

The background of the slide is a composite image of space. On the left, a large, detailed view of the Moon's surface is shown, with a small satellite or probe orbiting it, leaving a bright blue trail. Above the Moon, the reddish, cratered surface of Mars is visible. The rest of the background is a dark, star-filled sky. In the bottom right, the silhouette of a person's head and shoulders is visible against a lighter, hazy horizon.

# EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

## *EXPLORE: Autonomous Systems & Robotics (ASR)* NASA Space Technology Mission Directorate

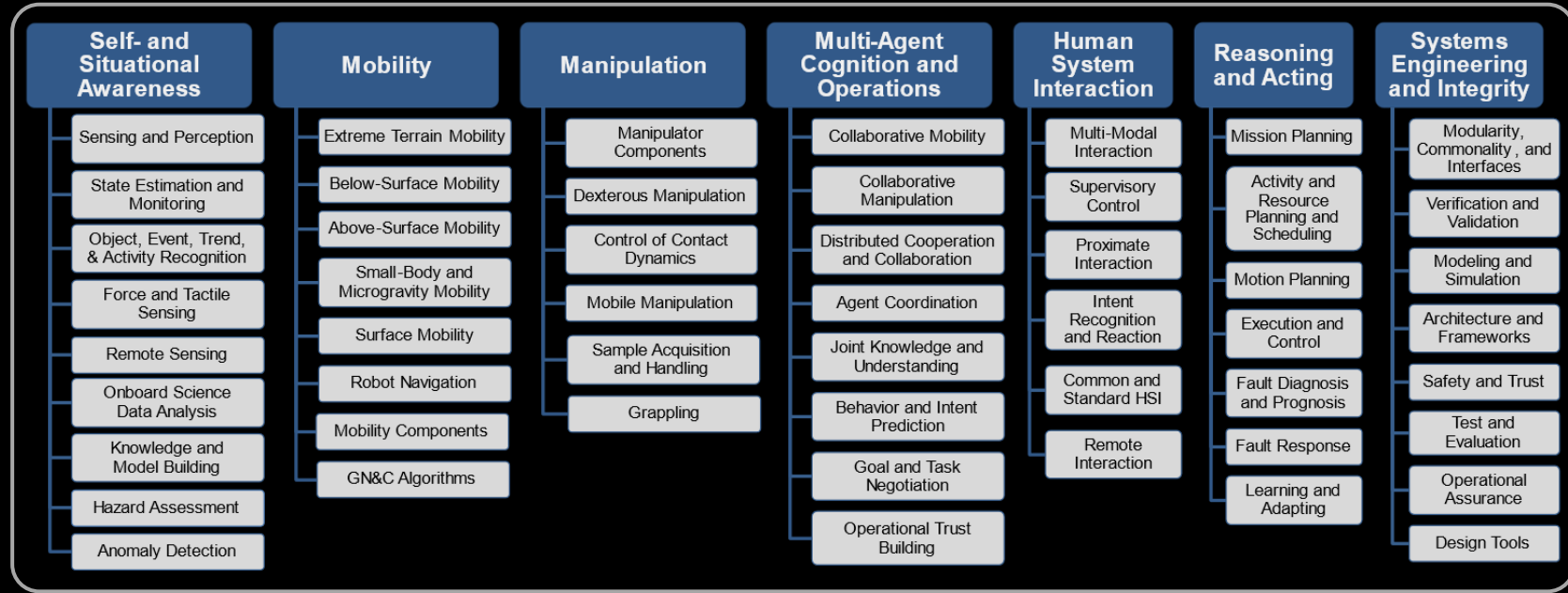
STMD welcomes feedback on this presentation. Please visit <https://techport.nasa.gov/framework/feedback> if you have any questions or comments regarding this presentation.



# 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



**“Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions”**

**On-Orbit Servicing, Assembly, and Manufacturing**

**Spacecraft Operations and Utilization**

**Sustainable Lunar Infrastructure**

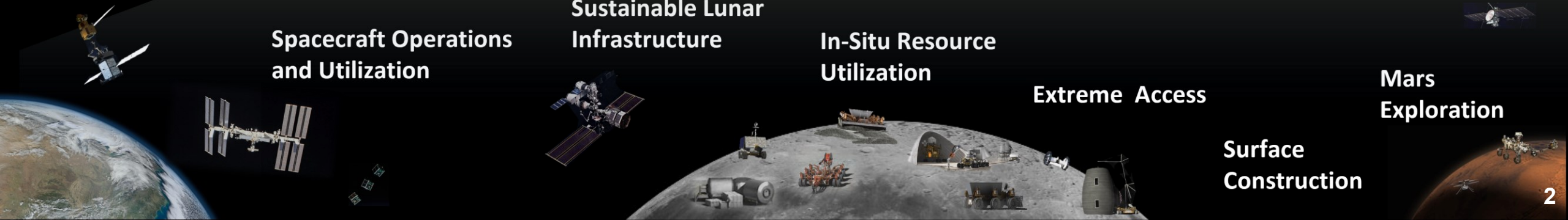
**In-Situ Resource Utilization**

**Extreme Access**

**Surface Construction**

**Planetary Science**

**Mars Exploration**





## Goals

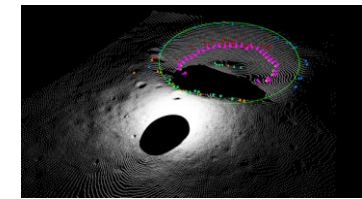
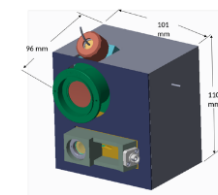
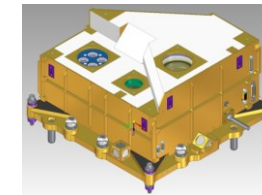
- Enable space missions that cannot currently be performed
- Increase space mission effectiveness, productivity, and safety
- Respond to the needs of commercial missions, human exploration missions, and science missions
- Establish a self-sustaining community of academia, government, and industry to 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

ROS

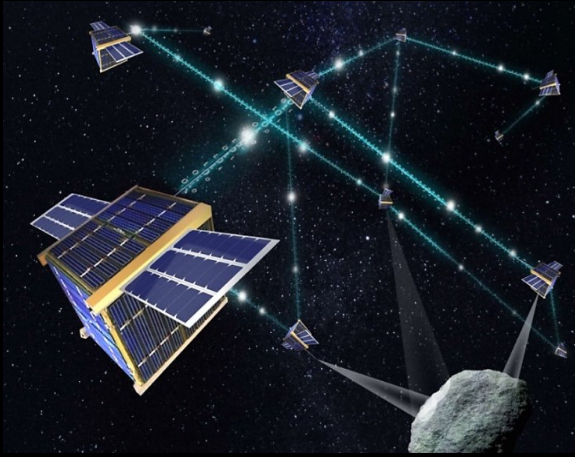
Lunar Surface Innovation  
CONSORTIUM



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



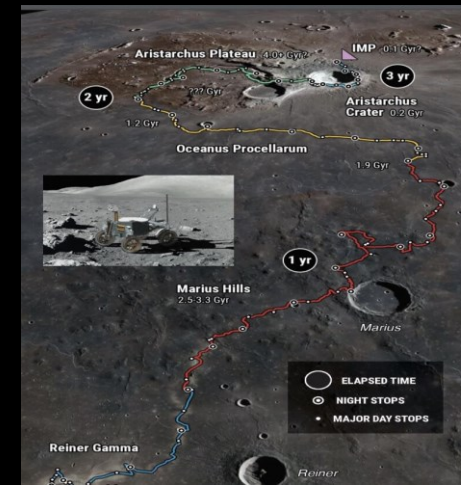
## AUTONOMOUS MULTI-SPACECRAFT SYSTEM FOR DISTRIBUTED SCIENCE MEASUREMENTS



## 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.



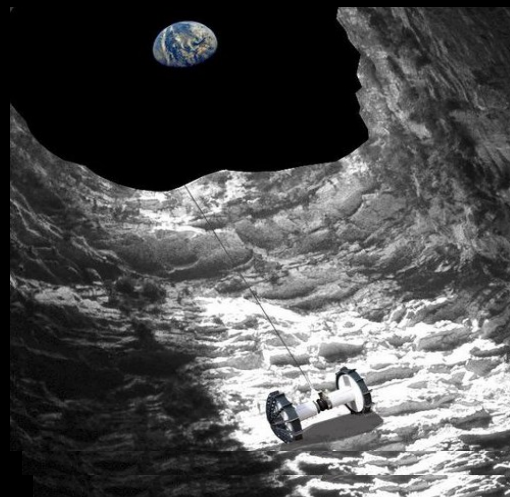
# EXPLORE: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.



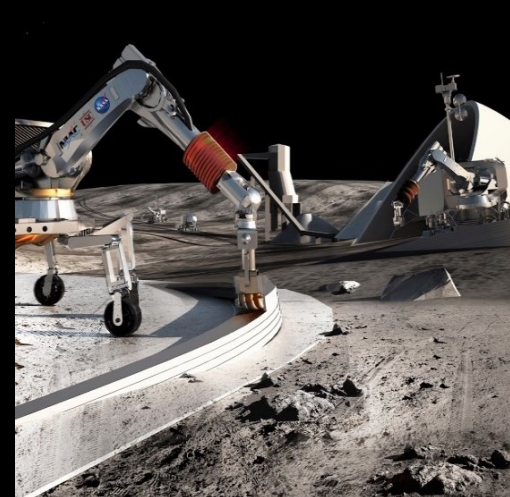
ROBOTIC CARETAKING INSIDE HABITATS AND SPACECRAFT



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.

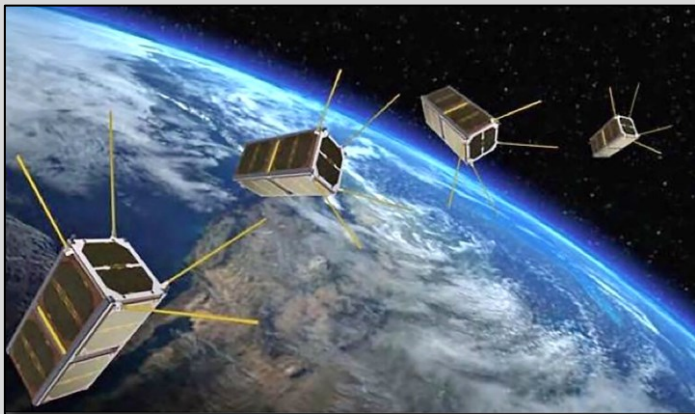


# State of the Art: Spacecraft Autonomy Technologies

## Cooperative multi-spacecraft system with efficient human teaming

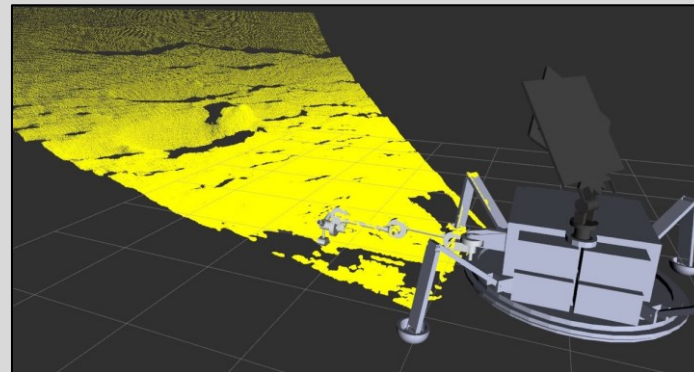


Multi-robot autonomy and commanding for distributed measurements (JPL, 2021) **TRL 5**

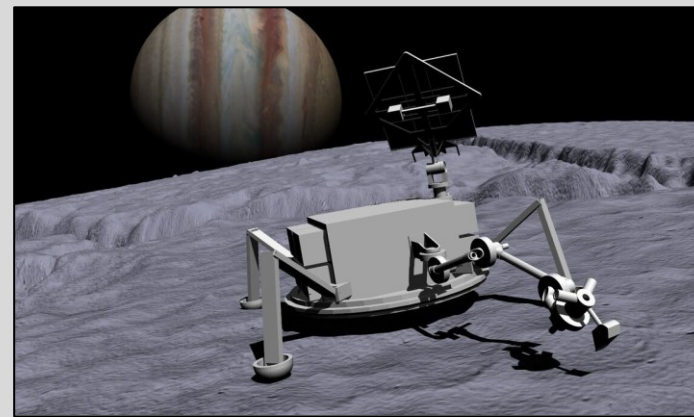


Distributed spacecraft autonomy and human-swarm control tech demo (ARC, 2022) **TRL 6**

## 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



Image courtesy of Carnegie Mellon University © 2013

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

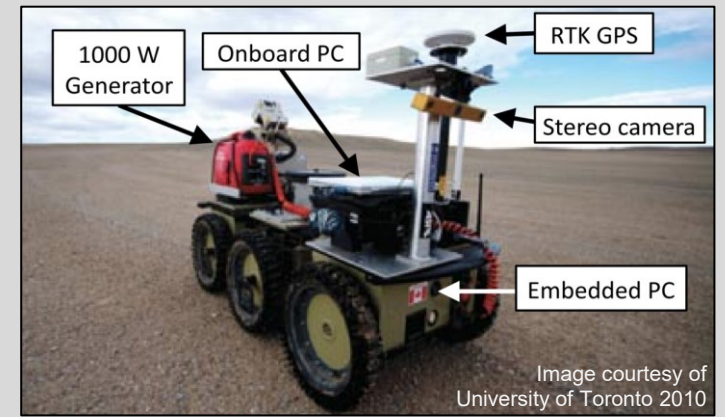


Image courtesy of University of Toronto 2010

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



# 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**

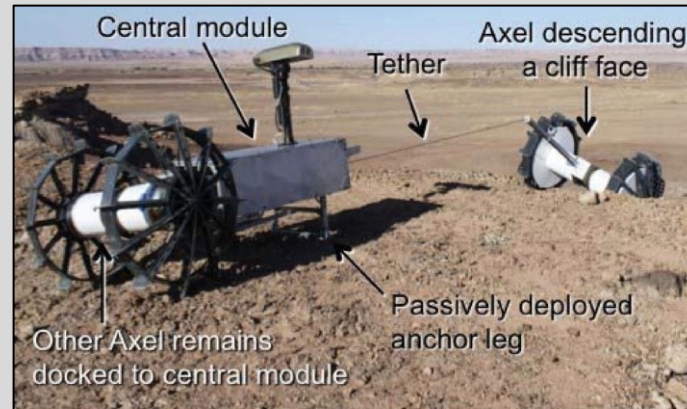


Dexterous manipulation demonstrations on ISS (Robonaut 2, JSC, 2014) (GITAI, 2021) **TRL 6**

## Robust robot mobility for extreme access



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

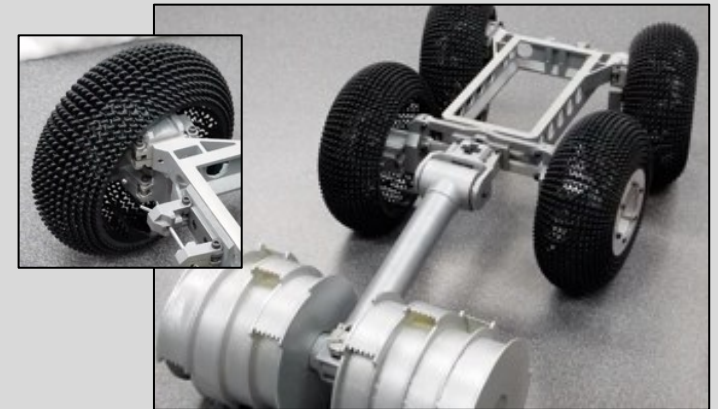


Dual tethered robots for handling steep terrain and cliffs (DuAxel, JPL, 2013) **TRL 5**

## 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**

# 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



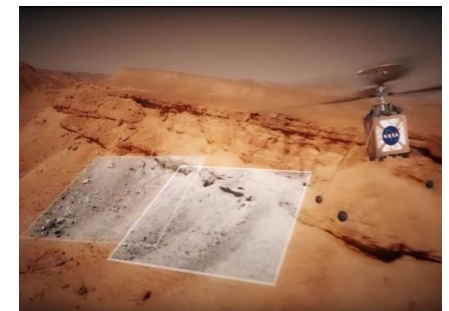
## Human Exploration

- 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



## STRG

ECF 20  
HOME STRI  
RETHi STRI  
NSTRF / NSTGRO

## SBIR/STTR

DRSOMA (Phase 2)  
RESET (Seq Phase 2)

## GCD

PASS  
CADRE  
CubeRover  
DSA  
FOCCUS  
SQRLi  
ISAAC  
LUnA  
LunarCam  
LunarNav  
Space ROS ACO

## ECI

Assemblers, LANDO

Total Life Cycle Cost

----- < \$1M  
————— \$1 to 5M  
————— > \$5M

## ASR Technology Objectives

**Cooperative multi-spacecraft system with efficient human teaming**

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

**Efficient on-board autonomy for continuous surface operations**

**Remotely operated IV robotics for maintenance and utilization**

**Robust robot mobility for extreme access**

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

# ASR Strategy: Grow the Space Economy and Workforce

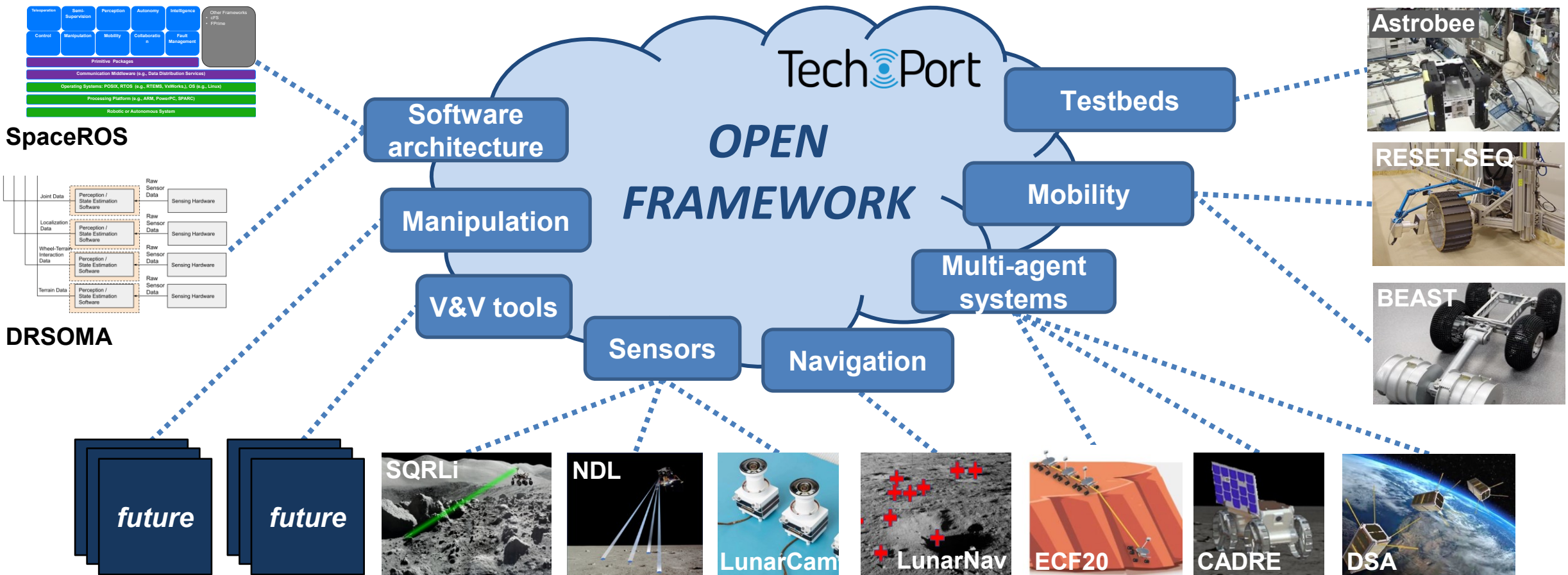


- 1. Open framework approach to create **sustainable, industry-driven hardware and software****
  - Modular, interoperable, and reusable components (open-source & proprietary) developed by many parties
  - Lower barriers to entry for infusion and adaptation of industry/terrestrial ASR technologies into 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 Astrobees 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

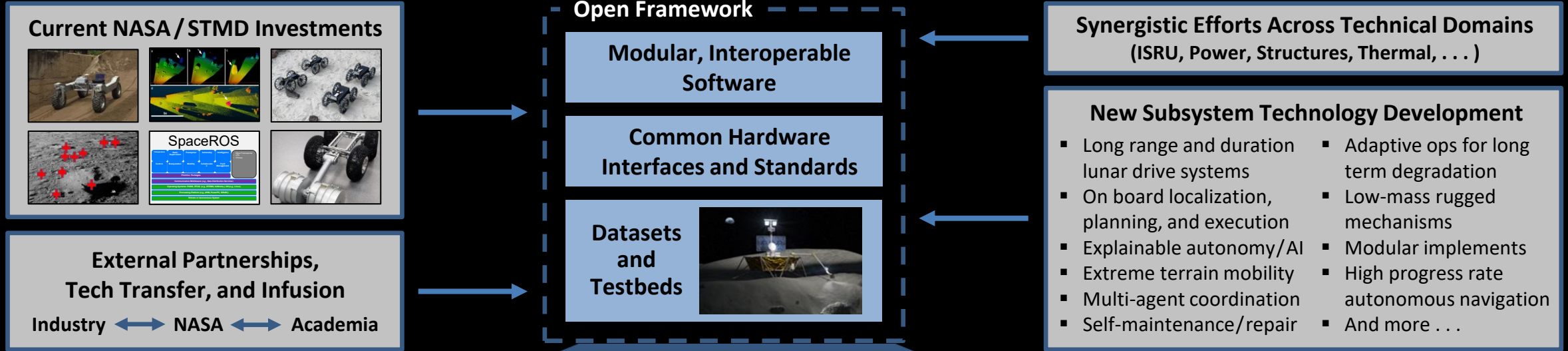
- **Objective:** sustainable **technology** that is **modular**, **interoperable**, and **reusable**
- Create a public **catalog** for ASR technology – build off of **TechPort v3.8** to create a tool for the ASR community (not just NASA!) and to motivate continuous tech transfer and reuse to/from all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

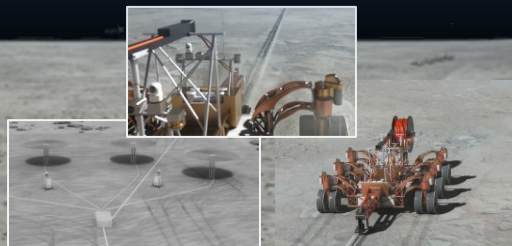


Interoperability and reusable technology enable **rapid integration** and **collaborative operations** across multiple vendors and systems

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

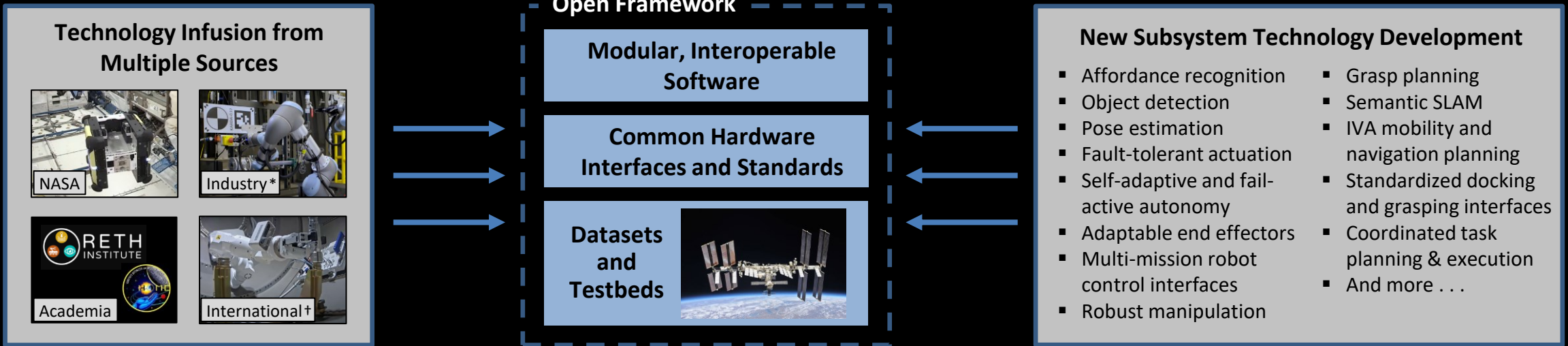




# Example: Human Spacecraft Support

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



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

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
<b>Autonomy</b>	<ul style="list-style-type: none"> <li>Develop on-board planning for extreme terrain traversal (STMD-ASR-002, STMD-ASR-003)</li> <li>Develop on-board rover terrain embedding &amp; entrapment recovery methods (STMD-ASR-014, SMD-PESTO)</li> <li>Develop reusable autonomous manipulation behaviors and task planning (STMD-ASR-003, STMD-ASR-008)</li> </ul>	<ul style="list-style-type: none"> <li>Site preparation and regolith collection robotics must be capable of reliable continuous operations to handle surface operations at scales beyond proof-of-concept demos.</li> <li>Reliable autonomous navigation over unmodified terrain is required for all lunar surface operations.</li> <li>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.</li> </ul>
<b>Robotics</b>	<ul style="list-style-type: none"> <li>Develop long-range and rugged drive systems (STMD-ASR-002, STMD-ASR-010)</li> <li>Develop field-swappable repair units (STMD-ASR-013)</li> <li>Develop fault-tolerant robotic actuators and end-effectors (STMD-ASR-020, STMD-ASR-021)</li> </ul>	<ul style="list-style-type: none"> <li>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.</li> <li>Resilient robotics technology is needed to support IVA utilization, inspection, maintenance, and contingency response inside habitable volumes (in-space and surface).</li> </ul>
<b>R&amp;D Infrastructure</b>	<ul style="list-style-type: none"> <li>Open Framework: Establish clearinghouse and implement incentivization strategy</li> <li>Extend ISS Astrobees facility to support IVA robotics technology development</li> </ul>	<ul style="list-style-type: none"> <li>Open Framework approach will help industry, NASA, &amp; other organizations move away from custom, one-off development</li> <li>STMD can leverage on-going ESDMD investment to support and accelerate ASR development</li> </ul>



# Next Steps (Mid-term)



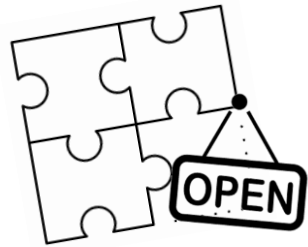
	Subsystem Tech (Gaps)	Rationale
<b>Autonomy</b>	<ul style="list-style-type: none"> <li>Develop adaptive ops for long-term degradation (STMD-ASR-008, HEOMD-2021-3449-TX10)</li> <li>Develop auto recovery from loss of data comm (HEOMD-2021-3052-TX10.1)</li> <li>Develop efficient robot perception systems suitable for space computing (STMD-ASR-018)</li> </ul>	<ul style="list-style-type: none"> <li>Establishing a long-distance power transmission/distribution network requires autonomous navigation and reliable handling of communications.</li> <li>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).</li> </ul>
<b>Robotics</b>	<ul style="list-style-type: none"> <li>Develop low-mass rugged mechanisms (STMD-ASR-012, STMD-ASR-022)</li> <li>Develop very low-temperature mechatronics (STMD-ASR-0012)</li> <li>Develop steep slope climb/descent systems (STMD-ASR-010)</li> </ul>	<ul style="list-style-type: none"> <li>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.</li> <li>Long-lived robotic work systems must be repairable or serviceable in order to maintain nominal operation and recover from component failures and degradation.</li> </ul>
<b>R&amp;D Infrastructure</b>	<ul style="list-style-type: none"> <li>Open Framework: Connect ASR community to other government agencies</li> <li>Adapt SMD OceanWaters simulator to support STMD solicitations (ACO/TP, SBIR, or STRG)</li> </ul>	<ul style="list-style-type: none"> <li>Open Framework approach can increase ASR workforce and speed system development in support of government activities beyond NASA</li> <li>STMD can leverage on-going SMD investment to support and accelerate ASR development</li> </ul>

# Next Steps (Long-term)



	Subsystem Tech (Gaps)	Rationale
<p><b>Autonomy</b></p>	<ul style="list-style-type: none"> <li>• Develop explainable autonomy / AI operator interfaces for use by ground control and crew (STMD-ASR-005, STMD-ASR-015)</li> <li>• Develop methods and tools for V&amp;V of autonomous systems used for critical functions</li> </ul>	<ul style="list-style-type: none"> <li>• 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)</li> <li>• Reliance on autonomy for safety-critical and mission-critical functions requires new V&amp;V capabilities.</li> </ul>
<p><b>Robotics</b></p>	<ul style="list-style-type: none"> <li>• Develop interchangeable implements &amp; tools (STMD-ASR-012, STMD-ASR-013)</li> <li>• Develop mission-rated multi-robot tethering (STMD-ASR-013)</li> <li>• Develop low-mass thermal control modules for lunar robotics (STMD-ASR-012)</li> </ul>	<ul style="list-style-type: none"> <li>• Planetary robotic work systems will greatly benefit from modular end-effectors and devices in terms of flexibility, maintainability, and task performance.</li> <li>• Tethered multi-robot systems have significant potential for increasing access to extreme locations, improving rescue capabilities, and force multiplication.</li> </ul>
<p><b>R&amp;D Infrastructure</b></p>	<ul style="list-style-type: none"> <li>• Develop ASR standards</li> <li>• Release NASA curated datasets for ASR development</li> </ul>	<ul style="list-style-type: none"> <li>• 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).</li> <li>• Curated reference datasets can speed R&amp;D by providing key information for benchmarking and testing.</li> </ul>





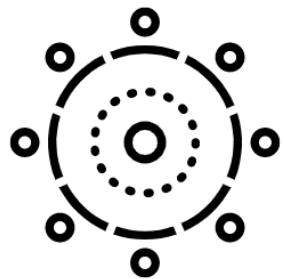
## Develop **ASR open framework** implementation

- 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
- DRSONA - 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
- NDJ – 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