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
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

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<th>Lead</th>
<th>Thrusts</th>
<th>Outcomes</th>
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| **Ensuring American global leadership in Space Tech** | **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. |
| **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. |
| **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. |
| **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 transformative technologies that enable future NASA or commercial missions and discoveries. |
EXPLORE: Develop **advanced robotics** and spacecraft autonomy technologies to enable and augment science/exploration missions

- **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

**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)

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

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

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)

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

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

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

- 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
...
⑨ Humans arrive →
- 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
  2. Structural Assembly
  3. Connecting Utilities
  4. Ability to Disjoin
  5. Sensing, ModSim, & Verification
  6. Interoperability
  7. Automation/Autonomy
  8. Precision
  9. Adaptive Correction
  10. Design
  11. Tunability
  12. Stability
  13. Standard Interfaces
  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

Cooperative Autonomous Distributed Robot Exploration (CADRE)

Distributed Spacecraft Autonomy (DSA)

Coordinated Multi-Robots for Planetary Exploration (ECF 2020)

Smart Deep Space Habitats (STRI 2018)

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”)
Open Framework: Modular, Interoperable, and Reusable Technology

Core Flight System
(flight software)

“App Store” registry

Space ROS
(robotics software)

DoD FACE
(avionics)
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*
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.

Lunar Terrain Vehicle could include technology modularity requirements

Interoperable ASR hardware technologies
- SQRLi Lidar
- Commercial Robot Arm
- International payloads

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

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.