EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

NASA Autonomous Systems & Robotics
Roadmap and Investments

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Demand for Autonomous Systems & Robotics (ASR)

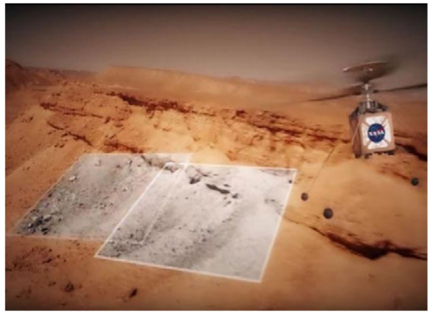
2022 NASA Strategic Plan: Innovate and advance transformation space technologies. Develop revolutionary, high-payoff space technologies driven by diverse ideas to transform NASA missions and ensure American leadership in the space economy.

Commercial Space

- Commercial space autonomy and robotics lacks common, interoperable technology to support cost-effective products
- Industry needs shared infrastructure (communications, computing services, data, etc.) upon which to build and operate

Human Exploration (HEOMD)

- All future human spacecraft (Gateway, surface habitats, etc.) need to be monitored, maintained, and utilized when uncrewed
- Artemis architecture includes uncrewed deployment, surface mobility and robotic ISRU



Science (SMD)

- Future missions cannot be achieved without new technology, particularly cooperative multi-spacecraft and self-reliant autonomy
- Planetary science encompasses the hardest requirements (SMD chief technologist)
- Large-scale observatories (20m telescope) require autonomous in-space assembly, inspection, and maintenance

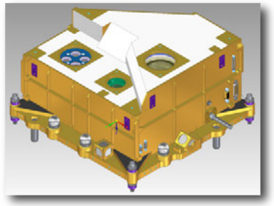
Autonomous Systems & Robotics (ASR)

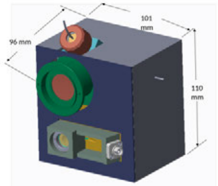
Objectives

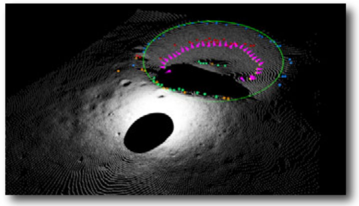
- Grow and sustain the space economy & workforce
- Respond to demand from **commercial space**, **human exploration**, and **science**
- Enable missions that currently cannot be performed
- Create and accelerate a consortium of **academia**, **government**, and **industry** to develop technology
- Reduce barriers to collaboration and reuse

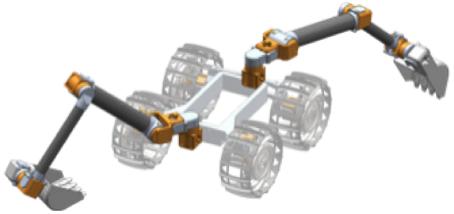
Approach

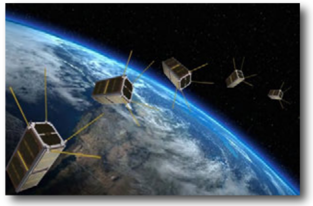
- **Technology vision**: focus on achieving “envisioned future” (six primary technology objectives)
- Define ASR scope (technology taxonomy)
- NASA develops prototypes to **break barriers** and to **reduce technical risk** where needed
- Establish **collaborative** projects to integrate technology into flight missions (NASA and non-NASA)
- **Open framework** – enable sustained development of modular, interoperable, and reusable technologies by many parties

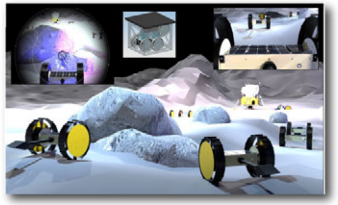












STMD Strategic Framework

<table>
<tr><th>Lead</th><th>Thrusts</th><th>Outcomes</th></tr>
<tr><td rowspan="4">Ensuring American global leadership in Space Tech
• Advance US Space technology innovation and competitiveness in a global context
• Encourage technology driven economic growth with an emphasis on the expanding space economy
• Inspire and develop a diverse and powerful US aerospace technology community</td>
<td>Go
Rapid, Safe, and Efficient Space Transportation</td>
<td>• 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.</td></tr>
<tr><td>Land
Expanded Access to Diverse Surface Destinations</td>
<td>• 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.</td></tr>
<tr><td>Live
Sustainable Living and Working Farther from Earth</td>
<td>• 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.</td></tr>
<tr><td>Explore
Transformative Missions and Discoveries</td>
<td>• 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 transformative technologies that enable future NASA or commercial missions and discoveries.</td></tr>
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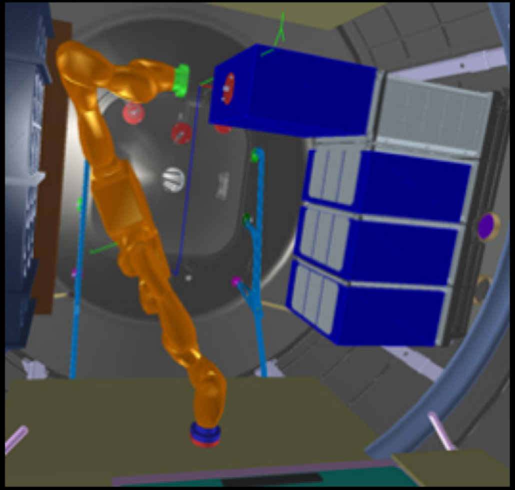
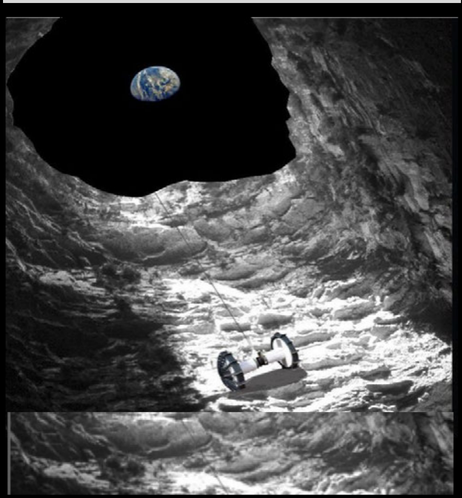
EXPLORE: Develop **advanced robotics** and spacecraft autonomy technologies to enable and augment science/exploration missions

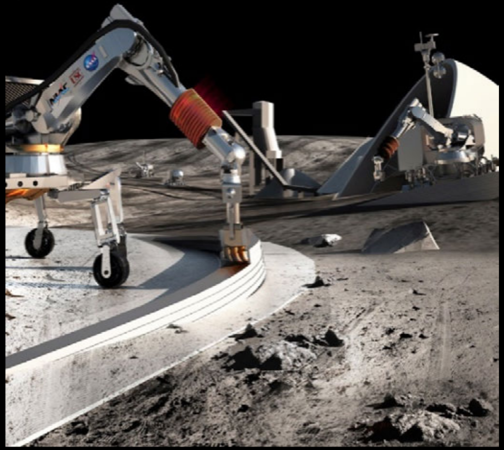
ROBOTIC CARETAKING INSIDE HABITATS AND SPACECRAFT



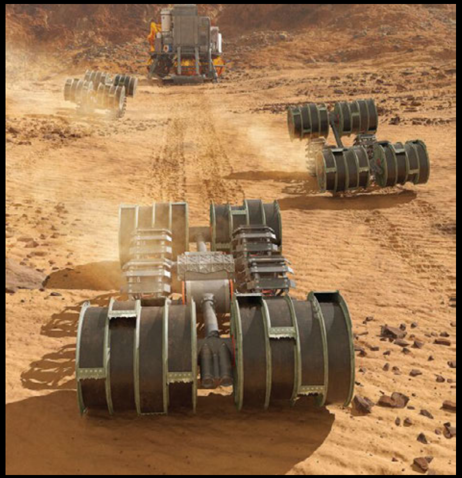
ROBOTIC EXPLORATION OF EXTREME ENVIRONMENTS



ROBOTIC CONSTRUCTION OF SURFACE INFRASTRUCTURE



ROBOTIC RESOURCE EXTRACTION + TRANSPORT



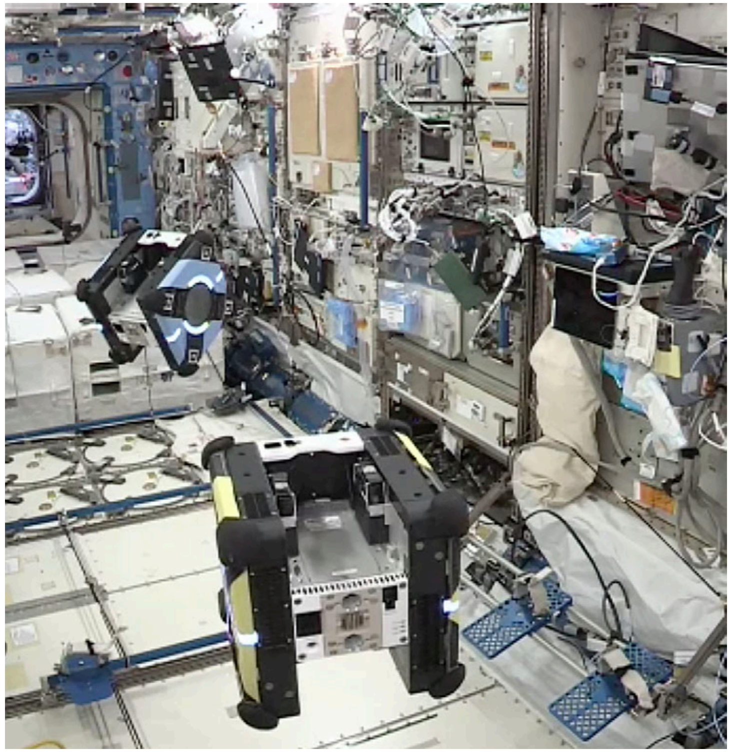
Technology Objectives

- **Remotely operated intra-vehicular robotics for maintenance and utilization** (4,000+ hr/yr) of uncrewed (up to 90% time) exploration spacecraft and surface habitats
- **Robust robot mobility for extreme access**: surfaces (5,000 km life-cycle drive), deep interiors (up to 25 km) through rock and cryogenic ice, and handling of dangerous topography (up to 90° slopes)
- **Durable, self-maintainable robotics for heavy-duty surface work**: bulk excavation (100-400 metric tons), material transport (500-600 km/yr), and surface construction (15,000 kg carrying capacity)

All activities depicted not currently funded or approved. Depicts "envisioned future" to guide technology vision.

State of the Art: Advanced Robotics

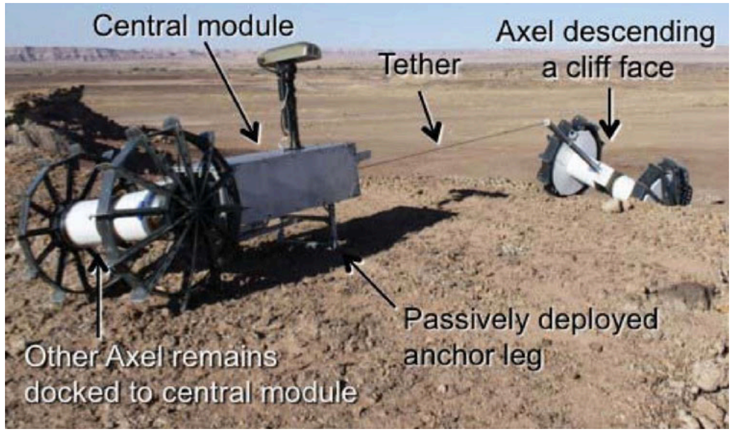
Remotely operated intra-vehicular robotics for maintenance and utilization



STMD developed the Astrobee robot system for use as an ISS IVA facility. Astrobee supports microgravity robotics research and testing of a wide variety of payloads. (TRL 9)

Robust robot mobility for extreme access

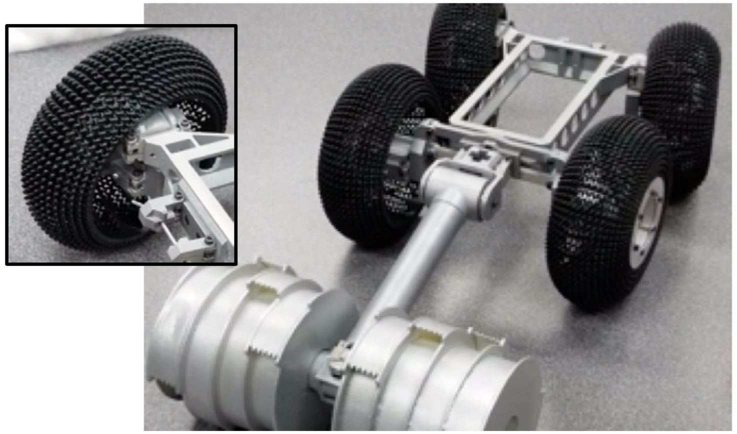
RoboSimian (JPL) traversing obstacles 3x wheel radius at Death Valley in 2020 (TRL 5)



DuAxel (JPL, 2013) is a modular robot that combines two Axel robots with a tether (TRL 5)

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

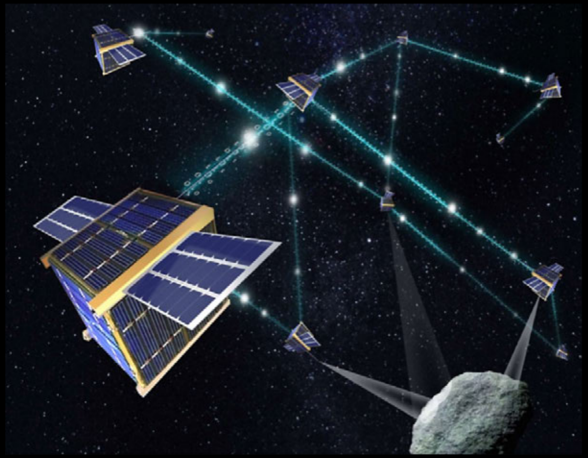
RASSOR (KSC) is designed for robotic excavation of lunar regolith (TRL 5)



Field-serviceable, modular vehicle concept (BEAST project) for lunar surface (TRL 3)

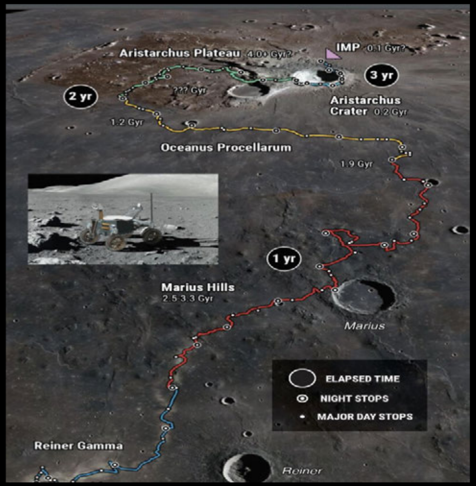
EXPLORE: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions

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 interdependent and distributed action (system operable as a single "entity")
- **Self-adaptive and fail-active autonomy for high-tempo missions** in high-risk environments (example: guaranteed acquisition of 5 high-value samples during 20-day Europa mission)
- **High progress rate self-driving planetary rover** with cost-effective mission control (1/10 cost of current practice) and increased performance (10x productivity / time) for long range (450 km/yr) or continuous worksite operations (750 km/yr)

All activities depicted not currently funded or approved. Depicts "envisioned future" to guide technology vision.

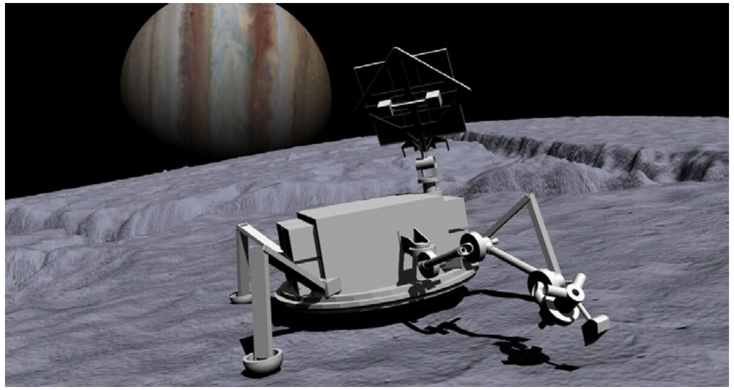
State of the Art: Spacecraft Autonomy Technologies

Cooperative multi-spacecraft system with efficient human teaming

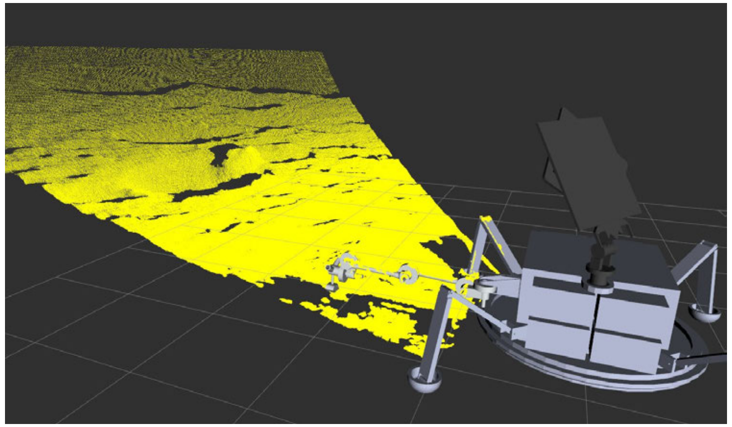
Autonomous PUFFERs (JPL) cooperatively explored the mini Mars Yard in 2021 (TRL 5)

Distributed Space Autonomy (ARC) has developed human-swarm interaction technology (TRL 6) in preparation for a 2022 flight demo

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



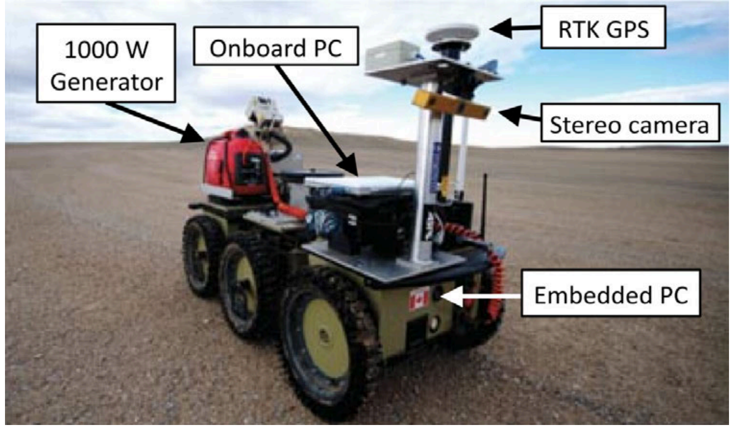
Stochastic fail-operational robotic task planning (Honeybee Robotics, 2021) for Europa (TRL 4)



Anomaly detection for autonomous adaptation to faults (Caltech, 2021) for Europa (TRL 3)

High progress rate (250 km/year) self-driving planetary rover

Zöe rover (CMU) autonomously drove 26 km in 10 days across the Atacama in 2015 (TRL 5)



“Visual Teach and Repeat” (U Toronto) achieved 99.6% autonomy in 2010 (TRL 5)

ASR Technology Taxonomy

- **Self- and Situation 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

- Includes elements from multiple areas (TX4, TX10, TX11) of the 2020 NASA Technology Taxonomy
- Achieving a specific functional capability generally requires multiple technology areas
- The technologies used from each area depends on mission requirements, concept of operations, program constraints (budget, schedule, etc), risk tolerance, management approach, etc.

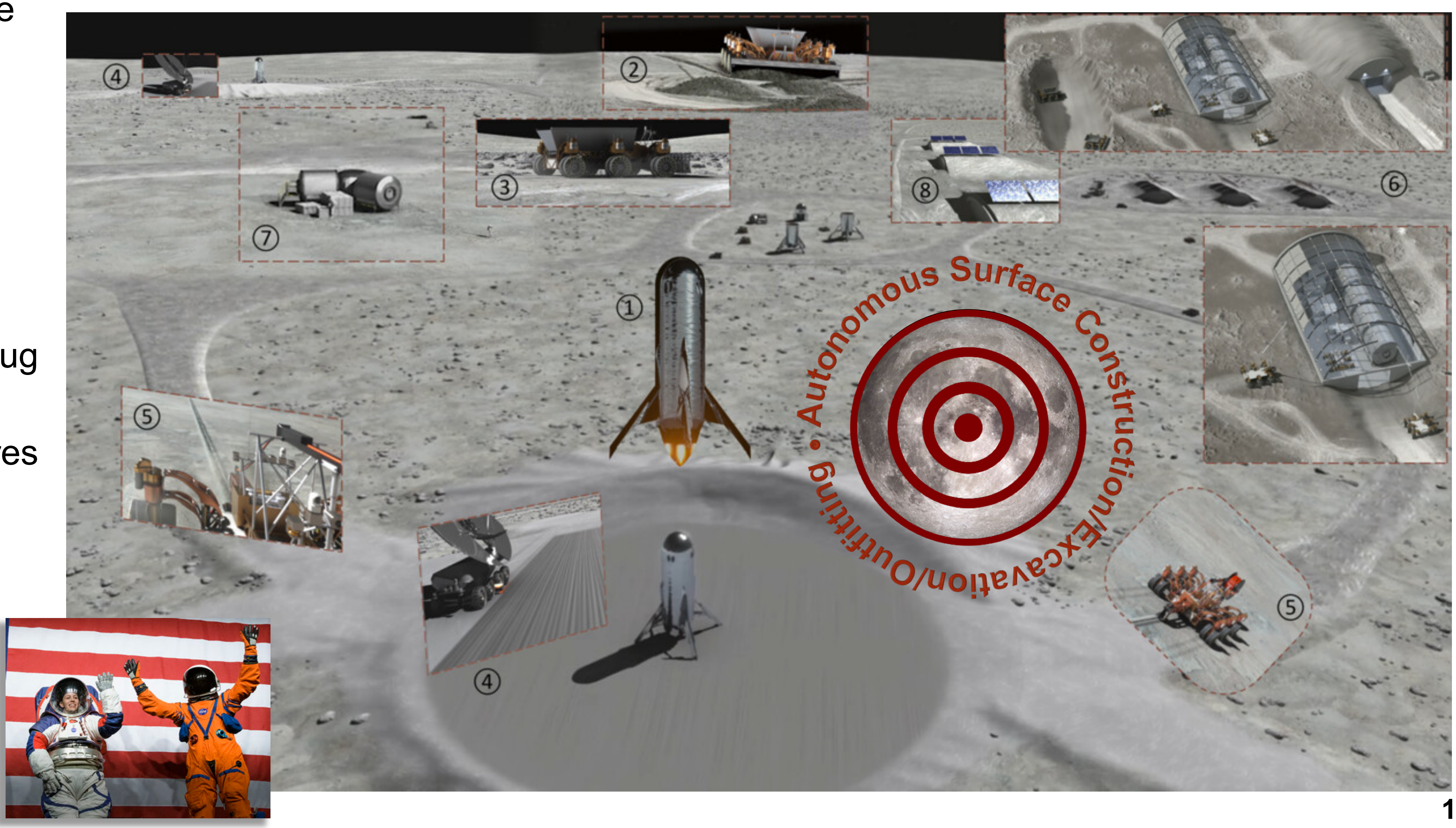
Example: ASR Technology for Lunar Site Preparation

Autonomous, cooperative, durable, and high-progress rate robotics

1. supplies arrive on the lunar surface
2. excavation begins
3. materials are transported
4. sintering of landing pad begins
5. cable trenches are dug and cables are laid
6. outrigging of structures starts
7. fuel depots are erected and filled
8. power is harnessed

…

? Humans arrive →

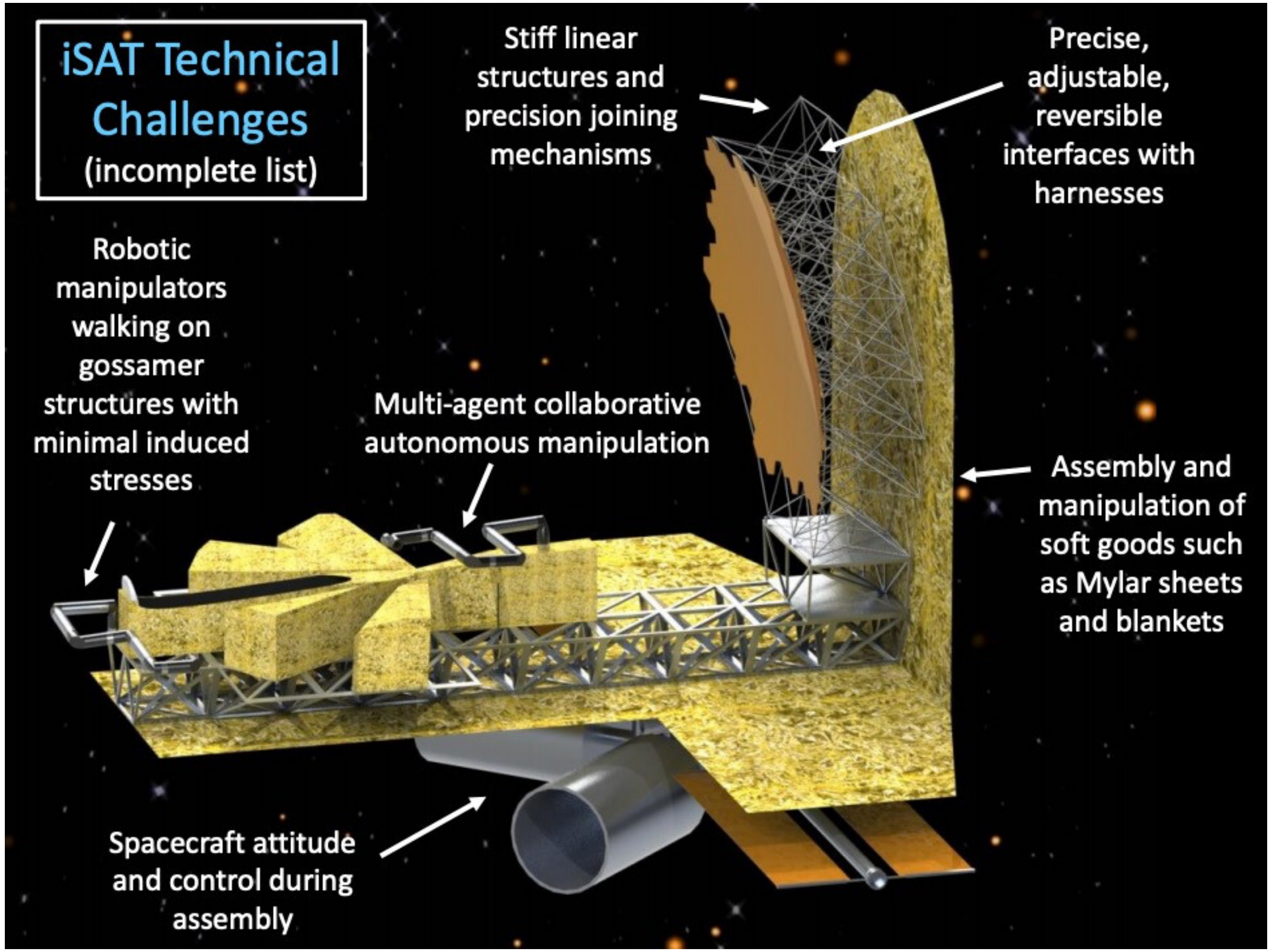


Example: ASR Technology for 20m iSAT Telescope (2019)

- 5 of the top 6 top technical challenges involve autonomy and robotics
- iSAT study identifies 14 In-Space Assembly (ISA) Capability Needs. 12 of these needs involve ASR technology:

1. Deployable Modules	8. Precision
2. Structural Assembly	9. Adaptive Correction
3. Connecting Utilities	10. Design
4. Ability to Disjoin	11. Tunability
5. Sensing, ModSim, & Verification	12. Stability
6. Interoperability	13. Standard Interfaces
7. Automation/Autonomy	14. Docking/Berthing

- "Automation/Autonomy" Need (#7):
  - 7.1 Intelligence to make stereotyped decisions correctly without human input.
  - 7.2 Intelligence for full autonomy
  - 7.3 Fail-safe modes of behavior on failure detection
  - 7.4 Multi-agent autonomy
- Autonomy need 7.3 is the most important overall need (ranked #1 by tri-agency team)

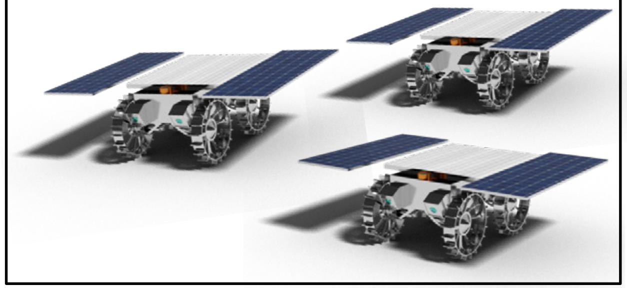


https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

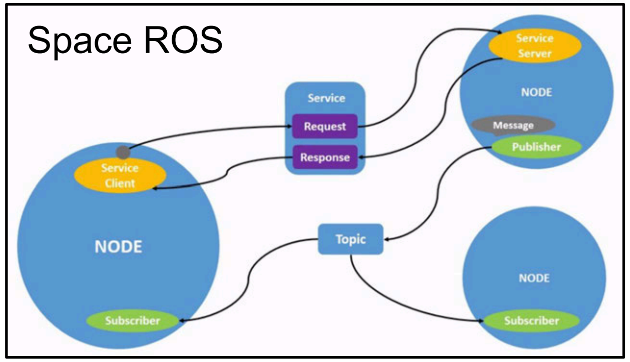
Current Investment: Cooperative Multi-Spacecraft Systems

Distributed Spacecraft Autonomy (DSA)

Cooperative Autonomous Distributed Robot Exploration (CADRE)



Space ROS

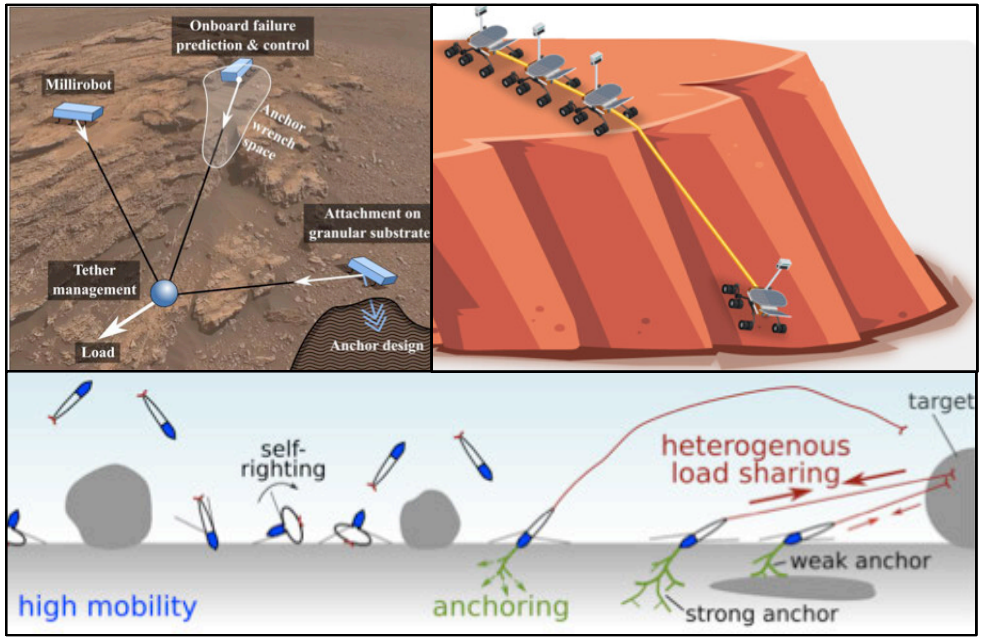


Smart Deep Space Habitats (STRI 2018)

HABITATS OPTIMIZED FOR MISSIONS OF EXPLORATION
HOME

RETH INSTITUTE

Coordinated Multi-Robots for Planetary Exploration (ECF 2020)



Future Capabilities

- Cooperative activity (load sharing, mapping, comm and power relay, etc)
- Extreme terrain access (cliff walls, skylights, etc)
- Large payload deployment
- Mutual assist & rescue (entrapment, falls, etc)
- On-demand positioning, navigation, & timing
- Redundancy & resilience for long-term operations
- Virtual instrument (concurrent, distributed measurements)

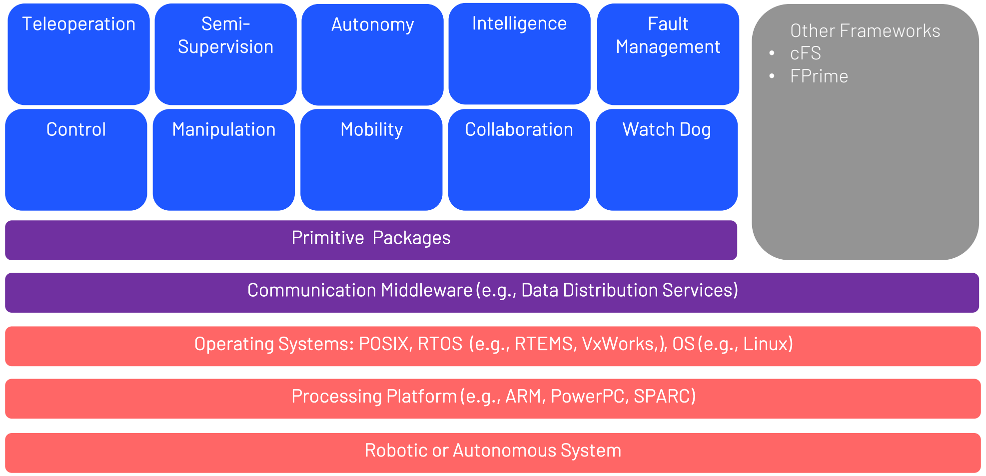
Current Investment: Space Robot Operating System (Space ROS)

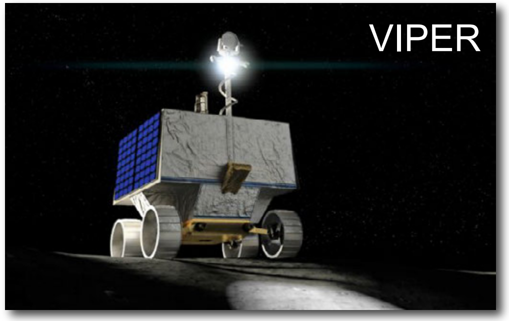
Public-private partnership (ACO 2020)

- Create a reusable, modular, and interoperable framework for space-qualifiable space robotic software
- Adapt and mature terrestrial open-source robotics software technology for space missions
- Space ROS will do for space robotics what the Core Flight System (cFS) has done for spacecraft flight software

Robot Operating System 2 (ROS)

- Modify the open-source ROS 2 core to align it with space software standards and space robotic needs
- Develop a "continuous qualification" approach that is compatible with software standards such as DO-178C and NASA NPR 7150.2C
- Create a registry to facilitate reuse (inspired by DoD "ROS-M")



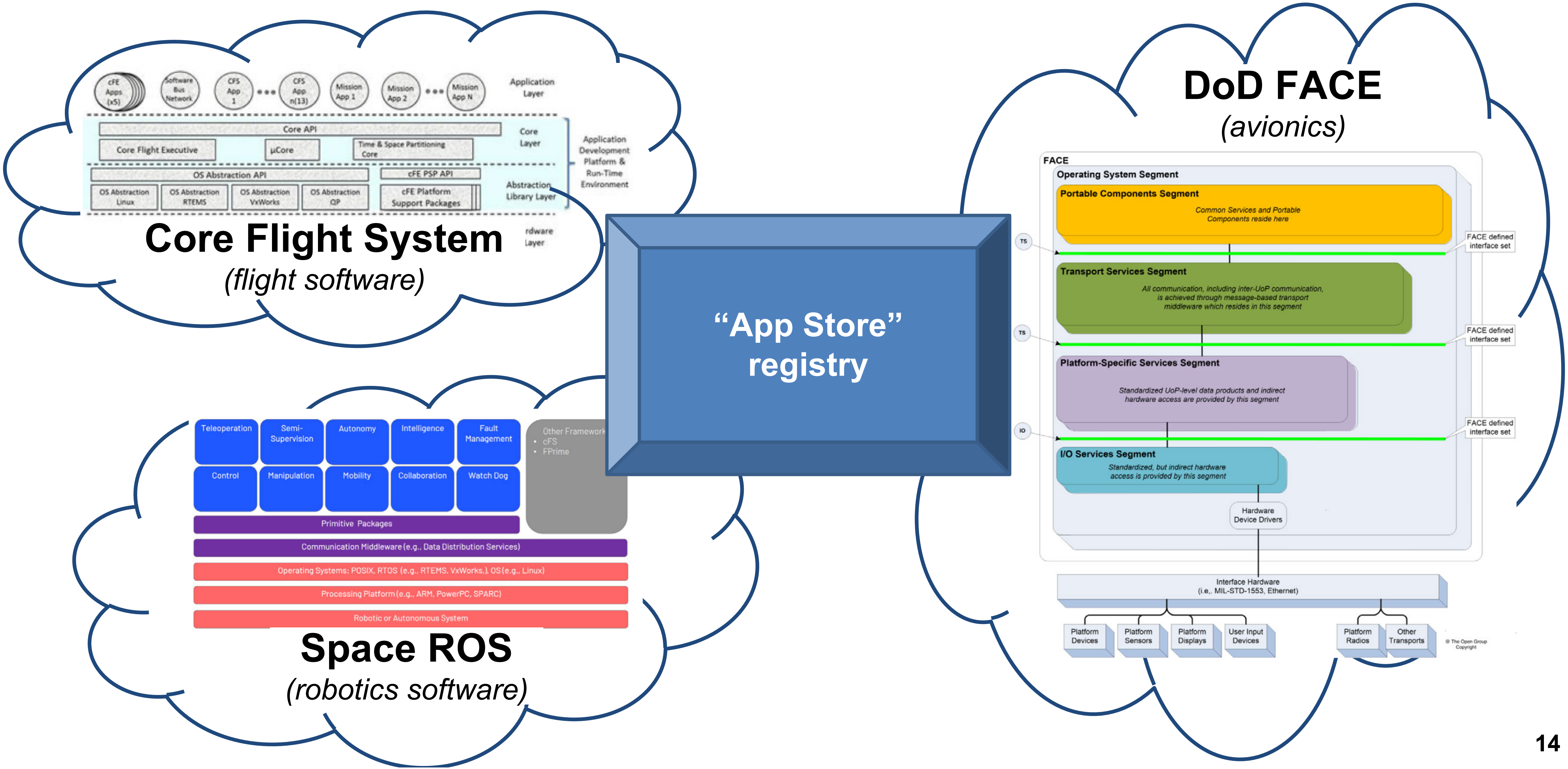


BLUE ORIGIN

Ames (ARC)
Goddard (GSFC)
Johnson (JSC)

open robotics

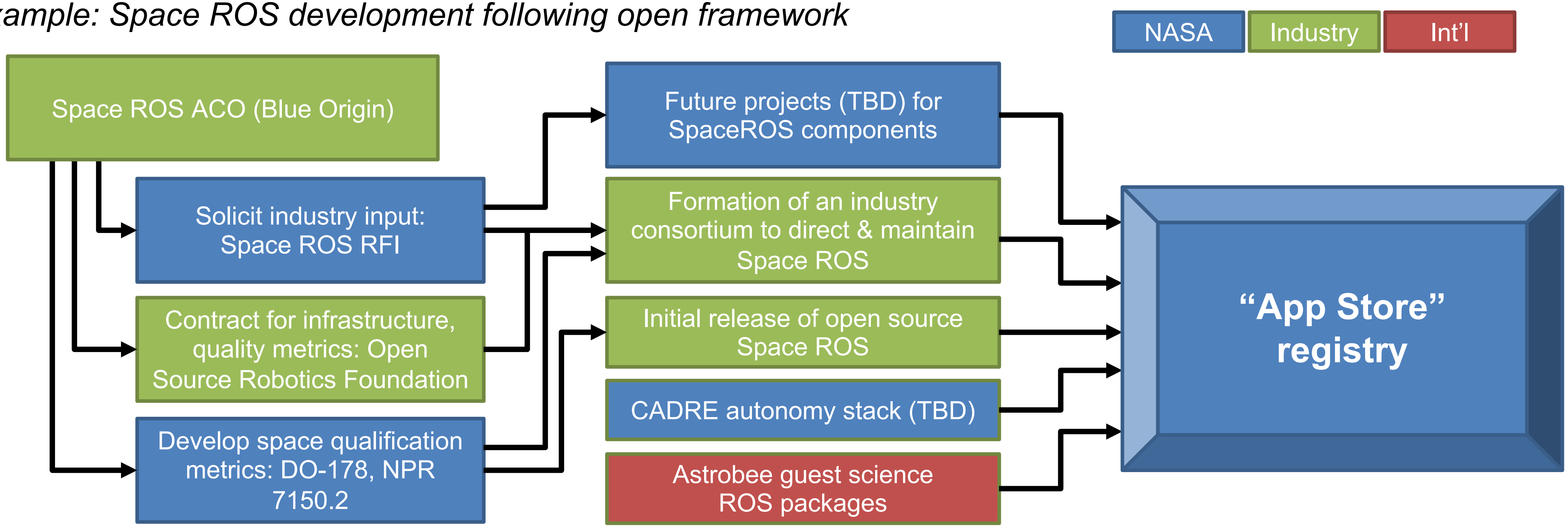
Open Framework: Modular, Interoperable, and Reusable Technology



Open Framework: Software

- **Core principal**: sustainable **software** that is **modular**, **interoperable**, and **reusable**
- Create an “App Store” like registry to serve as a **clearinghouse** for open-source and proprietary software
- Adapt and leverage best practices from DoD’s “Robot Operating System-Military” (ROS-M) community
- Start with existing flight software systems (cFS, F-prime, etc) and current STMD investments (Space ROS, CADRE autonomy, ISAAC robotics, DSA multi-spacecraft, STRI SmartHabs, SBIR/STTR)

Example: Space ROS development following open framework

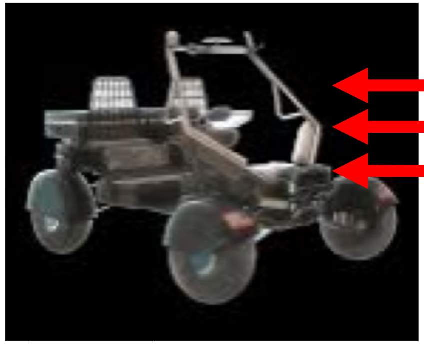


Infusion with Open Framework

NASA | Industry | Int'l

LTV

Lunar Terrain Vehicle could include technology modularity requirements

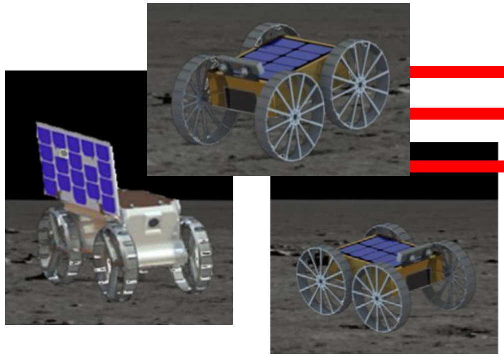


Interoperable ASR hardware technologies

- SQRLi Lidar
- ⋮
- Commercial Robot Arm
- International payloads

CADRE

Multi-robot autonomy software used for 2023 lunar tech demo (5 kg class rovers)

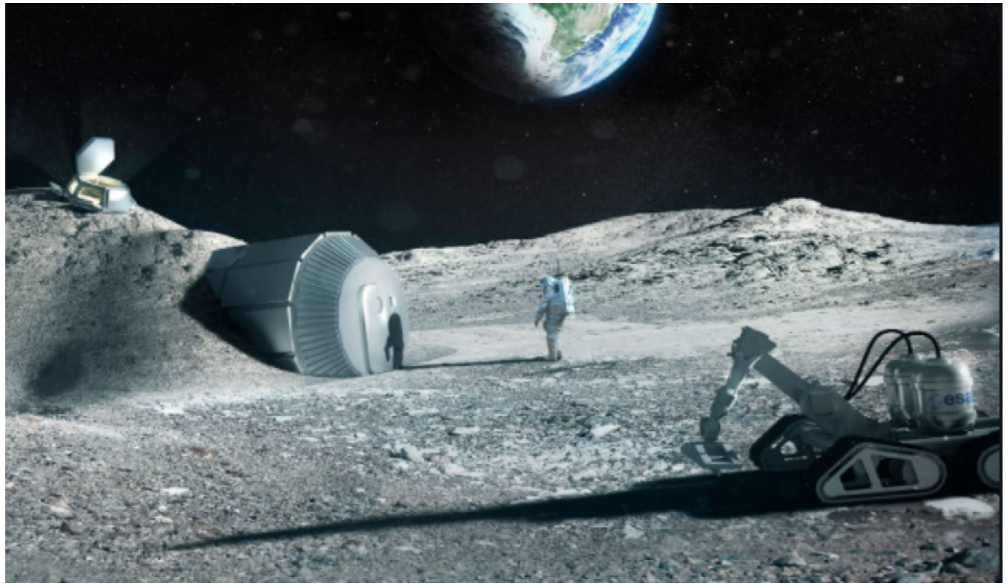


Open release to US industry

- Cooperative planning, scheduling, and execution
- Cooperative GN&C
- ⋮
- Collaborative data comm

Operations / Outfitting / Excavation & Construction

Multi-system autonomy will create a sustainable, interoperable ecosystem to enable ISRU, to maintain the on-surface supply chain, to perform surface assembly & construction, etc.



- ConOps, Ops, Outfitting, Planning/Scheduling
- Additive Manufacturing, Data Comm, Habitats
- International Robot Arm


www.nasa.gov/spacetech