools that provide weather and environmental information to avoid inclement weather/environmental conditions affecting ground and flight deck operations.

Example Technologies

- Improved weather and hazard awareness detection, prediction and alerting technologies, including aircraft state and health management
- Hazards include precipitation, winds, wind shears, microbursts, clear air turbulence, and icing

Urban air mobility means a safe and efficient system for vehicles, piloted or not, to move passengers and cargo within a city. (NASA)

TX16.3 Traffic Management Concepts

This area covers technologies and procedures to enable improved efficiency and predictability of ground, departure, en-route and descent portions of flight, for high density of mixed manned and unmanned vehicles.

Example Technologies

- Deployment of NextGen technologies including enhanced required navigation performance (RNP) arrival, integrated arrivals/departures/surface operations, and integrated air-ground applied weather demonstration
- Operator prioritization services integrated with air navigation service provider tools
- Safety analyses for new airspace concepts
- Fully integrated, service-based ground, flight deck and operations management technologies
- Scalable integration of airspace and application technologies

TX16.4 Architectures and Infrastructure

This area covers architectures and infrastructure that support existing operations and enable the integration of new vehicles, new operations and new business models, including advanced communications technologies and infrastructure and cyber-security.

Example Technologies

- Operator prioritization services integrated with air navigation service provider tools
- Develop requirements for a secure integrated CNS (Communications, Navigation, Surveillance) system for Trajectory Based-Operations (TBO) and future autonomous operations
- Guidelines and standards for initial Unmanned Aircraft Systems (UAS) integration in the NAS
- Technologies, guidelines, scalable architecture and standards for integration of all vehicles types into the NAS

A view of the electronic display used in simulations of the FIM technology to prepare pilots and flight coordinators for test flights that took place in 2017. (NASA)

TX16.5 Range Tracking, Surveillance, and Flight Safety Technologies

Technologies to increase the efficiency of range operations across land, air, sea, and space applications by increasing overall responsiveness and providing a greater ability to track the entire course of a launch vehicle, without expensive ground assets, for quantifying mission safety/risk/success. While these functions are similar to those conducted by the Federal Aviation Administration (FAA), they are unique because of the relative speed of launch vehicles and have traditionally been handled separately from traditional air traffic management operations.

Example Technologies

- Space based surveillance assets, “smart” sonar buoys for range (sea) operations
- Onboard tracking
- Advanced (near-zero loss) telemetry systems for ascent or re-entry
- Advanced antenna systems; multiple simultaneous tracking solutions
- Autonomous onboard flight analysis
- Autonomous flight abort/termination systems
- Anti-jamming and anti-spoofing communications
- Aerospace traffic control system capable of monitoring, deconflicting, debris tracking, weather overlays, and local and global scheduling
- Rapid reconfiguration for concurrent launches, reentries, and flights of diverse flight platforms (manned/unmanned aircraft/launch vehicles/buoyant systems)

A NASA Langley team will capture long range images of the SpaceX launch with the help of a sophisticated camera and telescope system on a gyro-stablized tracking mount. (NASA)

TX16.6 Integrated Modeling, Simulation, and Testing

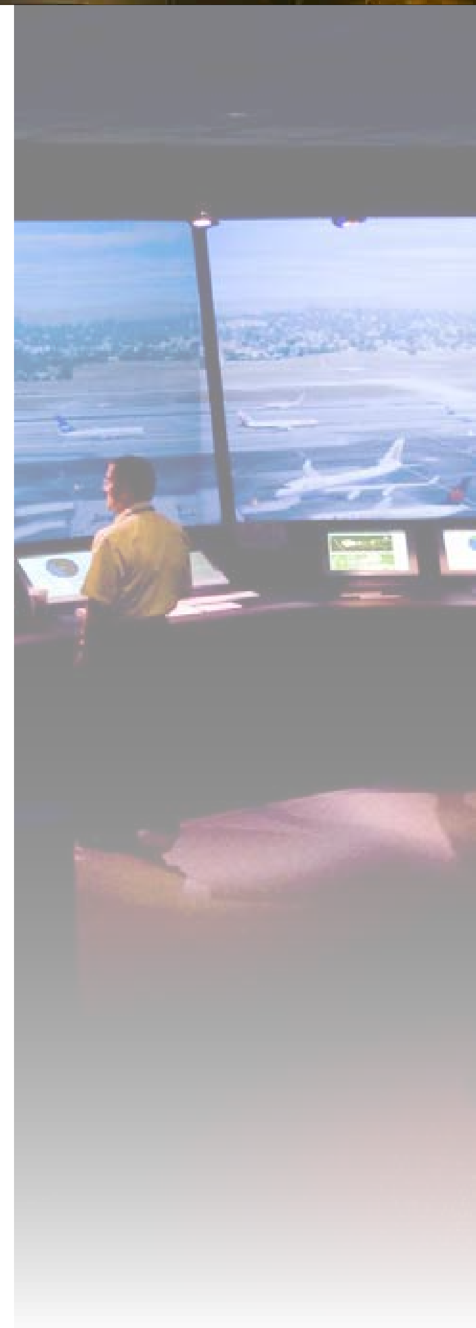
This area covers tools and methodologies that combine live, virtual, and constructive assets for developing, analyzing, testing and integrating novel concepts.

Example Technologies

- ATM testbed
- Operational ATM testbed with predictive capabilities
- Shadow-mode capability in which virtual and constructive simulations run in tandem with the live NAS
- Modeling to include real-time multi-vehicle near continuous optimization with real-time data
- Virtual and augmented reality injection into live systems so that they perceive a test range as a different target environment (e.g. UAM);
- Visualization tools and technologies for autonomous ATM methods

TX16.X Other Air Traffic Management and Range Tracking Systems

This area covers Air Traffic Management and Range Tracking Systems technologies that are not otherwise covered by the sub-paragraphs outlined in TX16 of the 2020 NASA Technology Taxonomy.



Researchers are testing new tools at FutureFlight Central, a comprehensive, 360-degree simulation of an air traffic control tower at NASA Ames Research Center in California's Silicon Valley. (NASA)

TX17

Guidance, Navigation, and Control (GN&C)

Overview

All forms of aerospace systems require some form of guidance, navigation, and control (GN&C) capability, either on-board, ground-based or a combination of both. This section of the taxonomy captures the unique GN&C system technologies that enable new missions; reduce cost, schedule, mass or power while maintaining or improving GN&C performance; improve system safety and longevity; or reduce environmental impact of aerospace vehicle operations.

TX17 Guidance, Navigation, and Control (GN&C)

TX17.1 Guidance and Targeting Algorithms

17.1.1 Guidance Algorithms

17.1.2 Targeting Algorithms

TX17.2 Navigation Technologies

17.2.1 Onboard Navigation Algorithms

17.2.2 Ground-based Navigation Algorithms

17.2.3 Navigation Sensors

17.2.4 Relative Navigation Aids

17.2.5 Rendezvous, Proximity Operations, and Capture Sensor Processing and Processors

17.2.6 Rendezvous, Proximity Operations, and Capture Trajectory Design and Orbit Determination

TX17.3 Control Technologies

17.3.1 Onboard Maneuvering/ Pointing/Stabilization/ Flight Control Algorithms

17.3.2 Dynamics Analysis, Modeling, and Simulation Tools

17.3.3 Ground-based Maneuvering/ Pointing/Stabilization/ Flight Control Algorithms

17.3.4 Control Force/Torque Actuators

17.3.5 GN&C Actuators for 6DOF Spacecraft Control During Rendezvous, Proximity Operations, and Capture

TX17.4 Attitude Estimation Technologies

17.4.1 Onboard/Attitude Rate Estimation Algorithms

17.4.2 Ground-Based Attitude Determination/ Reconstruction Algorithm Development

17.4.3 Attitude Estimation Sensors

TX17.5 GN&C Systems Engineering Technologies

17.5.1 GN&C System Architectures, Requirements, and Specifications

17.5.2 GN&C Fault Management/Fault Tolerance/Autonomy

17.5.3 GN&C Verification and Validation Tools and Techniques

17.5.4 GN&C Ground Testbeds/Test Facilities

17.5.5 Vehicle Flight Dynamics and Mission Design Tools/ Techniques

17.5.6 System Identification

17.5.7 End-to-End Modeling and Simulation of GN&C Systems

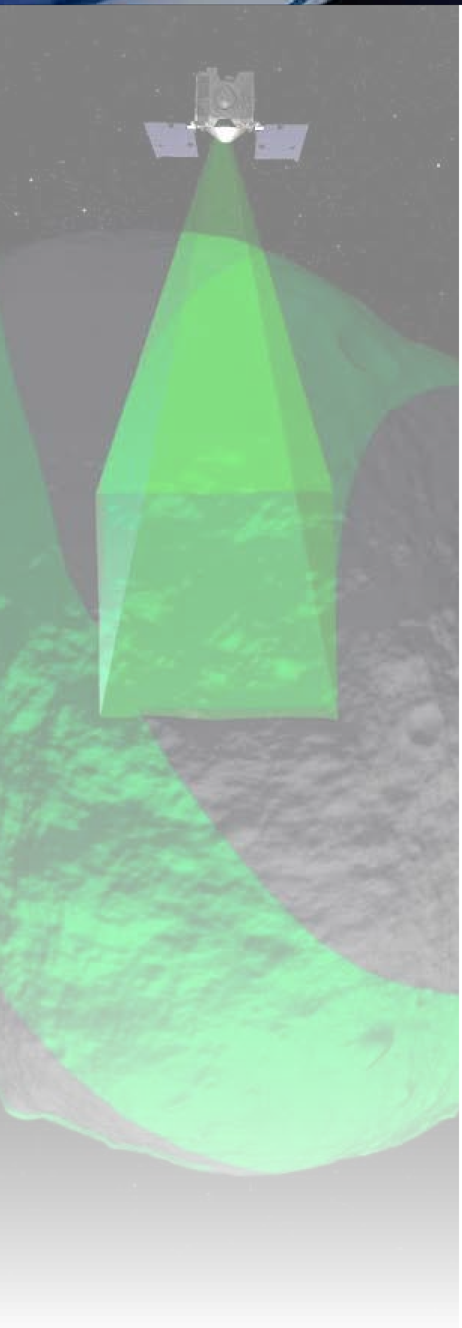
17.5.8 Flying/Handling Qualities

17.5.9 Onboard and Ground-Based Terrain and Object Simulation, Mapping, and Modeling Software

TX17.6 Technologies for Aircraft Trajectory Generation, Management, and Optimization for Airspace Operations

17.6.1 Strategic Management of Air Vehicles

17.6.2 Tactical Management of Air Vehicles



TX17.1 Guidance and Targeting Algorithms

Guidance and targeting algorithms primarily constitute the development of robust, reliable, and computationally efficient mathematical algorithms (and their associated software implementation) for the functions of on-board or ground-based computation of desired/reference space system flight paths and/or attitudes, and changes in flight paths and/or attitudes, required to meet mission requirements.

TX17.1.1 Guidance Algorithms

This area covers technologies for the development of algorithms (and associated software) for autonomous real-time or near-real-time selection of desired targets and the computation of the maneuvers to attain those targets while optimizing system performance.

Example Technologies

- Ascent guidance, abort guidance, and multi-vehicle formation flying guidance
- Vehicle 6DOF path planning
- Optimal attitude slewing guidance
- Next-generation entry guidance and powered descent guidance to support the functions of entry, descent, and landing (EDL) precision/pinpoint landing on planets/small bodies
- Computationally efficient trajectory/attitude optimization tools for onboard use

TX17.1.2 Targeting Algorithms

This area covers technologies for the development of algorithms (and associated software) for autonomous real-time or near-real-time selection of desired targets and the computation of the maneuvers to attain those targets.

Example Technologies

- On-the-fly adaptive guidance for opportunistic exploration and science observation

OSIRIS-REx is the third mission in NASA's New Frontiers Program. OSIRIS-REx launched in September 2016 and arrives at Bennu on December 3, 2018. This image illustrates the mission's carefully-designed orbit maneuvers and mapping campaigns on its journey to Bennu and back.

TX17.2 Navigation Technologies

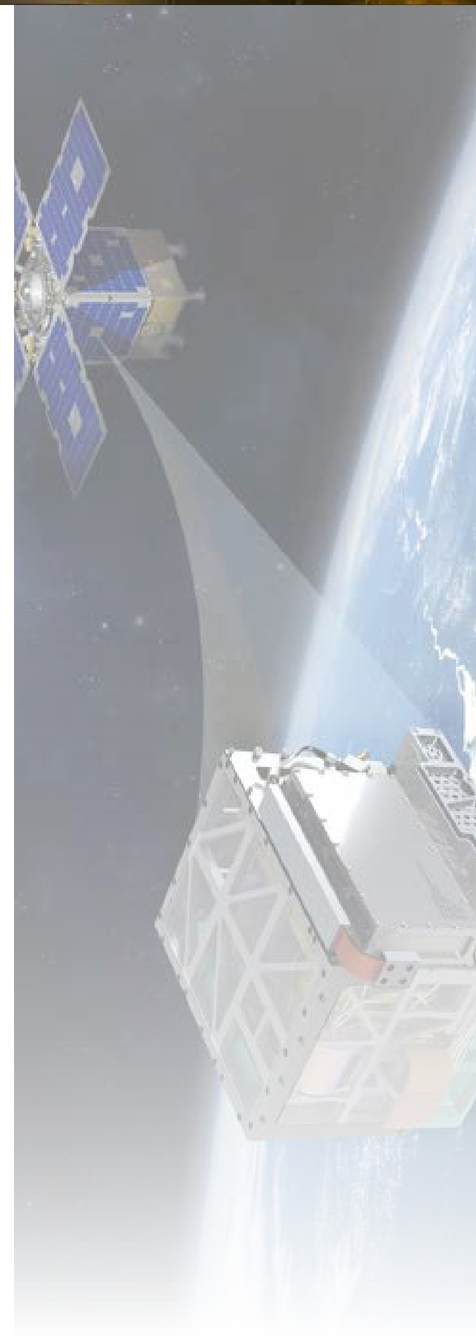
Navigation technologies primarily consist of the robust, reliable, and computationally efficient mathematical algorithms (and their associated software implementation) for the functions of flight path/orbit/trajectory state estimation.

TX17.2.1 Onboard Navigation Algorithms

This area covers algorithms (and their associated flight software) for autonomous onboard estimation of flight path/orbit/trajectory parameters and associated uncertainties from navigation sensor measurements.

Example Technologies

- Algorithms for optical navigation
- Terrain relative navigation
- Autonomous rendezvous and docking
- Autonomous hazard detection and avoidance
- Autonomous space-based navigation (optical or Global Positioning System (GPS) Cislunar)
- X-ray and X-ray pulsar navigation
- Simultaneous Localization and Mapping (SLAM)
- Light detection and ranging (LIDAR)-based navigation
- Inertial navigation (translation) filter and Inertial attitude estimation filter
- Ascent vehicle filter
- Earth-independent deep space navigation
- Celestial and landmark navigation
- Vehicle-relative navigation (translation) filter and vehicle-relative attitude filter
- Swarm navigation
- Angles-only navigation
- Double line of sight navigation
- Small body proximity operations and landing filter



NASA's Deep Space Atomic Clock, lanched in 2019, is testing new technology for deep-space navigation. (NASA)

TX17.2.2 Ground-based Navigation Algorithms

This area covers algorithms and tools for the ground-based estimation of flight path/orbit/trajectory parameters and associated uncertainties from navigation sensor measurements.

Example Technologies

- Filtering and estimation technologies for the optimum selection of data types
- Measurement frequencies and advanced techniques/methods for uncertainty analysis
- Technologies for 'lights out' ground system navigation autonomy to reduce flight operations team size/cost

TX17.2.3 Navigation Sensors

This area covers technologies for onboard sensors/sensor systems (sensor hardware and embedded sensor software) for taking measurements required to estimate flight path/orbit/trajectory parameters. This area includes navigation sensors/sensor systems for both absolute navigation function and relative navigation functions.

Example Technologies

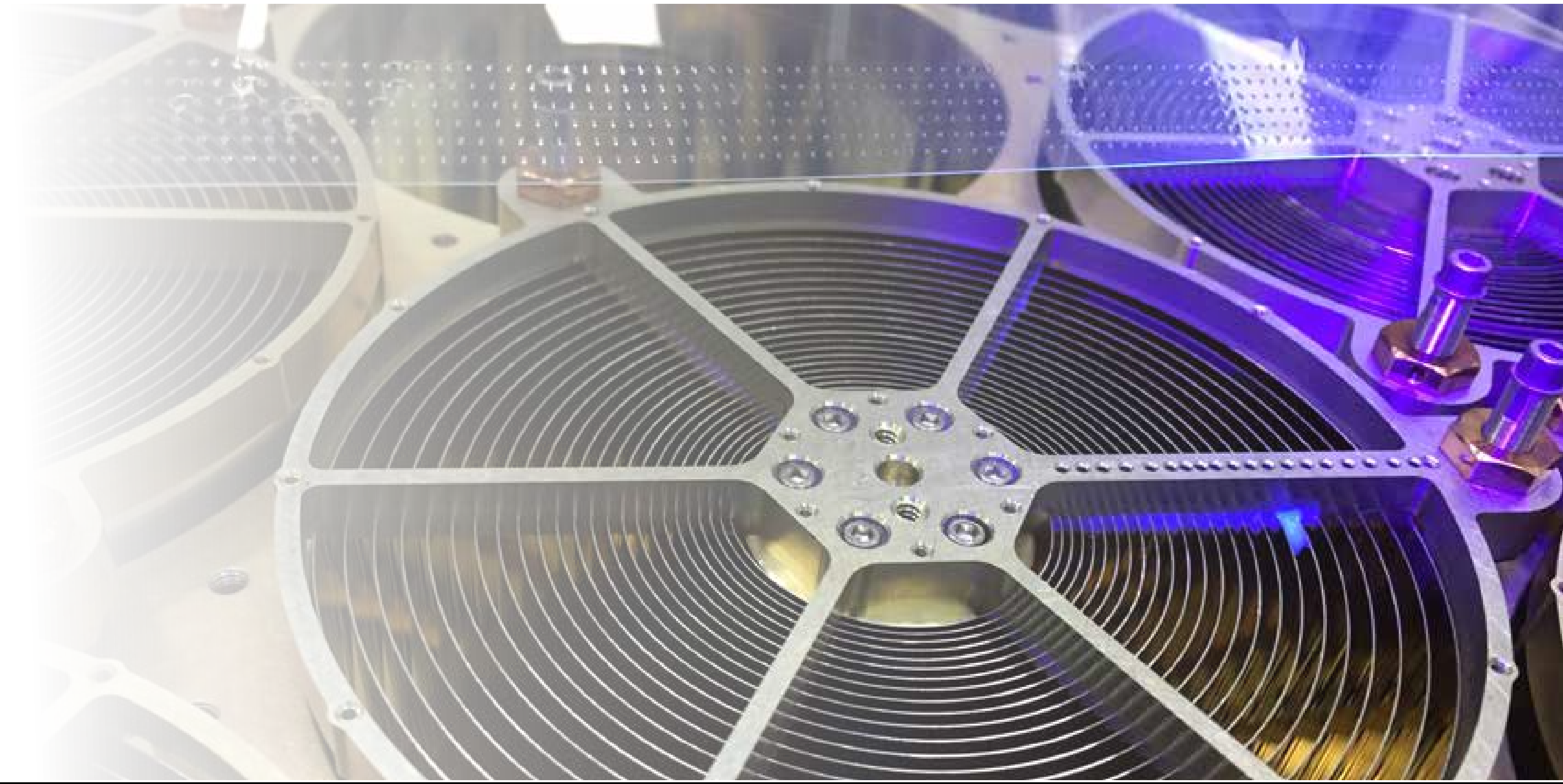
- Inertial Measurement Units (IMUs)
- Precision gyroscopes
- Accelerometers
- GPS/Global Navigation Satellite System (GNSS) receivers
- LIDARs, laser rangefinders, and laser altimeters
- Radio frequency (RF)-based inter-spacecraft ranging systems
- Visible and IR wavelength cameras
- Precision frequency and timing devices such as oscillators and clocks
- Cold atom sensors
- Navigation transponders and beacons
- Velocimeters
- Radars

TX17.2.4 Relative Navigation Aids

This area covers technologies for cooperative onboard relative navigation aids for improving the accuracy, range, and computational complexity of measurements required to estimate the orbit/trajectory parameters of one object with respect to another. These aids may be paired with specific sensors or general aids installed on spacecraft to facilitate future planned or unplanned on-orbit operations. This area includes technologies for cooperative onboard relative navigation aids for improving the accuracy, and range of, and reducing the computational complexity of measurements required to estimate the orbit/trajectory parameters of one object with respect to another. These may be paired with specific sensors or general aids installed on spacecraft to facilitate future planned or unplanned on-orbit operations.

Example Technologies

- Retro-reflective corner cubes
- Visual and IR fiducials
- Reflective tape
- LED targets
- RF beacon
- Radio Wave Marker (RF Retro-Reflector)



The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) technology demonstration, which NASA's Space Technology Mission Directorate had funded under its Game Changing Program, took advantage of the 52 X-ray telescopes and silicon-drift detectors that make up NASA's Neutron-star Interior Composition Explorer, or NICER, to study the potential for x-ray navigation. (NASA)

TX17.2.5 Rendezvous, Proximity Operations, and Capture Sensor Processing and Processors

This area includes all types of sensor processing algorithms, software, and firmware, to convert raw sensor data into relative navigation measurements, including range, bearing, relative position, relative velocity or Doppler, accelerations, and relative position and attitude (pose). This area also includes algorithms necessary for calibration of sensors, and for the control of sensors (i.e. automatic gain control). This area also includes compute elements specifically designed to accommodate rendezvous and capture measurement processing.

Example Technologies

- Vis. Cam. Vehicle Centroid/Bearing; IR cam. Vehicle Centroid/Bearing; Retroreflector Centroid Bearing; Landmark (i.e. crater) Bearing; Terrain Feature Bearing; Laser Retro Range & Bearing; Laser Vehicle Range & Bearing
- Relative GPS (LEO); Relative GPS Beyond LEO
- Coop RF Range, Doppler (Veh-to-Veh); Coop RF bearing (veh-to-veh); Non-Coop RF Range, Bearing, Doppler (Veh-to-Veh);
- Marman Ring tracking
- Illum Retro 2D Image 6DOF pose; Coop LIDAR 6DOF pose; Coop Vis. Cam. 6DOF pose; Coop. RF/Radar pose; Non-Coop. Vis. Cam. 6DOF pose; Non-Coop. Stereo Vis 6DOF Pose; Non-Coop. IR Cam. 6DOF pose; Non-Coop. LIDAR-based 6DOF pose; Non-Coop. RF-based 6DOF pose; Terrain-Relative Visible 6DOF pose; Terrain-Relative LIDAR 6DOF pose
- Camera Automatic Gain Control (AGC)
- High performance space flight computing elements
- Relative Navigation Sensor imbedded pose and terrain-relative navigation processing
- LIDAR calibration
- IR Camera calibration

TX17.2.6 Rendezvous, Proximity Operations, and Capture Trajectory Design and Orbit Determination

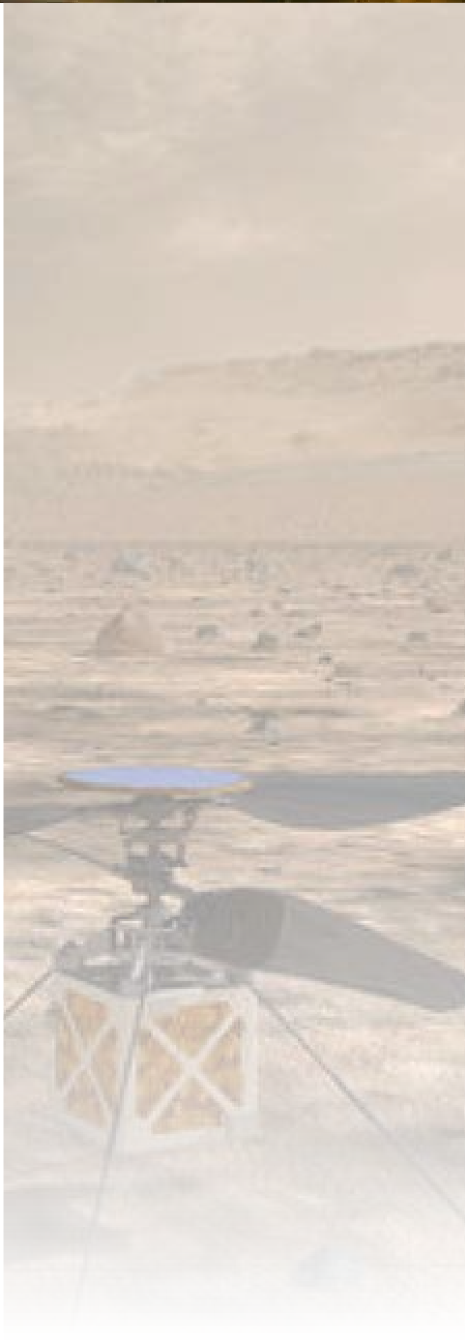
This area covers spacecraft trajectory design and orbit determination to support rendezvous and proximity operations in several specific orbital regimes. Trajectory design for missions performing rendezvous and proximity operations includes the inertial motion of a spacecraft starting and launch, and continuing to the design of relative motion to achieve rendezvous, proximity operations, capture, and departure from another space object (spacecraft or small body). Orbit determination is the inertial navigation function (ground or onboard) required to allow onboard systems to acquire the relative navigation estimate required to complete the mission.

Example Technologies

- LEO Rendezvous and Proximity Operations (RPO) trajectory design and orbit determination
- Geosynchronous Earth Orbit (GEO) RPO trajectory design and orbit determination
- Sun-Earth Lagrange Point RPO trajectory design and orbit determination
- Lunar Near Rectilinear Halo Orbit (NRHO) RPO trajectory design and orbit determination
- Lunar Distant Retrograde Orbit (DRO) RPO trajectory design and orbit determination
- Lunar Orbit RPO trajectory design and orbit determination
- Highly Elliptical Orbit (HEO) (aka Phasing Orbit) RPO trajectory design and orbit determination

TX17.3 Control Technologies

Control technologies primarily constitute the development of robust, reliable, and computationally efficient mathematical algorithms (and their associated software implementation) for the functions of autonomous exo- and endo-atmospheric flight path/orbit/trajectory control and/or space system attitude/attitude rate control. This area also includes advanced technologies for modeling and simulation as well as technologies for the development of a new generation of control force, moment, and torque actuators.



The Mars Helicopter is a technology demonstration that will travel to the Red Planet with the Mars 2020 rover. It will attempt controlled flight in Mars' thin atmosphere, which may enable more ambitious missions in the future. (NASA)

TX17.3.1 Onboard Maneuvering/Pointing/ Stabilization/Flight Control Algorithms

This area covers algorithms (and associated flight software) for autonomously commanding actuators (e.g. spacecraft thrusters, reaction wheels or control surfaces/propulsors) to orient/slew/point/stabilize a vehicle's attitude/attitude rate or to influence changes in a vehicle's flight path/orbit/trajectory.

Example Technologies

- Adaptive flight control for launch vehicles/spacecraft/landers/atmospheric exploration vehicles time optimal (or fuel optimal) spacecraft slew control
- Orbital rendezvous (Lambert Targeted Finite Burn)
- Clohessy-Wiltshire (CW) Targeted Finite Burn
- Deep Space (DS) Rendezvous (DS Rendezvous Finite Burn)
- Proximity Operations (vehicle and small body) (Closed-loop Relative Translation Control, Closed-loop Relative Translation Control (uncontrolled client), Closed-loop Relative Attitude Control, Vehicle 6DOF Path Planning, Payload Extraction from Launch vehicle)
- Formation flying (Formation acquisition control, Precision formation flying control)

TX17.3.2 Dynamics Analysis, Modeling, and Simulation Tools

This area covers technologies/techniques for the development of advanced software tools to model, simulate, and analyze the dynamic response of an air or space vehicle to forces exerted by actuators (e.g. thrusters, control surfaces) or by the environment, or by an active spacecraft on a nearby object (e.g. contact dynamics, thruster plume impingement). This area also includes technologies to analyze the stability and control of the vehicle including control-structure interaction and to assess the ability to meet mission requirements.

Example Technologies

- Flexible multi-body dynamics modeling tools/codes
- Finite element model reduction and manipulation tools/codes
- Modeling and simulation graphical display tools/codes
- Multi-vehicle closed loop hi-fidelity attitude and orbit simulation
- Capture contact dynamics
- Flexible modes analysis
- Proximity operations thruster plume impingement modeling and analysis
- Robotic manipulator kinematic simulation (reach and access, etc.)
- Robotic Manipulator high fidelity dynamics simulation of capture and berthing
- Relative navigation sensor hardware-in-the-loop (HWIL) testing of vehicle and small body proximity operations
- Grapple, berthing, docking, and small body contact (TAG/landing) HWIL testing with high fidelity 6DOF motion and contact dynamics
- High fidelity synthetic image generation for testing of vehicle- and terrain-relative pose/nav estimation systems

TX17.3.3 Ground-based Maneuvering/Pointing/ Stabilization/Flight Control Algorithms

This area covers technologies/strategies/techniques for the highly-automated ground-based formulation of space system maneuvers to change the vehicle's attitude/flight path/orbit/trajectory to meet mission requirements/constraints.

Example Technologies

- Algorithms for ground-based maneuver design, in a highly-automated manner
- Emphasis on attitude and trajectory optimization technologies that can accommodate various system constraints

TX17.3.4 Control Force/Torque Actuators

This area covers technologies for space systems onboard force/torque producing actuators (both hardware and embedded software) for the six degrees of freedom control of vehicle flight path or attitude. This area includes technologies that enable safe operations during rendezvous, proximity operations, and capture while allowing attitude to be constrained by relative navigation sensor pointing towards and limiting thruster plume on the object.

Example Technologies

- Next generation reaction wheels
- Cold-gas attitude control micro-thrusters
- Precision delta-v thrusters
- Thrust Vector Control (TVC) actuators

TX17.3.5 GN&C actuators for 6DOF Spacecraft Control During Rendezvous, Proximity Operations, and Capture

This area covers technologies that enable spacecraft to perform safe proximity operations with other space objects while allowing spacecraft attitude to be constrained by relative navigation sensor pointing towards and limiting thruster plume on the object.

Example Technologies

- 6DOF RCS thrusters

TX17.4 Attitude Estimation Technologies

Attitude estimation technologies primarily constitute the development of robust, reliable, and computationally efficient mathematical algorithms (and their associated software implementation) for the functions of autonomous space system attitude/attitude rate state estimation. This area also includes advanced technologies for the development of a new generation of attitude/attitude rate measurement sensors.

TX17.4.1 Onboard Attitude/Attitude Rate Estimation Algorithms

This area covers algorithms (and associated flight software) for functions of autonomous onboard estimation of attitude/attitude rate and their associated uncertainties/biases from attitude/attitude rate sensor measurements.

Example Technologies

- Kalman filters
- Relative pose estimators

TX17.4.2 Ground-Based Attitude Determination/ Reconstruction Algorithm Development

This area covers technologies for the development of algorithms and software for ground-based estimation/reconstruction of attitude and associated uncertainties from measurements.

Example Technologies

- Sparse data trajectory reconstruction tools
- Orbit determination tools/codes for formation flying spacecraft constellations

TX17.4.3 Attitude Estimation Sensors

This area covers technologies for the development of sensors (hardware plus embedded software) for measuring attitude. This area includes attitude sensors/sensor systems for both single-platform absolute attitude measurement functions and vehicle-to-vehicle relative attitude (i.e., relative "pose") measurement functions.

Example Technologies

- Star trackers
- Celestial sensors
- Inertial measurement units
- Gyroscopes
- LIDAR/Vis Cameras/IR Cameras (for relative pose measurement)
- Limb sensors

TX17.5 GN&C Systems Engineering Technologies

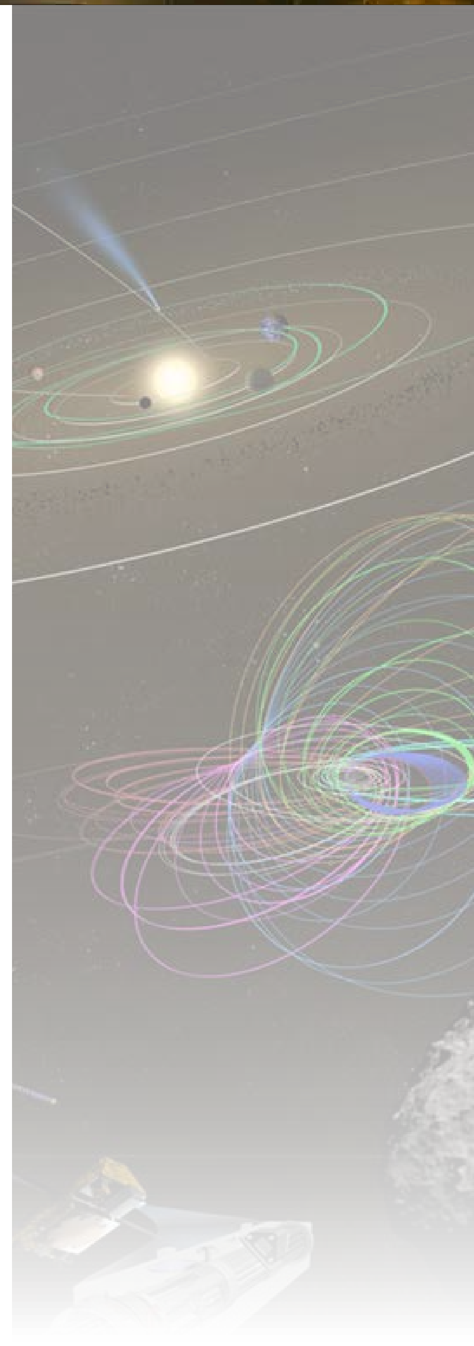
This area covers technologies for developing GN&C architectures and fault management systems and providing and improving the testing and verification of GN&C systems.

TX17.5.1 GN&C System Architectures, Requirements and Specifications

This area covers technologies for modern tools (tool sets) that support the development of GN&C conceptual/behavioral models and requirements, and development of system specifications to meet requirements. This area includes technologies that support the assessment of architectural autonomy trades (i.e. advanced GN&C System Engineering tools that reveal where infusion of autonomy has greatest payoff/return on investment in terms of mission performance and risk).

Example Technologies

- GN&C system architectural trade analysis tools/codes
- GN&C system sensitivity analysis tools/codes
- Multi-parameter system optimization tools/codes



An artistic rendering of simulated trajectories within the Solar System. (NASA)

TX17.5.2 GN&C Fault Management/Fault Tolerance/ Autonomy

This area covers technologies and strategies for the architecting and development of autonomous GN&C and robotic systems with high reliability and robustness.

Example Technologies

- GN&C fault management / fault tolerance algorithms, filters, and estimators for increased autonomy in GN&C systems
- Proximity operations (Collision Detection (RPO), Collision Avoidance Maneuver design (LEO), Collision Avoidance Maneuver design (GEO), Collision Avoidance Maneuver design (Deep Space))
- Capture (Collision Detection (Robot), Collision Avoidance (Robot))
- Landing (Descent Corridor Monitoring, Hazard Detection and Avoidance, Onboard Mission Manager (autonomous task sequencing))

TX17.5.3 GN&C Verification and Validation Tools and Techniques

This area covers technologies for modern tools (tool sets) that support the testing/checking that a GN&C system meets requirements (verification) and that it fulfills its intended purpose (validation).

Example Technologies

- Technologies for the verification and validation of highly autonomous systems
- Technologies/techniques/methods for modeling non-deterministic systems

TX17.5.4 GN&C Ground Testbeds/Test Facilities

This area covers technologies for the development of modern ground-based GN&C, robotic, and capture motion simulation testbeds. This area also includes hi-fidelity simulation of relative navigation sensors (e.g. for generation of synthetic imagery).

Example Technologies

- GN&C system autonomy assessment testbeds, high-precision pointing and micro-vibration jitter assessment testbeds

TX17.5.5 Vehicle Flight Dynamics and Mission Design Tools/Techniques

This area covers technologies for the design and optimization of space vehicle and air vehicle trajectories, including technologies for new mission design tools and associated mission design techniques that optimize mission/vehicle performance.

Example Technologies

- Computationally efficient trajectory and attitude optimization tools for onboard use
- Improved trajectory and mission design tools and visualization methods for faster trajectory, vehicle, and mission design cycles

TX17.5.6 System Identification

This area covers technologies for extracting vehicle models, onboard or on the ground, from flight data through the use of planned maneuvers or effector commands. These technologies allow comparison of flight-derived vehicle models with ground-based predictions and allow updating of ground-based flight simulations to more closely represent observed flight characteristics.

Example Technologies

- Computationally efficient algorithms for embedded online real time parameter estimation
- Tools/code for advanced maximum likelihood system dynamics estimation
- Prediction-error minimization (PEM) tools, codes, and algorithms
- Tools for sub-space system identification
- Tools and codes to represent nonlinear system dynamics
- Tools/codes for nonlinear autoregressive with external input (ARX) models with wavelet network, tree-partition, and sigmoid network nonlinearities
- Tools and codes for grey-box system identification for estimating parameters of a user-defined model
- Tools and codes for exploiting the identified model for system response prediction and plant modeling

TX17.5.7 End-to-End Modeling and Simulation of GN&C Systems

This area covers technologies for the development of software-based models and tools and tool sets for end-to-end flight system simulation and for the purposes of system robustness and performance assessment. This area includes development of improved uncertainty quantification and modeling techniques, development of visualizations of the flight vehicle to better communicate and determine operational performance, and development of automation for manually intensive analyses and processing large volumes of data.

Example Technologies

- GN&C modeling and simulation for increased autonomy
- Technologies, techniques, and methods for modeling non-deterministic systems

TX17.5.8 Flying/Handling Qualities

This area covers technologies for improving analysis and prediction of air or space vehicle flying and/or handling qualities, and evaluation of vehicle and/or pilot ability to adequately perform the desired mission profile. This area includes pilot-in-the-loop handling qualities (vehicle performance and workload) methods, analysis, and testing.

Example Technologies

- Advanced tools for designing-in desired handling qualities and for evaluating handling qualities for piloted space vehicles
- Tools for assessing pilot workloads, pilot performance, and handling qualities for advanced air and space vehicles (e.g. vehicles with increased structural flexibility, vehicles with increased levels of automation/autonomy)

TX17.5.9 Onboard and Ground-Based Terrain and Object Simulation, Mapping, and Modeling Software

This area includes technology, either onboard or on the ground that generates models or maps of a space object (spacecraft or small natural body) from images or other data acquired by a spacecraft flying in the vicinity of said space object.

Example Technologies

- Terrain digital elevation map or three dimensional (3D) model generation (offline)
- Terrain digital elevation map or 3D model generation (onboard)
- Vehicle 3D model generation (offline)
- Vehicle 3D model generation (onboard)

TX17.6 Technologies for Aircraft Trajectory Generation, Management, and Optimization for Airspace Operations

This area covers technologies for strategic and tactical management of air vehicles.

TX17.6.1 Strategic Management of Air Vehicles

This area covers technologies for traffic flow management and operations optimization for air vehicles.

Example Technologies

- Algorithms, ground software, and onboard software for improved traffic flow management and operations optimization for air vehicles

TX17.6.2 Tactical Management of Air Vehicles

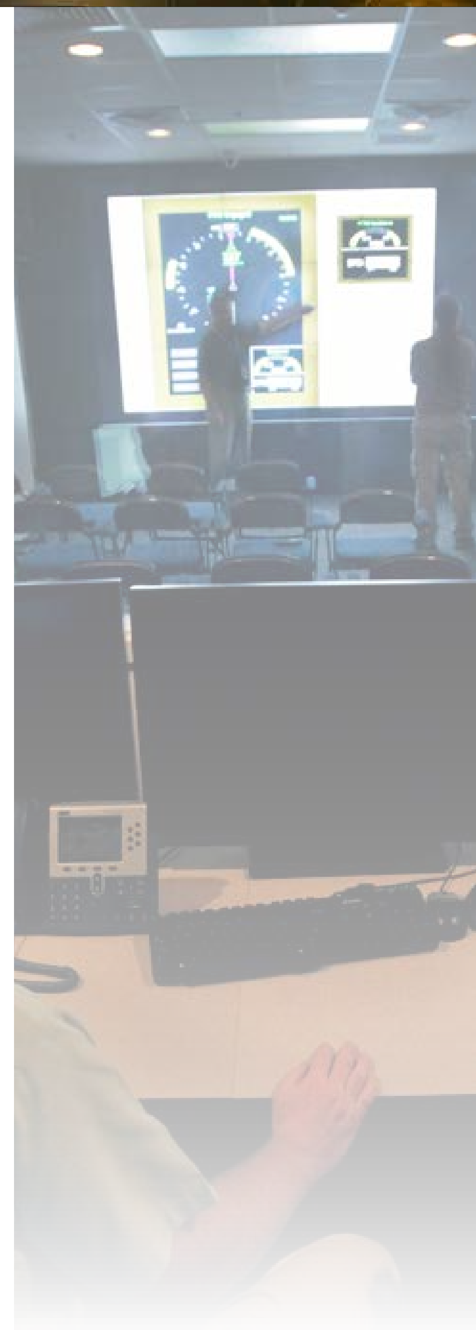
This area covers technologies for separation assurance and conflict resolution for air vehicles.

Example Technologies

- Algorithms, ground software, and onboard software for separation assurance and conflict resolution for air vehicles

TX17.X Other Guidance, Navigation, and Control

This area covers GN&C technologies that are not otherwise covered by the sub-paragraphs outlined in TX17 of the 2020 NASA Technology Taxonomy.



Members of the Air Traffic Operations Lab (ATOL) team look into a briefing room from one of the control rooms. (NASA/ David C. Bowman)

Acronyms


Neutralizer
Cathode
Magnets
Thrust
Beam
Conditioned
Power
Ionization
Chamber
Ion
Acceleration
Electrodes
Atoms
Ions
Electrons

Acronyms

2D	Two Dimensional
3D	Three Dimensional
3DOF	Three Degrees of Freedom
6DOF	Six Degrees of Freedom
AAE	Aeroassist and Atmospheric Entry
AC	Alternating Current
ACH	Analysis of Competing Hypotheses
ADC	Analog to Digital Converter
ADP	Advanced Diagnostics and Prognostics
ADU	Adaptive Model Updating
AFG	Analog Fluxgate Magnetometer
AGC	Automatic Gain Control
AI	Artificial Intelligence
AR	Augmented Reality
AR/VR	Augmented Reality / Virtual Reality
AR&D	Autonomous Rendezvous and Docking
ARX	Autoregressive with External Input
ASIC	Application-Specific Integrated Circuits
ATM	Air Traffic Management
C&DH	Command and Data Handling
CCC	Contaminant Control Cartridge
CFD	Computational Fluid Dynamics
CNS	Central Nervous System
CNS	Communications, Navigation, Surveillance
COPV	Composite Overwrap Pressure Vessel
COTS	Commercial-Off-The-Shelf
CPU	Central Processing Unit
CTE	Composite Technology for Exploration
CW	Clohessy-Wiltshire
DAC	Digital to Analog Converter
DC	Direct Current
DCS	Decompression Sickness
DDR3/4	Double Data Rate Type 3/4
DES	Discrete Event Simulation
DES	Dual Electron Sensors

Acronyms

DFB	Distributive Feedback
DIMM	Solar Differential Image Motion Monitor
DIS	Dual Ion Sensors
DRM	Design Reference Missions
DRO	Distant Retrograde Orbit
DSLIM	Double-Sided Linear Induction Motor
DSP	Digital Signal Processors
DTN	Disruption Tolerant Networking
E3	Electromagnetic Environment Effects
ECLSS	Environmental Control and Life Support System
EDL	Entry, Descent, Landing
EDM	Electrical Discharge Machining
EM	Electromagnetic
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
ESD	Electrostatic Discharge
ESP	Emission of Solar Protons
EVA	Extravehicular Activity
FAA	Federal Aviation Administration
FDIR	Fault Detection, Isolation, and Recovery
FDTD	Finite Difference Time Domain Technique
FEM	Finite Element Modeling
FIDR	Failure Isolation, Detection, and Recovery
FMA	Flight Mode Annunciators
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FPGA	Field Programmable Gate Array
FPI	Fast Plasma Instrument
FSI	Fluid Structure Interaction
GCMS	Gas Chromatograph Mass Spectrometer
GEO	Geosynchronous Earth Orbit
GN&C	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphical Processor Unit

Acronyms

HEO	Highly Elliptical Orbit
HERF	Hazards of Electromagnetic Radiation to Fuel
HERO	Hazards of Electromagnetic Radiation to Ordnance
HERP	Hazards of Electromagnetic Radiation to Personnel
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HPS	High-Performance Simulations
HSI	Human-Systems Integration
HVAC	Heating, Ventilations, and Air Conditioning
HVPS	High Voltage Power Supplies
HW/SW	Hardware/Software
HWIL	Hardware-In-The-Loop
ICME	Integrated Computational Materials Engineering
IMR	Inspection, Maintenance and Repair
IMU	Inertial Measurement Unit
InGaAs	Indium Gallium Arsenide
IP	Intellectual Property
IR	Infrared
ISHM	Integrated Structural Health Monitoring
ISRU	In-situ Resource Utilization
ISS	International Space Station
IVA	Intravehicular Activity
JWST	James Webb Space Telescope
LAE	Low Altitude Emission
LDMS	Laser Desorption Mass Spectrometry
LEA	Launch, Entry, and Abort
LEAF	Laser Enhanced Arc-Jet Facility
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
InGaAs	Indium Gallium Arsenide
LWIR	Longwave Infrared
M&S	Modeling and Simulation
MAR	Mid-Air Retrieval
MBMA	Model-Based Mission Assurance
MBSE	Model-Based System Engineering
MCD	Multi-Channel Digitizer

Acronyms

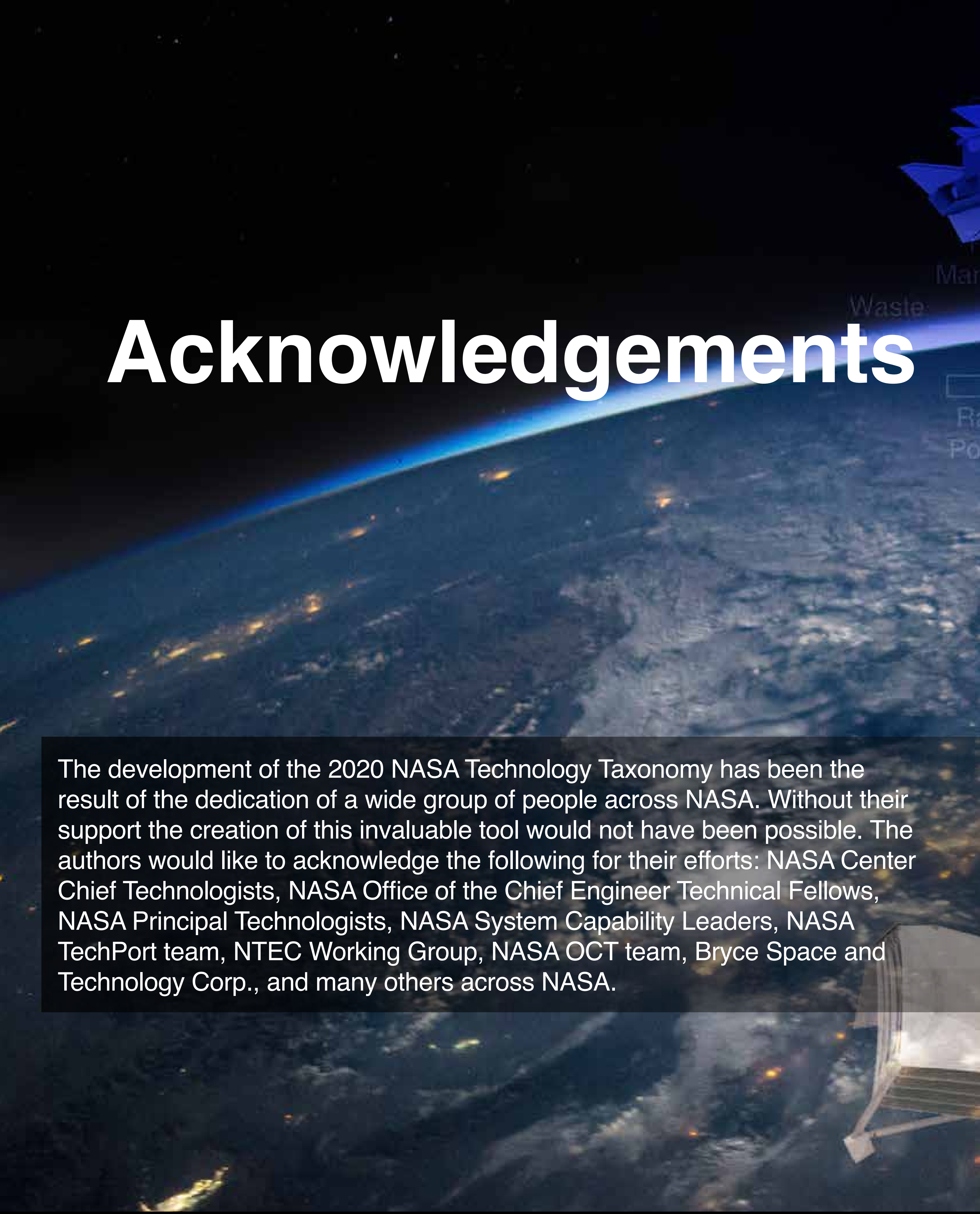
MCNP	Monte Carlo N-Particle
MCNPX	Monte Carlo N-Particle eXtended
MDM	Multi-Domain Modeling
MEMS	Micro Electro Mechanical Systems
MgB2	Magnesium Diboride
MGI	Materials Genome Initiative
MIMO	Multiple Input Multiple Output
MMIC	Monolithic Microwave Integrated Circuit
MMOD	Micrometeoroid Orbital Debris
MOMA	Mars Organic Molecule Analyser
MPD	Magnetoplasmadynamic
MRAM	Magnetoresistive Random Access Memory
MUSTANG	Modular Unified Space Technology Avionics for Next Generation
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NDE	Non-Destructive Evaluation
NEA	Near-Earth Asteroid
NextGen	Next Generation Air Transportation System
NISAR	NASA-ISRO Synthetic Aperture Radar
NRHO	Near Rectilinear Halo Orbit
NTP	Nuclear Thermal Propulsion
NUSTAR	Nuclear Spectroscopic Telescope Array
O&M	Operations and Maintenance
OTE	Optical Telescope Element
PACRATS	Payloads and Components Real-Time Automated Test System
PAT	Point, Acquisition, and Tracking
PBAN	Polybutadiene Acrylic Acid Acrylonitrile Prepolymer
PCB	Printed Circuit Board
PDE	Pulse Detonation Engine
PEM	Prediction-Error Minimization
PGC	Pressure Gain Combustion
PGS	Pressure Garment System
PLSS	Portable Life Support System
PMAD	Power Management and Distribution

Acronyms

PMD	Propellant Management Device
PNT	Position, Navigation, and Timing
POL	Point-of-Load
PPE	Personnel Protective Equipment
PPM	Pulse-Position Modulation
PRA	Probabilistic Risk Assessment
psi	Pounds per square inch
PVT	Psychomotor Vigilance Task
QE	Quantum Efficiency
R&D	Research and Development
RAT	Rock Abrasion Tool
RCS	Reaction Control Systems
RDE	Rotating Detonation Engine
RDM	Robust Decision-Making
RF	Radio Frequency
RFID	Radio Frequency Identification
RNP	Required Navigation Performance
RoCS	Roll Control Systems
ROIC	Readout Integrated Circuit
RPO	Rendezvous, Proximity Operations
RPOC	Rendezvous, Proximity Operations, & Capture
RTG	Radioisotope Thermoelectric Generator
S/C	Spacecraft
S/W	Software
SAM	Sample Analysis at Mars
SAR	Synthetic Aperture Radar
SCLT	System Capability Leadership Team
SEE	Single-Event Effects
SHM	Structural Health Monitoring
SIAD	Supersonic Inflatable Aerodynamic Decelerator
SLAM	Simultaneous Localization and Mapping
SMAP	Soil Moisture Active Passive
SoC	System-on-a-Chip
SPE	Solar Particle Event
SPECS	Submillimeter Probe of the Evolution of Cosmic Structure

Acronyms

SRP	Supersonic Retropropulsion
SRP	Solar Radiation Pressure
SSPA	Solid-State Power Amplifiers
STOP	Structural-Thermal-Optical
SWaP	Size, Weight, and Power
SWME	Spacesuit Water Membrane Evaporator
T/R	Transmitter/Receiver
TA	Technology Area
TAG	Touch-and-Go
TBO	Trajectory Based-Operations
THM	Thermal Health Monitoring
TPM	Thermal Protection Materials
TPS	Thermal Protection Systems
TVC	Thrust Vector Control
TWTA	Traveling Wave Tube Amplifiers
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UTM	Unmanned Aircraft Systems Traffic Management
UV	Ultraviolet
V&V	Verification and Validation
VE	Virtual Environment
VR	Virtual Reality
WSi	Tungsten Silicide



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