EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

LIVE: Surface Systems Envisioned Future
NASA Space Technology Mission Directorate

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Ground and Surface Support Systems to Enable Long Duration Surface Stays

Surface systems – making technologies to bring our world to the surface

Primary Impacts

Surface systems technologies serve an integrating and supporting function. Development of these technologies will result in seamless interfaces between "Live" outcomes and enable long-term mission operations while freeing crew to perform increased science investigations.

Thrusts	Outcomes	Primary Capabilities
	Transforming Space Missions	
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.	• Nuclear Systems • Cryogenic Fluid Management • Advanced Propulsion
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.	• Entry, Descent, Landing, & Precision Landing

Live
Sustainable Living and Working Farther from Earth
	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities.
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Habitation System technologies. [Low TRL STMD; Mid-High TRL SOMD/ESDMD]
		• Advanced Power
		• In-Situ Resource Utilization
		• Advanced Thermal
		• Advanced Materials, Structures, & Construction
		• Ground and Surface Support Systems
		• Advanced Habitation Systems

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop technologies for science instrumentation supporting new discoveries. [Low TRL STMD/Mid-High TRL SMD. SMD funds mission specific instrumentation (TRL 1-9)] • Develop transformative technologies that enable future NASA or commercial missions and discoveries.	• Advanced Avionics Systems • Advanced Communications & Navigation • Advanced Robotics • Autonomous Systems • Satellite Servicing & Assembly • Advanced Manufacturing • Small Spacecraft • Rendezvous, Proximity Operations & Capture • Sensors & Instrumentation

Secondary Impacts

Surface systems technologies are by their nature, cross-cutting. Technologies developed for surface applications likely impact other outcomes. In addition, developments targeting the lunar surface will feed forward to Mars and beyond.

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Envisioned Future (Lunar Space Port & Mars Forward Proving Ground)

Hardware Interfaces

Interoperable, standard, robotic interfaces
Robust, reusable interface seals
Autonomous integrity verification
Autonomous mate/de-mate of interfaces

Planning & Scheduling

Surface environment/weather forecasting
Autonomous, adaptive, supervisory monitoring and control of surface operations

Consumables Management

Real-time in-situ resource availability visualization
On-demand availability of all critical commodities
Autonomous, zero-loss fluid transfers
In-situ sampling and analysis

Logistics Management

Real-time, autonomous, global tracking and health monitoring of all surface assets
Recycling/reuse of 95% of Earth-born products
In-situ quality/damage assessments
Autonomous payload maneuvering

Hardware Health Management

Robotic caretakers to reduce crew-dependent maintenance and repairs
Intelligent devices to reduce troubleshooting
Prognostics for condition-based maintenance
Autonomous fault detection, isolation, and recovery from > 85% system faults
Data fusion enabled decision-making

Site Preparations

Reference the Excavation, Construction, and Outfitting Envisioned Future Priorities

Not all activities depicted are currently funded or approved. Depicts "notional future" to guide technology vision.

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Moon to Mars Objectives - Most Relevant Excerpts

RT-4: Crew Time: maximize crew time available for science and engineering activities with planned mission durations.
RT-5: Maintainability and Reuse: when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence.
RT-7: Interoperability: enable interoperability and commonality (technical, operations and process standards) among systems, elements, and crews throughout the campaign.

LI-9: Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.

OP-3: Characterize accessible resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable use of resources on successive missions.
OP-9: Demonstrate the capability of integrated robotic systems to support and maximize the useful work performed by crewmembers on the surface, and in orbit.
OP-12: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Surface systems – advancing technologies to bring our world to another surface

Logistics Management	Hardware Health Management	Consumables* Management	Planning & Scheduling	Hardware Interfaces
Autonomous tracking tools for surface assets (OP-12)	Autonomous, adaptable fault detection tools (RT-5)	Algorithms for autonomous leak evaluation and disposition (OP-3)	Surface-based instrumentation for full field debris characterization (LI-9)	Interfaces designed for robotic manipulator access (OP-9)
Scavenging database to inventory abandoned assets for potential reuse (OP-12)	Prognostics algorithms, including extreme environment factors (RT-5)	Reduced mass and volume vacuum-capable leak detectors (OP-3)	Integrated modeling and visualization tools for composite descriptions of extreme environments (LI-9)	In-situ interface integrity verification (OP-12)
Autonomous inventory management algorithms for part sourcing decision making (OP-12)	Reduced maintenance of surface-based hardware/components through intelligent devices (RT-5)	Autonomous commodity recovery (OP-3)	Decision making algorithms for robotic task prioritization (OP-9)	Autonomously operated surface umbilicals to enable fluid transfers (OP-9)
Supervisory waste/trash management tools (OP-12)	Fault isolation and recovery capabilities (RT-4)	Autonomous surface-based cryogenic flow control (RT-4)	Solar wind/flare tracking and forecasting (LI-9)	Interoperability adaptors (RT-7)
Surface-born resource tracking and visualization (OP-3)	Instrumentation and modeling for surface hardware impact damage assessment (LI-9)	In-situ fluid purity sampling (OP-9)	Master planning models (RT-4)	Cold and dust tolerant interface seals to enable surface transfers (RT-5)
Common repair toolkits (RT-7)	Robotic care-takers (OP-9)	In-situ food quality sampling (OP-9)	Autonomous ascent vehicle pre-flight checkout and preparation (RT-4)	Multi-use, mobile, self-alignment tool (RT-7)
Mobility outfitting and servicing station (RT-5)	Reconfigurable sensor systems (RT-7)	Commodity consumption monitoring and prediction to insure on-demand availability (OP-3)	Autonomous maintenance scheduling (RT-4)	Electrical grounding systems (RT-5)
Payload maneuvering tools for offloading, positioning, and delivery (OP-12)	Data fusion tools to merge complex and disparate data for real-time autonomous decision making (RT-4)	Mobile commodity transfer capabilities (RT-5)	Debris early warning system (LI-9)	Autonomous robotic seal replacement (OP-9)

*Consumables include propellants, buffer gases, life support fluids, food, etc.

This table lists all the currently identified surface systems gaps, broken down into five categories. Eight of these gaps have been selected as high priority for short term investment based on anticipated need date, current and planned investment level, and the extent of the required development. The following eight slides characterize each of these high priority gaps in detail.

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Autonomously operated surface umbilicals to enable fluid transfers (including data and power)

Current State of the Art

<u>**Ground-based:** Exploration Upper Stage Umbilical – provides propellant fill/drain services to the Space Launch System's upper stage</u>

Transfer Distance: ~12 m
Mass: ~11,500 kg
Number of interfaces: 16 electrical & 15 fluid
Personnel required for mate/de-mate: 4 local
Bonding force required for seal integrity: ~800 N
Serviceable fluid mass: ~125,000 kg, minimal active thermal management

Goal Metrics (Use Case Dependent)

<u>**Surface-based:** Fluid transfers (Ascent vehicle propellant fill, purge gas resupply transfer, breathing air transfer, etc.)</u>

Transfer Distance: ~3 m (ECLSS), > 5 m (propellant)
Mass: < 50 kg (ECLSS), < 250 kg (propellant)
Number of interfaces: 1 – 6+ electrical & fluid
Personnel required for mate/de-mate: 0 (automated) – 1 (operator assist)
Bonding force required for seal integrity: < 400 N
Serviceable fluid mass: ~100 kg - 15,000 kg, often including active thermal management

Capability Touch Points

Advanced Robotics (mechanisms and alignment)
Autonomous Systems (controls)
Advanced Power (bi-directional power)
Advanced Thermal (thermal control)
Advanced Comm & Nav (data xfer and positioning)
Rendezvous, Proximity Operations & Capture
In-Situ Resource Utilization (Extracted resource transfer: cryos, non-cryo liquid, and gas)
Advanced Habitation Systems (Non-cryo, ECLSS fluid transfers: GN2, GO2, water, urine, etc.)
Cryogenic Fluid Management (Ascent propellant, breathing air storage, etc.)

Current Investments

Robotic Umbilical Arm Fluid Transfer Quick Disconnect (ESDMD)

Planned Investments

None

Leverageable Investments

<u>Cold Operable Lunar Deployable Arm (TRL 3):</u> Cold operable actuator focused
<u>**In-Space:** Space Infrastructure Dexterous Robot (TRL 4):</u> Focused on in-space construction
<u>**In-space:** On-orbit Servicing, Assembly, and Manufacturing 1 mission's robotic arm (TRL 6)</u>
Transfer Distance: ~2.5 m, Mass: ~220 kg, Number of interfaces: 0 electrical & 1 fluid,
Bonding force required for seal integrity: ~80 N (capability up to 350 N)
<u>**In-space:** Prototype Efforts and Refueling Lunar Studies (TRL 3)</u> – On-orbit refueling for HLS
<u>**In-space:** Multiple Cryo coupler focused projects (TRL 3/4):</u> Cryo fluid interface focused

Recommendations

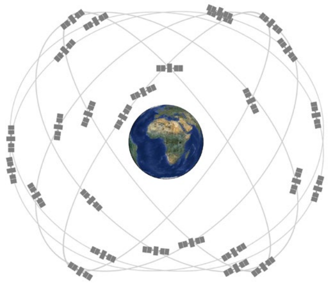
Establish a highly partnered mid-TRL project to develop and test a fully integrated, propellant scale umbilical arm (Game Changing Development). Establish close coordination between technology development and architecture teams. Engage with the Consortium for Execution of Rendezvous and Servicing Operations to establish standards.

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Autonomous tracking tools for surface assets

Current State of the Art

Ground-based: GPS tracking, cellular network enabled tracking
Number of trackable assets: unlimited
Trackable area: Global coverage
Tracking accuracy: +/- 1 m
Update frequency: real-time



In-space: ISS - Manual bar code reading with ground support database updates (likely not relevant to over surface transverses)
Number of trackable assets: > 90,000
Trackable area from device: ~1 m
Tracking accuracy: ~1 m
Update frequency: manual, on-demand

Goal Metrics

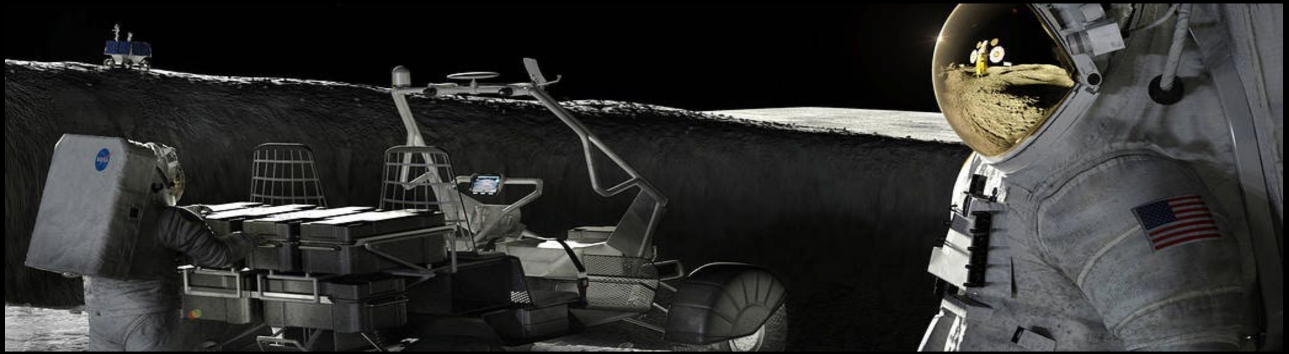
Surface-based: Tracking of all surface assets during over surface traverses and through transitions between elements (including crew, tools, logistics, rovers, etc.). Tracking of assets within an element is the responsibility of the host element.
Number of trackable assets: 10,000 min, evolvable
Trackable area: 2 km radius min, expandable
Tracking accuracy: +/- 1 m
Update frequency: on-demand when stationary, 1 minute while in motion (evolvable to real-time)

Capability Touch Points

Autonomous Systems (tracking)
Advanced Comm & Nav (positioning)
Advanced Habitation Systems (intra-habitat/suit tracking interfaces)

Recommendations

Initiate trade studies for full coverage concepts. Solicit low TRL concepts for asset tracking technologies (NIAC/STRG). Coordinate between technology development and architecture teams.



Leverageable Investments

In-space: ISS – RFID Enabled Autonomous Logistics Management REALM (link, ESDMD, TRL 6): Number of trackable assets: > 8,000 Trackable area from device: +/- 3 m
Tracking accuracy: +/- 1 cm Update frequency: millisecond reads, 15-minute downlink to ground for processing

Current/Planned Investments

Integrated System for Autonomous and Adaptive Caretaking (GCD) – Data integration

Internet of Things (MSD) – Terrestrial data storage, transport, and analysis with cloud integration and AI/ML

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Surface-based instrumentation for full field debris characterization

Current State of the Art

Ground Debris Characterization: Dual-polarization doppler radar & video and image analysis for Earth weather data

Detectable debris diameter: ~ 3mm or greater

Debris velocity determination band: ~2 to 40 m/s

Sensing distance: ~230 km

Coverage area: ~230 km radius

In-space Debris Characterization: NASA Orbital Debris Program Office (ODPO) using multiple radar and optical systems (ground instruments) & DoD Space Surveillance Network (orbital instruments)

Detectable debris diameter: 5mm - 1m; 5cm - 1m

Debris velocity determination band: up to ~8 km/s

Sensing distance: up to GEO

Coverage area: LEO (radar) and GEO (optical)

Credit: MIT Lincoln Laboratory, Lexington, MA.

Goal Metrics

Surface-based: Detection of debris entering Artemis Base Camp perimeter (from PSI, meteoroids, ECO, Mobility, or any other high energy source)

Detectable surface-born debris diameter: 50 µm

Detectable meteoroid size: 3 mm (evolvable down to 0.4 mm) to 1 m

Debris velocity determination band: up to 70 km/s

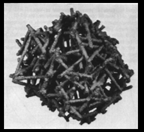
Sensing distance: > 100 km

Coverage area: 0.5 km radius (evolvable to >2 km)

At Risk Equipment (Meteoroid Size with Sufficient Energy to Damage)*	Annual Meteoroid Impact Rate Forecast (2 km radius near lunar south pole)
Spacesuits (0.4 mm)	~335,000
Delicate components (1 mm)	~12,000
Sturdy components (3 mm)	~165
Mission critical (1 cm)	~1-2

*Assumes meteoroids with average density and velocity. Data provided by Meteoroid Environment Office

Capability Touch Points



Entry, Descent, and Landing (Plume Surface Interaction instruments)

Sensors and Instruments (meteoroid detection)

Advanced Power (instrument grid power supply)

Advanced Comm & Nav (intra-grid comm)

Autonomous Systems (data fusion and prognostics)

Recommendations

Solicit low TRL concepts for meteoroid sensing technologies (STRG), which are not detectable by radar or optical methods due to no radar cross section and low albedo. Initiate trade studies for full coverage concepts. Coordinate between technology development and architecture teams.

Current Investments

None

Planned Investments

None

Leverageable Investments

In-space Debris Detection and Characterization: ISS - Space Debris Sensor & camera systems with image processing (TRL 6): Minimum detectable debris diameter & velocity: 50 µm projectiles; 7 km/s

Vehicle induced debris detection: PSI Lunar Measurement System; 4 sensors in development (TRL 3 – 5): Minimum detectable debris diameter & velocity: 125 µm to 20 m projectiles; up to 820 m/s (DERT)

Advanced Lunar Array for Regolith Monitoring (TRL 3): Optical ejecta fallout monitoring

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Supervisory waste/trash management tools

Current State of the Art

Ground-based: Landfills and Recycling plants
Trash management capacity (US): ~734M kg/day
Trash sorting: Manual (~6 categories), then hybrid (manual/autonomous) in recycling plants
Disposition options: Compost, landfill, recycling, hazardous waste, incineration
Disposition management: manual

In-space: Trash/waste is packaged for return to Earth or for jettison/atmospheric burn (ISS)
Disposal management capacity: ~30 - 55 kg/day,
Waste/trash sorting: Manual (~6 categories)
Disposition options: 2 (atmospheric burn, return to Earth)
Disposition management: manual

Goal Metrics

Surface-based: Enable maximum reuse/recycling of waste/trash/scavenged parts, while minimizing disposal. Autonomous disposition for recycling, on-surface disposal, return-to Earth disposal, or in-flight jettison.
Disposal management capacity: 100 kg/day, evolvable
Waste/trash sorting: Manual (~6 categories), then autonomous, using sensor-based material flow characterization informed decision making (24 categories, evolvable)
Disposition options: 10 minimum (route to new user, repurpose, incinerate, store for future reuse, on-surface disposal, on-surface release, orbital jettison, deep space jettison, atmospheric jettison, return to Earth, etc.)
Disposition management: Autonomous

Leverageable Investments

Input waste stream modeling for trash management, recycling, and manufacturing processes (STMD, TRL 2)

Capability Touch Points

Autonomous Systems (decision making)
Advanced Robotics (sorting)
Advanced Comm & Nav (waste stream interfaces)
In-Situ Resource Utilization (Spent regolith and otherwise unallocated product inputs; User)
Advanced Habitation Systems (Processed waste & trash inputs)
Advanced Manufacturing (Customer)
Advanced Materials, Structures, & Construction (Customer)
Planetary Protection (Disposition constraints)
Mission Management (Disposition constraints)

Recommendations

Initiate mid-TRL investment (Tipping Point) to partner Earth-based trash management/recycling companies with NASA teams to develop sensors, models, and algorithms for Lunar trash management. Form an integrated team to coordinate between technology developments, architecture teams, and planetary protection.

Current/Planned Investments

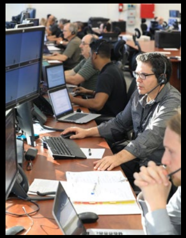
None

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Autonomous surface-based cryogenic flow control

Current State of the Art

Ground-based: Cryogenic propellant loading of a launch vehicle



Remote transfer operators : 4
Nominal transfer control: automated
Pre-planned contingencies requiring operator input: ~70
Cryo flow environment: Ground, open vent

Ground-based: GRC cryogenic test chamber (SMiRF):

Remote transfer operators: 1-2
Nominal transfer control: manual
Pre-planned contingencies requiring operator input: ~50
Cryo flow environment: Ground, open vent

Goal Metrics

Surface-based: Cryogenic flow modeling to enable autonomous flow control
Remote transfer operators: 0 nominal – 1 on call
Nominal transfer control: autonomous
Pre-planned contingencies requiring operator input: 0 (only unanticipated anomalies)
Cryo flow environment: Moon & Mars, open vent & no vent
Predictive diagnostic speed: Faster than real time, operating on a surface-based computer
Accuracy: +/- 5% in 2-phase flow regime

Current Investments

None

Planned Investments

None

Capability Touch Points

Autonomous Systems (FDIR, digital twin)
Advanced Comm & Nav (inter-element comm)
Cryogenic Fluid Management (Cryo transfer into Ascent Vehicles)
In-Situ Resource Utilization (In-situ produced cryos)
Advanced Habitation Systems (Transfer of stored LO2 for breathing air)

Recommendations

Add a high-fidelity, reduced gravity, physics-based cryogenic fluid dynamics model, to inform FDIR systems (digital twin), task to the CFM portfolio (TDM). Collaborate with ESD to establish cryogenic transfer system surface analog to advance model maturity to trusted autonomy level. Coordinate co-development of required avionics systems.

Leverageable Investments

Autonomous Cryogenic Loading Operations (STMD - GCD, TRL 6, 2015): Matlab, C++ based physics model
Cryo flow environment: Ground, open vent Predictive diagnostic speed: Faster than real time on a ground computer Accuracy: +/- 15% in 2-phase flow regime
CFM Portfolio Project (STMD - TDM, Modeling Tasks): Thermal Desktop based physics model
Cryo flow environment: Ground, open vent Predictive diagnostic speed: Faster than real time on a ground computer Accuracy: +/- 15% in 2-phase flow regime
Advanced Cryo Modeling (STMD – ESI, TRL 4): CFD/Nodal coupling techniques to improve accuracy and reduce computational time
In-Space: NASA Platform for Autonomous Systems NPAS (ESDMD funded leveraging STMD CIF, TRL 7): Development of intelligent ground and space systems using machine learning, model-based analysis, live digital twins, and integrated health management strategies

Ground and Surface Support Systems to Enable Long Duration Surface Stays

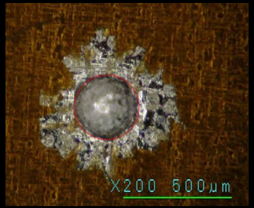
Instrumentation for and modeling for surface hardware impact damage assessment

Current State of the Art

Ground-based: Visual inspection, photogrammetry, LiDAR, and 3D scanning
Detectable damage size: Distance and image resolution dependent (0.2-0.5mm)
Time between impact and detection: Dependent on time between inspections

Hail damage on Shuttle external Tank

In-space Damage Assessment: ISS - Visual inspection, video analysis, photogrammetry
Detectable damage size: Distance and image resolution dependent (0.2-0.5mm)
Time between impact and detection: Dependent on time between inspections



Picture of damage discovered on ISS ATA-3, Impact No. 17

Goal Metrics

Surface-based: Detection of damage induced by debris impacting surface-based assets (from PSI, meteoroids, ECO, Mobility, or any other high energy source) and accurate severity estimation
Detectable damage size: < 0.5 mm (evolvable to 0.05 mm)
Time between impact and detection: < 30 minutes (evolvable to near real-time)

Capability Touch Points

Sensors and Instruments (damage detection)
Advanced Comm & Nav (damage location & notification)
Advanced Structures (sensor integration)

Recommendations

Solicit low-mid TRL concepts for new detection technologies (SBIR). Demonstrate fiber optic sensor technology. Initiate studies to assess traditional visual based inspection implications to mass, power, communications, and data needs.

High velocity impact damage Photo from NASA's Hypervelocity Impact Technology office

Current/Planned Investments

None

Leverageable Investments

ISS - Space Debris Sensor & camera systems with image processing (TRL 6, 2019):
Damage detectable from debris as small as 50 μm with a velocity of up to 7 km/s
MMOD Impact detection and location using fiber optic bragg grating sensing technology (link, 2017)
Habitat Particle Impact Monitoring System (STMD, TRL 3, 2012): Development toward a fully automated, end-to-end particle impact detection system for crewed modules
Relevant Environment Additive Construction Technology (TRL2, 2022): Includes meteoroid impact models

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Reduced maintenance of surface-based hardware/components through intelligent devices

Current State of the Art

Ground-based, launch pads: Component health monitored manually with maintenance performed on a set schedule

Maintenance cycle: ~1-2 years, schedule-based, component type specific (examples: transducer calibration, relief valve set point verification, positional valve actuation functional verification, etc.)

In-space, ISS: Component health monitored manually with no maintenance performed in orbit

Maintenance cycle: No schedule-based calibration/verification of components (high reliability components are used to failure, with built-in redundancies providing robustness so that failed components can be removed and replaced with on-orbit spares)

Goal Metrics

Surface-based, Artemis Base Camp: Component health/calibration monitored autonomously through embedded instrumentation/algorithms to predict, diagnose, and recover from failures

Maintenance cycle: Condition-based, informed by embedded instrumentation and algorithms to increase reliance, reduce down-time, and reduce crew maintenance time

Fault/Degradation Prediction > 95%

Fault Prediction-before-failure: > 1 day (depending on device criticality), evolvable to > 14 days

Fault Identification: > 95%

Fault detection time: < 0.5 sec

Fault recovery: > 95%

Secured/reliable communication (protocol and media)

Capability Touch Points

Autonomous Systems (data fusion)

Advanced Communications (fault notification)

On-surface, long-term assets (embedded devices)

Recommendations

Solicit early-stage innovations (Prizes and Challenges) for the development of devices with embedded instrumentation and software algorithms to enable prognostication, diagnostics, and recovery capabilities. Devices should be plug-and-play, leveraging IEEE 1451 and operable in the extreme lunar environment.

Focus developments on intelligent devices that are cross-cutting for ground and surface use cases.

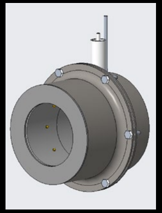
Establish NASA standardized protocols for secured, resilient device communication.

Leverageable Investments

Integrated Monitoring Awareness Environment IM-AWARE (SBIR, TRL 7, 2018): Smart sensor networks including self-diagnostics, fault detection, and troubleshooting

Internal Wireless Instrumentation System (ISS): Keeps a health and status log on structural health monitoring devices

In-Space: NASA Platform for Autonomous Systems NPAS (ESDMD funded leveraging CIF TRL 7): Development of intelligent/autonomous ground and space systems with on-board knowledge, model-based analysis, live digital twins, and integrated health management strategies



Current Investments

Intelligent soft actuators with self-diagnostic capabilities (SBIR)

Smart elastomer seal with remote monitoring for condition-based maintenance (SBIR)

Planned Investments

None

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Cold and dust tolerant interface seals to enable surface transfers

Current State of the Art

Ground-based: Cryogenic transfer seals
Lifetime: 1 mate/de-mate cycle (soft goods permanently deform upon sealing)
Temperature range: ~530 K to 60 K (material dependent)
Pressure Range: up to ~ 1200 psig (seal specific)
Seal integrity: ASTM F-37 Sealability ~0.009 mL/h
Environmental robustness: Seals are precision cleaned and kept bagged until installation. No active particulate mitigation employed during mate.

In-Space: Docking seals
Lifetime: ~ 50 mate/de-mate cycles
Temperature range: ~360 K to 220 K (material and use case dependent)
Pressure Range: ~0 - 15.5 psia
Seal integrity: ~50 mL/h (dry air @ 14.7 psid)
Environmental robustness: Seals are precision cleaned prior to installation. Assembled docking system is stored in environmentally controlled conditions. Tolerant to vacuum, atomic oxygen, UV, and ionizing radiation.

Goal Metrics

Surface-based: Re-usable interface seals, which will be subjected to dust and extreme cold surface temperatures
Lifetime: > 10 mate/de-mate cycles in cold, dusty environment (evolvable to > 50)
Temperature range: 300 K to 90 K (evolvable down to 20 K)
Pressure range: ~14 - 1200 psi (use case dependent)
Seal integrity: equal to or better than SoA (size and use case dependent)
Environmental robustness: No precision cleaning required. Seal integrity achievable in a dusty environment (no lubricants). Tolerant to vacuum, atomic oxygen, UV, and ionizing radiation.

Leverageable Investments

Dust tolerant automated umbilical (ESDMD, 2020, TRL 4): Staged sealing for dust tolerance.

Dust tolerant joint for in-space assembly (SBIR, on-going, TRL 4): Development of shape memory polymers for use in robotic joints.

Capability Touch Points

Advanced Power (Charging interfaces)
Advanced Communications (Communications interfaces)
Rendezvous, Proximity Operations & Capture (Multi-element mating seals)
In-Situ Resource Utilization (Extracted resource transfer: cryos, non-cryo liquid, and gas)
Advanced Habitation Systems (Habitation seals, ECLSS fluid transfers: GN2, GO2, LO2, water, etc.)
Cryogenic Fluid Management (Propellant Transfers)
Advanced Thermal (may employee thermal control)
Advanced Materials (may require novel materials)
Advanced Manufacturing (leverageable)

Recommendations

Solicit low/mid-TRL concepts (STRG, SBIR) for reusable soft goods materials that retain elasticity at very low temperatures (ex: shape memory polymers) and/or advanced manufacturing techniques for development of robust metallic seals. Continue developments related to dust tolerance. Coordinate potential solutions with integrated umbilical arm developments.

Current/Planed Investments

None

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Conclusions

- Surface Systems technologies bridge the gap between short-term and long-term surface stays by providing high-tech solutions to blue collar tasks, thus minimizing crew burden.

- Surface Systems gaps are highly integrated and require incremental technology advancements while maintaining coordination with end users.

- While there have been some prior investment in some of these areas in the past (which should be leveraged to the maximum extent possible), there are very few active investments addressing these needs.

<u>TOP 8 NEAR TERM PRIORITIES</u>

1. Autonomously operated surface umbilicals to enable fluid transfers (OP-9)
2. Autonomous tracking tools for surface assets (OP-12)
3. Surface-based instrumentation for full field debris characterization (LI-9)
4. Supervisory waste/trash management tools (OP-12)
5. Autonomous surface-based cryogenic flow control (RT-4)
6. Instrumentation for and modeling for surface hardware impact damage assessment (LI-9)
7. Reduced maintenance of surface-based hardware/components through intelligent devices (RT-5)
8. Cold and dust tolerant interface seals to enable surface transfers (RT-5)

Ground and Surface Support Systems to Enable Long Duration Surface Stays

Acronyms and Abbreviations

- CIF: Center Innovation Fund
- ECLSS: Environmental Control and Life Support System
- ECO: Excavation, Construction, and Outfitting
- ESDMD: Exploration Systems Development Mission Directorate
- GN2: Gaseous Nitrogen
- GO2: Gaseous Oxygen
- GPS: Global Positioning System
- IEEE: Institute of Electrical and Electronics Engineers
- ISS: International Space Station
- LiDAR: Light Detection And Ranging
- LO2: Liquid Oxygen
- NASA: National Aeronautics and Space Administration
- NIAC: NASA Innovative Advanced Concepts
- PSI: Plume Surface Interaction
- RFID: Radio Frequency Identification
- SBIR: Small Business Innovation Research
- SMD: Science Mission Directorate
- SoA: State of the Art
- SOMD: Space Operations Mission Directorate
- STMD: Space Technology Mission Directorate
- STRG: Space Technology Research Grants
- TRL: Technology Readiness Level
- UV: Ultraviolet