EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Autonomous Systems & Robotics (ASR)
NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

What is Autonomous Systems and Robotics (ASR)?

Autonomous Systems and Robotics

- … is a broad, multi-disciplinary technology domain
- … enables high priority outcomes across NASA's entire Strategic Framework
- … is foundational for establishing lunar infrastructure (survey, construction, deployment, outfitting, servicing, etc.)
- … is foundational for ISRU (prospecting, excavation, transport, handling, etc.)
- … is foundational for both in-space and planetary surface missions

Self- and Situational Awareness
- Sensing and Perception
- State Estimation and Monitoring
- Object, Event, Trend, & Activity Recognition
- Force and Tactile Sensing
- Remote Sensing
- Onboard Science Data Analysis
- Knowledge and Model Building
- Hazard Assessment
- Anomaly Detection

Mobility
- Extreme Terrain Mobility
- Below-Surface Mobility
- Above-Surface Mobility
- Small-Body and Microgravity Mobility
- Surface Mobility
- Robot Navigation
- Mobility Components
- GN&C Algorithms

Manipulation
- Manipulator Components
- Dexterous Manipulation
- Control of Contact Dynamics
- Mobile Manipulation
- Sample Acquisition and Handling
- Grappling

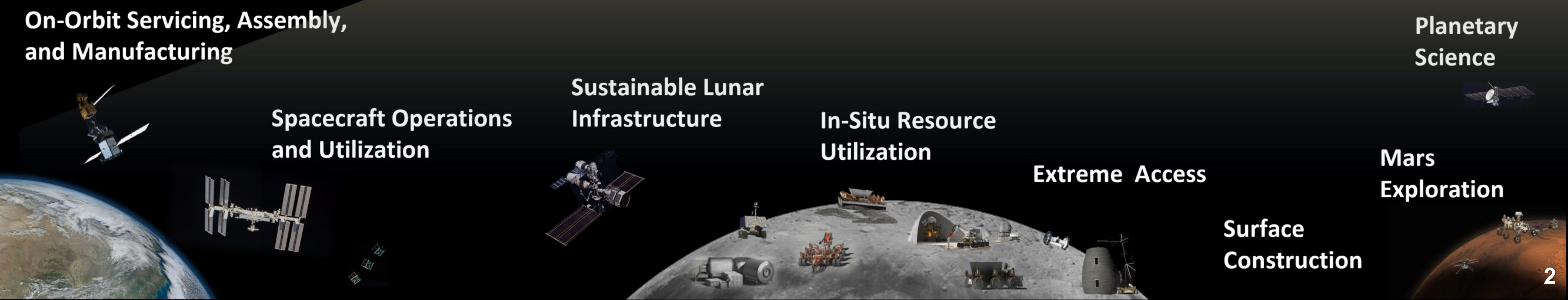
Multi-Agent Cognition and Operations
- Collaborative Mobility
- Collaborative Manipulation
- Distributed Cooperation and Collaboration
- Agent Coordination
- Joint Knowledge and Understanding
- Behavior and Intent Prediction
- Goal and Task Negotiation
- Operational Trust Building

Human System Interaction
- Multi-Modal Interaction
- Supervisory Control
- Proximate Interaction
- Intent Recognition and Reaction
- Common and Standard HSI
- Remote Interaction

Reasoning and Acting
- Mission Planning
- Activity and Resource Planning and Scheduling
- Motion Planning
- Execution and Control
- Fault Diagnosis and Prognosis
- Fault Response
- Learning and Adapting

Systems Engineering and Integrity
- Modularity, Commonality , and Interfaces
- Verification and Validation
- Modeling and Simulation
- Architecture and Frameworks
- Safety and Trust
- Test and Evaluation
- Operational Assurance
- Design Tools

"Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions"



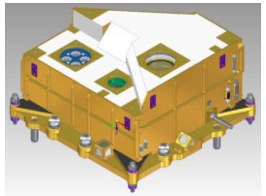
Key Points

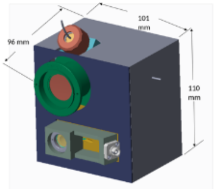
Goals

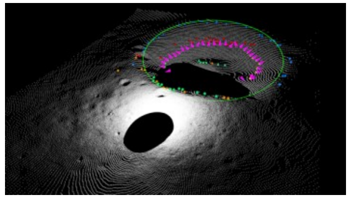
- Enable space missions that cannot currently be performed
- Increase space mission effectiveness, productivity, and safety
- Respond to the needs of commercial missions, human exploration missions, and science missions
- Establish a self-sustaining community of academia, government, and industry to develop ASR technology and expand workforce
- Reduce barriers (cost, schedule, risk, etc.) to collaboration, deployment, and reuse of new technology

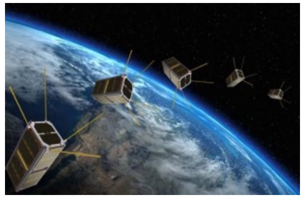
Approach

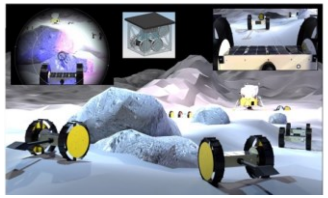
- Target cross-cutting (multi-mission) and STMD demo needs – not mission-specific autonomy and robotics technology
- Focus on six “envisioned future” technology objectives
- NASA helps break barriers and reduce tech risk for industry
- Adopt an Open Framework to enable incremental development of modular, interoperable, and reusable tech by many parties
- Leverage the Lunar Surface Innovation Consortium to engage the non-NASA space community





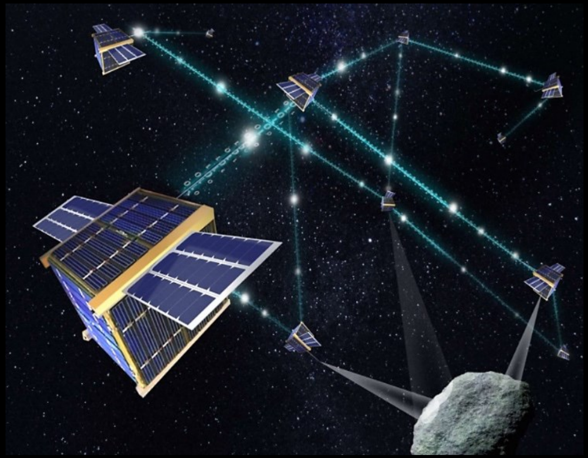






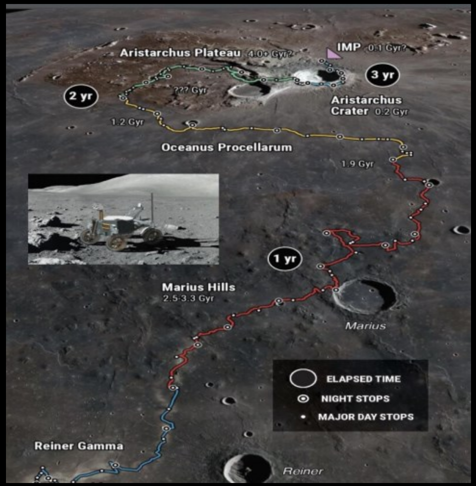
EXPLORE: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.

AUTONOMOUS MULTI-SPACECRAFT SYSTEM FOR DISTRIBUTED SCIENCE MEASUREMENTS



AUTONOMOUS FAIL-ACTIVE, HIGH-TEMPO SCIENCE MISSIONS

AUTONOMOUS HIGH PROGRESS RATE SCIENCE ROVER



AUTONOMOUS CONTINUOUS LUNAR SURFACE OPERATIONS

Technology Objectives

- **Cooperative multi-spacecraft system with efficient human teaming** for cost-effective interdependent and distributed work (system operable as a single “entity” for satellite and planetary science missions)
- **Self-adaptive and fail-active autonomy for high-tempo missions** in high-risk, dynamic, and uncertain environments (example: guaranteed sampling from one-time events during short duration mission)
- **Efficient on-board autonomy for continuous surface operations** with cost-effective mission control (1/10 cost of current practice) and increased performance (10x productivity / time) for long range (450 km/yr) or worksite operations (750 km/yr)

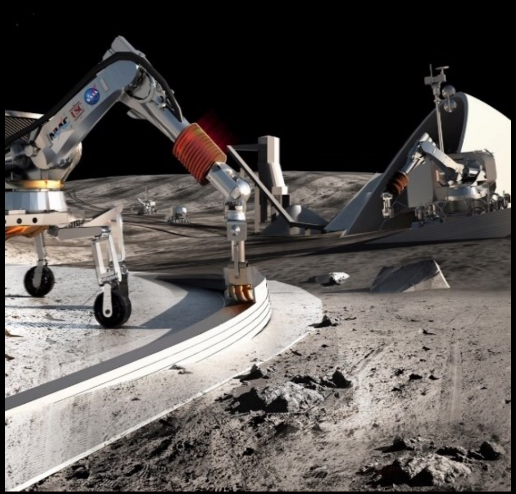
Examples shown depict “envisioned futures” to guide technology development vision and are not currently approved or funded.

EXPLORE: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.

Robotic Caretaking Inside Habitats and Spacecraft

Robotic Exploration of Extreme Environments

Robotic Construction of Surface Infrastructure



Robotic Resource Extraction and Transport

Technology Objectives

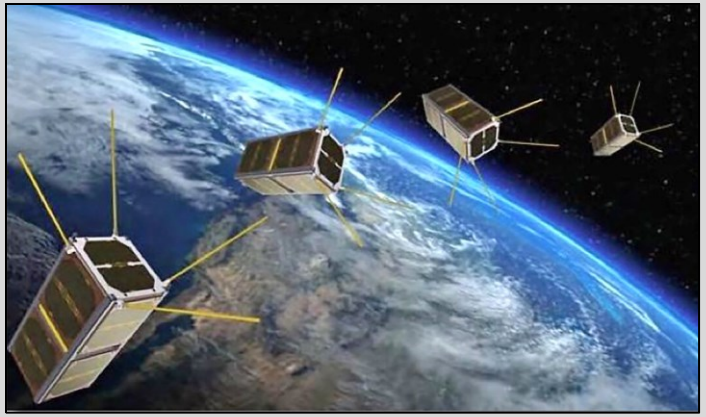
- **Remotely operated intra-vehicular robotics for maintenance and utilization:** 4,000+ hr/yr of high duty-cycle exploration spacecraft and surface habitat activities (uncrewed up to 90% of time)
- **Robust robot mobility for extreme access:** surfaces (up to 5,000 km life-cycle drive), deep interiors through rock (up to 10 km) and cryogenic ice (up to 25 km), and handling of dangerous topography (up to 90° slopes)
- **Durable, self-maintainable robotics for heavy-duty surface work:** bulk excavation (up to 400 metric tons), material transport (up to 600 km/yr), and surface construction (up to 15,000 kg carrying capacity)

Examples shown depict "envisioned futures" to guide technology development vision and are not currently approved or funded.

State of the Art: Spacecraft Autonomy Technologies

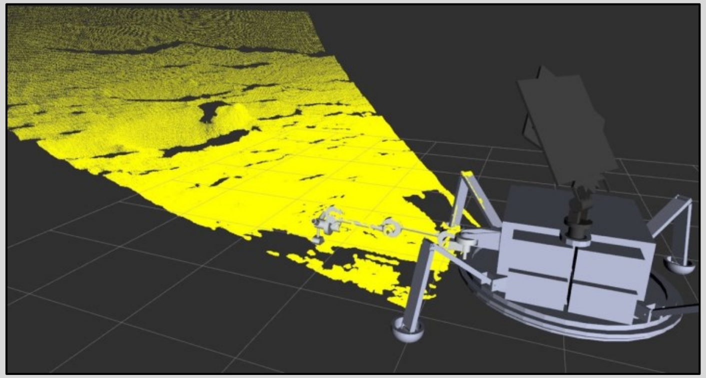
Cooperative multi-spacecraft system with efficient human teaming

Multi-robot autonomy and commanding for distributed measurements (JPL, 2021) ***TRL 5***

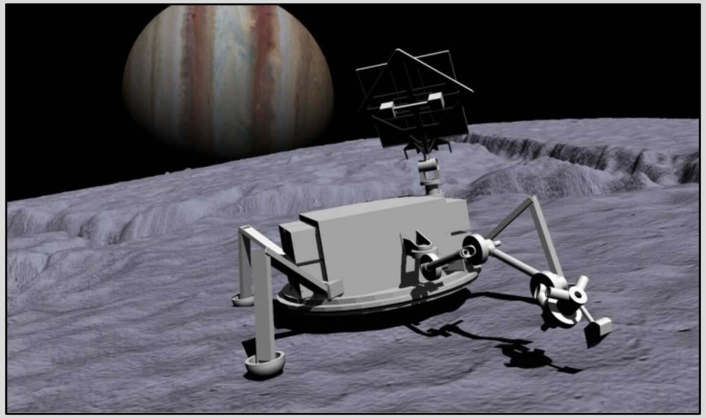


Distributed spacecraft autonomy and human-swarm control tech demo (ARC, 2022) ***TRL 6***

Self-adaptive and fail-active autonomy for high-tempo missions



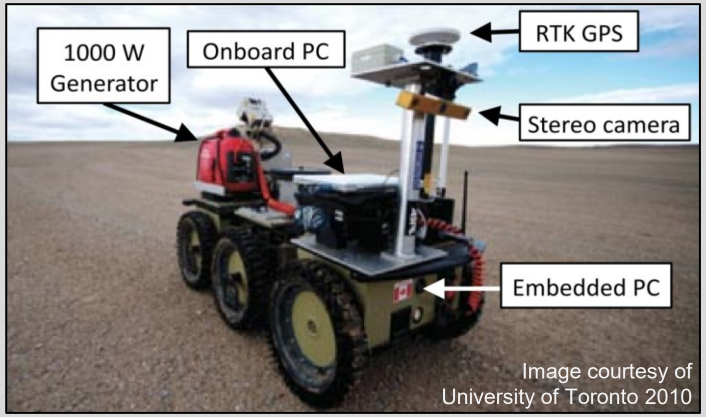
On-board recalibration for adaptation to faults for Europa (Caltech, 2021) ***TRL 3***



Stochastic fail-active robotic task planning for Europa (Honeybee Robotics, 2021) ***TRL 4***

Efficient on-board autonomy for continuous surface operations

Autonomous rover traverse (26 km in 10 days) across the Atacama (CMU, 2015) ***TRL 5***



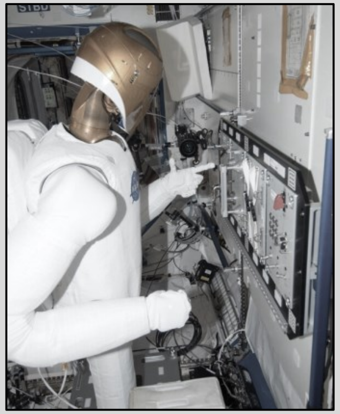
"Visual Teach and Repeat" achieving 99.6% repeatable traverse (U Toronto, 2010) ***TRL 5***

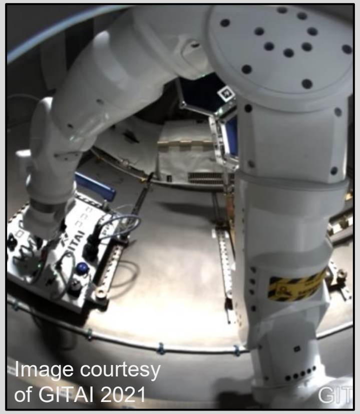
Examples shown are not intended to be comprehensive, an endorsement, or representative of all aspects of each technology objective.

State of the Art: Advanced Robotics

Remotely operated intra-vehicular robotics for maintenance and utilization

Astrobee, an operational ISS facility supporting IVA robotics R&D (ARC, 2019) ***TRL 7***

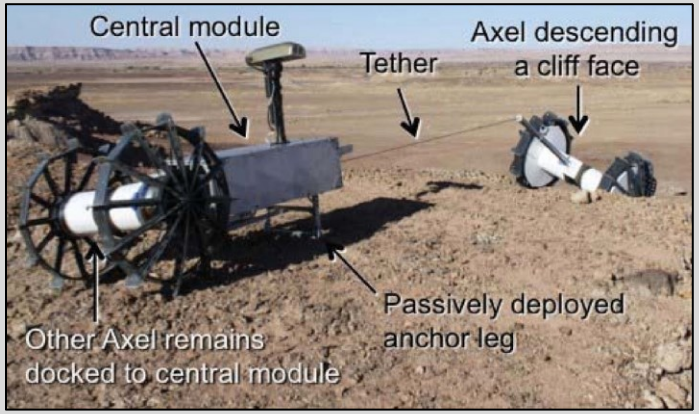




Dexterous manipulation demonstrations on ISS (Robonaut 2, JSC, 2014) (GITAI, 2021) ***TRL 6***

Robust robot mobility for extreme access

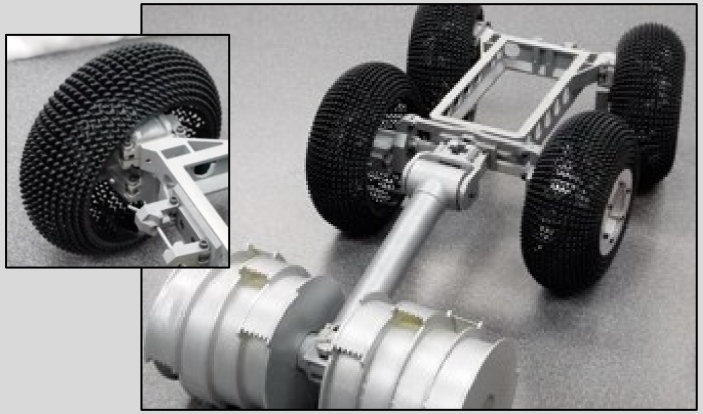
Traversing obstacles with 3x wheel radius with RoboSimian (JPL, 2020) ***TRL 5***



Dual tethered robots for handling steep terrain and cliffs (DuAxel, JPL, 2013) ***TRL 5***

Durable, self-maintainable robotics for heavy-duty surface work

Prototype robot for excavation of lunar regolith (RASSOR, KSC, 2021) ***TRL 5***



Field-serviceable, modular vehicle concept for the lunar surface (NASA, 2018) ***TRL 3***

Examples shown are not intended to be comprehensive, an endorsement, or representative of all aspects of each technology objective.

Demand for Autonomous Systems & Robotics (ASR)

2022 NASA Strategic Plan: STMD – Innovate and advance transformational space technologies. Develop revolutionary, high-payoff space technologies driven by diverse ideas to transform NASA missions and ensure American leadership in the space economy

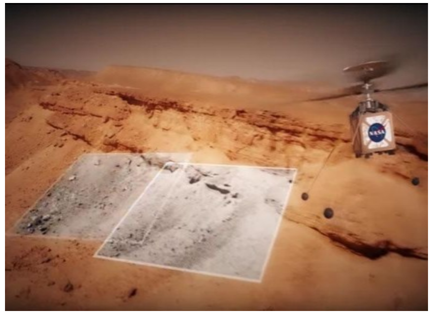
Commercial Space

- Sustainable infrastructure and common, interoperable technologies would facilitate broader industry integration and infusion of new technical capabilities
- Industry needs data sets, operational models, and testbeds to support rapid, cost-effective development of autonomy and robotic products

Human Exploration

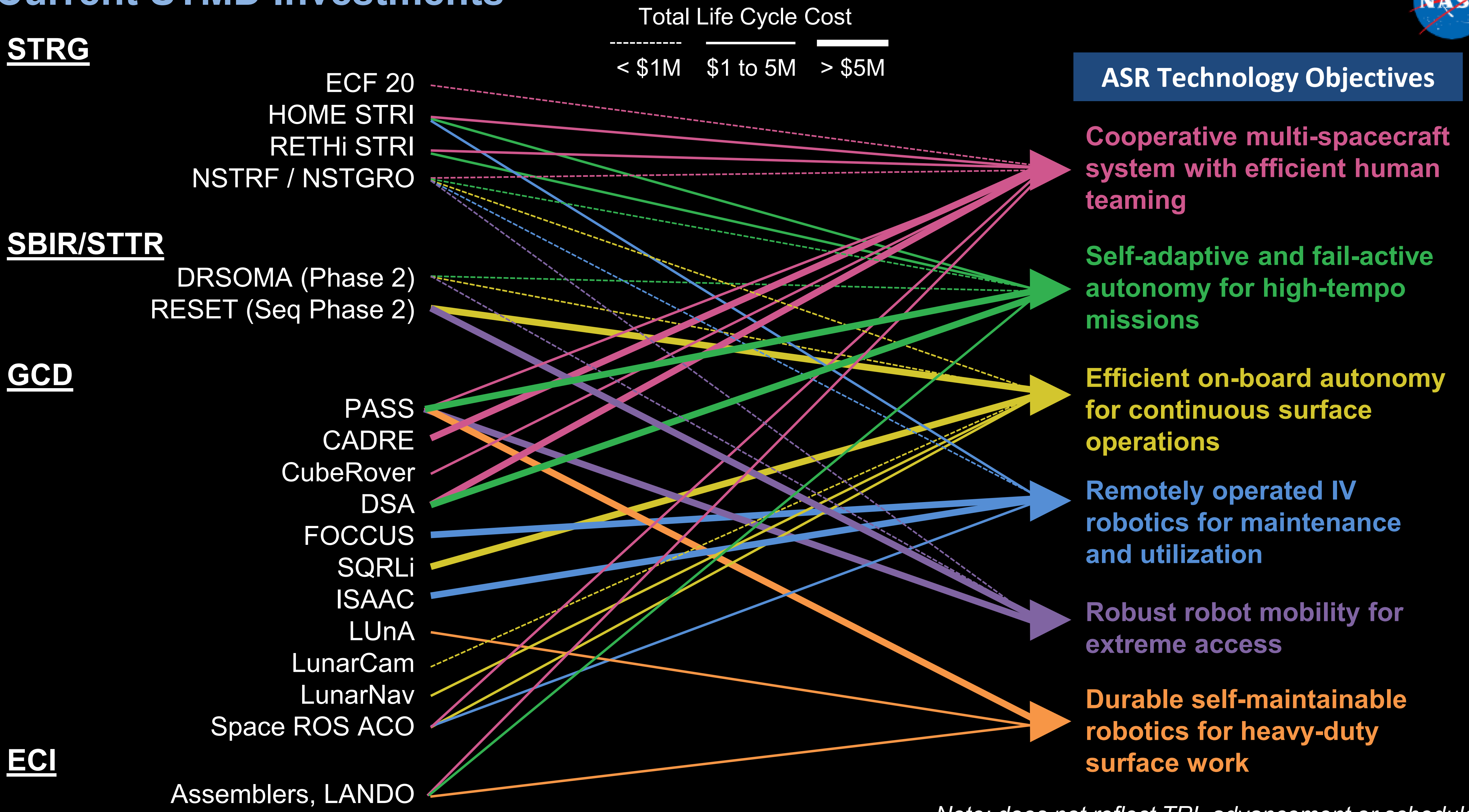
- All future human spacecraft need to be monitored and maintained during uncrewed periods to protect the vehicle and increase utilization
- Artemis architecture includes robotic deployment, surface mobility, and ISRU
- Autonomous systems and robots capable of efficient human interaction preserve valuable crew time for high-priority exploration and science activities

Science



- New missions to challenging destinations are made possible with technology advances, particularly in cooperative multi-spacecraft systems and self-reliant autonomy
- Large-scale observatories would benefit from autonomous in-space assembly, inspection, and/or maintenance

Current STMD Investments



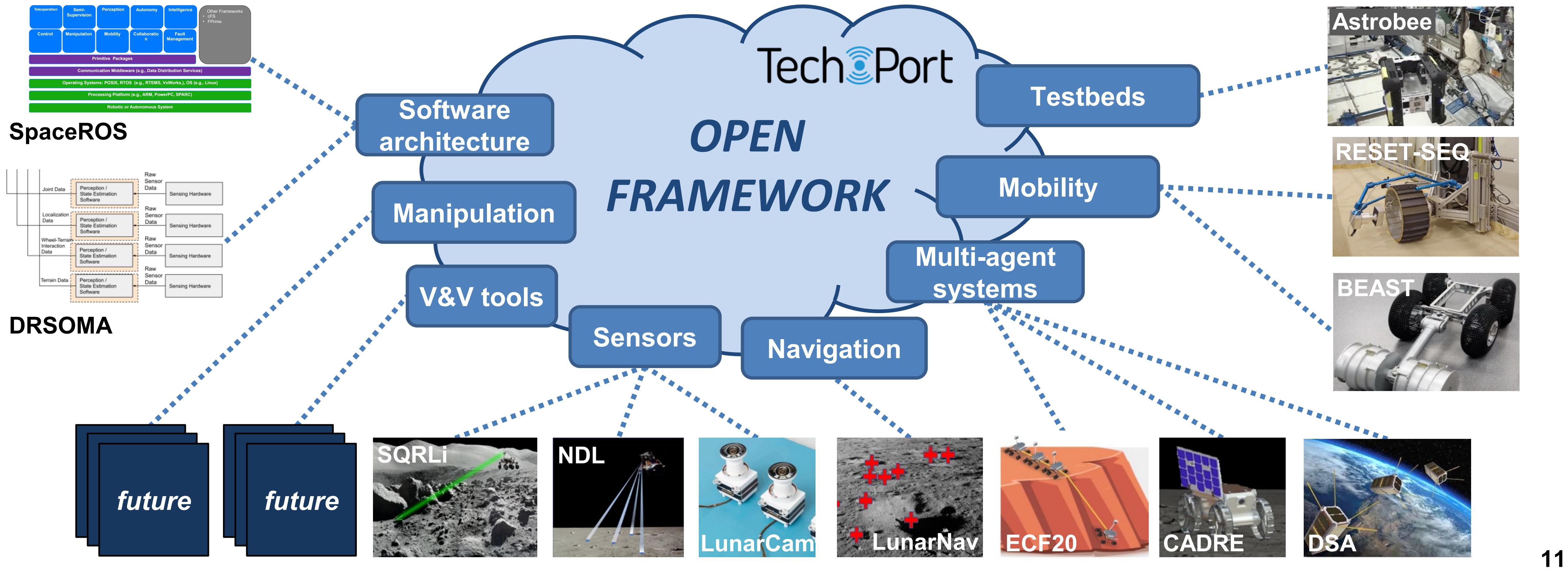
Note: does not reflect TRL advancement or schedule

ASR Strategy: Grow the Space Economy and Workforce

1. **Open framework approach to create sustainable, industry-driven hardware and software**
   - Modular, interoperable, and reusable components (open-source & proprietary) developed by many parties
   - Lower barriers to entry for infusion and adaptation of industry/terrestrial ASR technologies into spaceflight applications
   - Facilitate transfer/licensing/release of NASA investments to US entities (academic, government, and industry) with appropriate export control
2. **NASA develops prototypes to break barriers and reduce risk as needed (not constant level of effort)**
   - Demonstrate new technology and development processes/tools (V&V, etc.) as needed
   - Examples: DSA autonomy software, CADRE rover, SQRLi rover lidar, RASSOR excavator, etc.
3. **Encourage and support testbeds to accelerate development**
   - Leverage ESDMD investments (e.g., ISS Astrobee Facility) to support STMD development
   - Leverage SMD investments (e.g., COLDTech autonomy testbed) to support STMD development
   - Identify and support release of software simulators (LaRC AEON BEAM, ARC VIPER RSIM, etc.)
4. **Industry and NASA collaborate to integrate technologies for flight missions**
   - ASR technology drawn from both industry and NASA, tailored for mission need in partnership with relevant parties
   - Benefits not limited to STMD tech demos, but also human exploration and science missions
5. **Use LSIC to engage non-NASA space autonomy & robotics community**
   - TIMs and RFIs to support open framework approach
   - Industry site visits and targeted technology assessments

Open Framework: Modular, Interoperable, and Reusable Technology

- **Objective**: sustainable **technology** that is **modular**, **interoperable**, and **reusable**
- Create a public **catalog** for ASR technology – build off of **TechPort v3.8** to create a tool for the ASR community (not just NASA!) and to motivate continuous tech transfer and reuse to/from all parties (NASA and industry)
- STMD projects will seed the clearinghouse and lead **licensing/release** of NASA developed technology

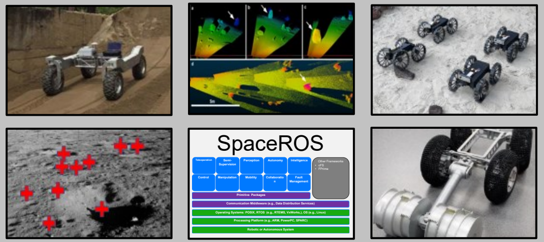


Example: Lunar Surface Infrastructure

Autonomous, cooperative, and durable robotic systems for deployment and long-term surface operations

- Requires extended duration robotic excavation, construction, outfitting, and maintenance capabilities in the lunar environment
- Builds on current STMD investments (e.g. COLDArm, ECF20, LSII Seq., PASS, SQRLi) toward mission infusion

Current NASA / STMD Investments



External Partnerships, Tech Transfer, and Infusion

Industry ⟷ NASA ⟷ Academia

Open Framework

- Modular, Interoperable Software
- Common Hardware Interfaces and Standards
- Datasets and Testbeds

Synergistic Efforts Across Technical Domains
(ISRU, Power, Structures, Thermal, . . .)

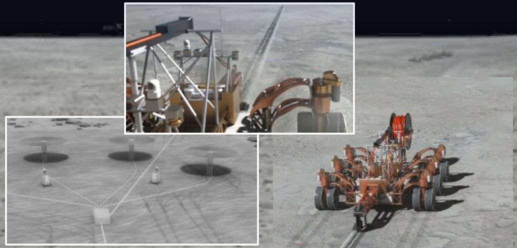
New Subsystem Technology Development

- Long range and duration lunar drive systems
- On board localization, planning, and execution
- Explainable autonomy/AI
- Extreme terrain mobility
- Multi-agent coordination
- Self-maintenance/repair
- Adaptive ops for long term degradation
- Low-mass rugged mechanisms
- Modular implements
- High progress rate autonomous navigation
- And more . . .

Interoperability and reusable technology enable rapid integration and collaborative operations across multiple vendors and systems

Production-scale ISRU prospecting and transport

Trenching, laying and connecting cables, etc. for long-distance power distribution



Full-scale excavation, transport, and construction for sustained surface activities

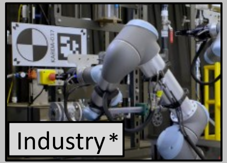
Autonomous surface operations over multiple lunar day/night cycles

Example: Human Spacecraft Support

Autonomous robotic systems that enable remote and uncrewed IVA maintenance and utilization

- Addresses key Artemis architecture capability gaps and needs in autonomy and robotics
- Builds on current STMD investments (e.g. FOCCUS, ISAAC, SpaceROS, STRI SmartHabs) toward mission infusion

Technology Infusion from Multiple Sources



* Image courtesy of Woodside Energy 2020
† Image courtesy of GITAI 2021

Open Framework

Modular, Interoperable Software

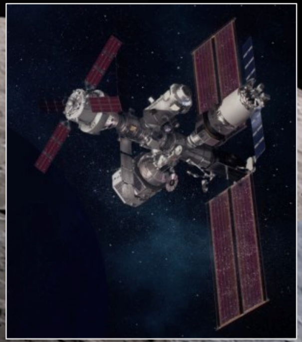
Common Hardware Interfaces and Standards

Datasets and Testbeds

New Subsystem Technology Development

- Affordance recognition
- Object detection
- Pose estimation
- Fault-tolerant actuation
- Self-adaptive and fail-active autonomy
- Adaptable end effectors
- Multi-mission robot control interfaces
- Robust manipulation
- Grasp planning
- Semantic SLAM
- IVA mobility and navigation planning
- Standardized docking and grasping interfaces
- Coordinated task planning & execution
- And more . . .

Open Framework approach enables cooperation across different vendor systems



Multi-mission reuse extensible from IVA to EVA surface ops and astronaut assistance (e.g. LTV manipulator)

Versatile robotic capabilities facilitate in-space commercial activity and lay the foundation for humans on Mars

Next Steps (Near-term)

	Subsystem Tech (Gaps)	Rationale
Autonomy	• Develop on-board planning for extreme terrain traversal (STMD-ASR-002, STMD-ASR-003) • Develop on-board rover terrain embedding & entrapment recovery methods (STMD-ASR-014, SMD-PESTO) • Develop reusable autonomous manipulation behaviors and task planning (STMD-ASR-003, STMD-ASR-008)	• Site preparation and regolith collection robotics must be capable of reliable continuous operations to handle surface operations at scales beyond proof-of-concept demos. • Reliable autonomous navigation over unmodified terrain is required for all lunar surface operations. • Robust dexterous manipulation for assembly work in unimproved environments is a key technology for deploying and maintaining surface power distribution infrastructure and other lunar assets.
Robotics	• Develop long-range and rugged drive systems (STMD-ASR-002, STMD-ASR-010) • Develop field-swappable repair units (STMD-ASR-013) • Develop fault-tolerant robotic actuators and end-effectors (STMD-ASR-020, STMD-ASR-021)	• Site preparation and regolith collection robotics must be able to traverse long-distances over their lifetime to handle surface operations at scales beyond proof-of-concept demos. • Resilient robotics technology is needed to support IVA utilization, inspection, maintenance, and contingency response inside habitable volumes (in-space and surface).
R&D Infrastructure	• Open Framework: Establish clearinghouse and implement incentivization strategy • Extend ISS Astrobee facility to support IVA robotics technology development	• Open Framework approach will help industry, NASA, & other organizations move away from custom, one-off development • STMD can leverage on-going ESDMD investment to support and accelerate ASR development

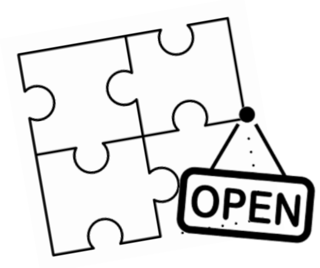
Next Steps (Mid-term)

	Subsystem Tech (Gaps)	Rationale
Autonomy	• Develop adaptive ops for long-term degradation (STMD-ASR-008, HEOMD-2021-3449-TX10) • Develop auto recovery from loss of data comm (HEOMD-2021-3052-TX10.1) • Develop efficient robot perception systems suitable for space computing (STMD-ASR-018)	• Establishing a long-distance power transmission/distribution network requires autonomous navigation and reliable handling of communications. • STMD tech demos and multiple stakeholder missions require on-board autonomy to operate at high cadence and be able to fail-active (i.e. continue to accomplish goals in spite of faults).
Robotics	• Develop low-mass rugged mechanisms (STMD-ASR-012, STMD-ASR-022) • Develop very low-temperature mechatronics (STMD-ASR-0012) • Develop steep slope climb/descent systems (STMD-ASR-010)	• Site preparation and regolith collection robotics must be low mass, yet capable of high force and payload capabilities, as well as able to tolerate multiple lunar day/night cycles and operate in permanently shadowed regions. • Long-lived robotic work systems must be repairable or serviceable in order to maintain nominal operation and recover from component failures and degradation.
R&D Infrastructure	• Open Framework: Connect ASR community to other government agencies • Adapt SMD OceanWaters simulator to support STMD solicitations (ACO/TP, SBIR, or STRG)	• Open Framework approach can increase ASR workforce and speed system development in support of government activities beyond NASA • STMD can leverage on-going SMD investment to support and accelerate ASR development

Next Steps (Long-term)

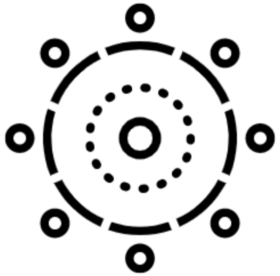
	Subsystem Tech (Gaps)	Rationale
Autonomy	• Develop explainable autonomy / AI operator interfaces for use by ground control and crew (STMD-ASR-005, STMD-ASR-015) • Develop methods and tools for V&V of autonomous systems used for critical functions	• Increased use of on-board autonomy requires effective supervisory control interfaces. This requires capabilities for efficient notification, summarization, and detailing of task execution (particularly autonomous fault management) • Reliance on autonomy for safety-critical and mission-critical functions requires new V&V capabilities.
Robotics	• Develop interchangeable implements & tools (STMD-ASR-012, STMD-ASR-013) • Develop mission-rated multi-robot tethering (STMD-ASR-013) • Develop low-mass thermal control modules for lunar robotics (STMD-ASR-012)	• Planetary robotic work systems will greatly benefit from modular end-effectors and devices in terms of flexibility, maintainability, and task performance. • Tethered multi-robot systems have significant potential for increasing access to extreme locations, improving rescue capabilities, and force multiplication.
R&D Infrastructure	• Develop ASR standards • Release NASA curated datasets for ASR development	• Based on 6+ years of experience with the Open Framework, NASA should lead an effort to establish open standards for ASR interoperability. This could involve partnerships with CCSDS, ISO, and/or technical societies (IEEE, SAE, etc). • Curated reference datasets can speed R&D by providing key information for benchmarking and testing.

Conclusion: ASR Strategy for Interoperability and Tech Transfer



Develop ASR open framework implementation
- Explore relevant existing standards for and develop licensing and controlled release models for hardware and software
- Determine baseline(s) for software interoperability (e.g., SpaceROS, cFS, DDS, etc.)
- Determine need(s) for creating and enhancing NASA testbeds
- Work with STRG, SBIR, GCD, LSIC, and tech partnership

Focus current ASR portfolio towards "envisioned future" tech objectives
- Revise gaps from ASR, ESDMD/SOMD, and SMD (including Decadal Survey) based on open framework approach
- Work with current STMD projects and programs to include tech transfer as deliverable (may require scope increase)
- Establish new starts (focus on ACO/TP, GCD, and SBIR)



Build ASR community
- Use LSIC to conduct TIMs and open framework engagement strategy
- Identify and support creation of testbeds to accelerate tech development

Acronyms

- ACO – Announcement of Collaboration Opportunity
- ARC – Ames Research Center
- AEON – Autonomous Entity Operations Network
- AI – Artificial Intelligence
- ASR - Autonomous Systems and Robotics
- BEAM – Baseline Environment for Autonomous Modeling
- BEAST – Build and Excavation Autonomous System with Transportation
- CADRE – Cooperative Autonomous Distributed Robotic Exploration
- CCSDS – Consultative Committee for Space Data Systems
- cFS – core Flight System
- CMU – Carnegie Mellon University
- COLDArm – Cold Operable Lunar Deployable Arm
- COLDTech – Concepts for Ocean worlds Life Detection Technology
- DDS – Data Distribution Service
- DRSOMA - Dynamically Reconfigurable Software and Mobility Architecture
- DSA – Distributed Spacecraft Autonomy
- ECF – Early Career Faculty
- ECF20 – Early Career Faculty 2020
- ECI – Early Career Initiative
- ESDMD – Exploration Systems Development Mission Directorate
- EVA – Extravehicular Activity
- FOCCUS – Fail Operational Capabilities for Caretaking and Utilization Scenarios
- GCD – Game Changing Development
- GN&C – Guidance, Navigation, and Control
- HEOMD – Human Exploration and Operations Mission Directorate
- HOME – Habitats Optimized for Missions of Exploration
- HSI – Human-Systems Integration
- IEEE – Institute of Electrical and Electronics Engineers
- ISAAC – Integrated System for Autonomous and Adaptive Caretaking
- ISO – International Organization for Standards
- ISRU – In-situ Resource Utilization
- ISS – International Space Station
- IVA – Intravehicular Activity
- JPL – Jet Propulsion Laboratory
- JSC – Johnson Space Center
- KSC – Kennedy Space Center
- LANDO - Lightweight Surface Manipulation System (LSMS) AutoNomy capabilities Development for surface Operations and construction
- LaRC – Langley Research Center
- LSIC – Lunar Surface Innovation Consortium
- LSII – Lunar Surface Innovation Initiative
- LTV – Lunar Terrain Vehicle
- LUnA – Lunar Underactuated Robotic Arm
- NASA – National Aeronautics and Space Administration
- NDL – Navigation Doppler LiDAR
- NSTRF – NASA Space Technology Research Fellowships
- NSTGRO – NASA Space Technology Graduate Research Opportunities
- PASS – Precision Assembled Space Structure
- PESTO – Planetary Exploration Science Technology Office
- R&D – Research and Development
- RASSOR – Regolith Advanced Surface Systems Operations Robot
- RESET – Rover Slip Estimation and Traction Control in Lunar Environments
- RETHi – Resilient Extra-Terrestrial Habitats Institute
- RFI – Request for Information
- ROS – Robot Operating System
- RSIM – Rover Simulation Software
- SAE – Society of Automotive Engineers
- SBIR – Small Business Innovative Research
- SLAM – Simultaneous Localization and Mapping
- SMD – Science Mission Directorate
- SOMD – Space Operations Mission Directorate
- SQRLi – Space Qualified Rover LiDAR
- STMD – Space Technology Mission Directorate
- STRG – Space Technology Research Grants
- STRI – Space Technology Research Institute
- STTR – Small Business Technology Transfer
- TIM – Technical Interchange Meeting
- TP – Tipping Point
- TRL – Technology Readiness Level
- US – United States
- V&V – Verification and Validation
- VIPER – Volatiles Investigating Polar Exploration Rover