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AUTONOMY AT SCALE

Intelligent Machines Advancing Technology to Improve our Future

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USE CASE: AUTONOMY FOR SPACE SYSTEMS

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The space industry has a proud and rich heritage of technological breakthrough, innovation and drive. While multiple government agencies have prioritized advancement of autonomy and technology, NASA alone spends $9.6B annually on research and development (R&D) contracts.

Returning to the Moon sustainably and exploring Mars and beyond places a greater emphasis on autonomous systems, especially since spacecraft will need to travel beyond human limitations. Resource and communications constraints demand much greater application and integration of autonomous systems to carry out high-level mission goals with no, or limited human intervention - while reducing costs and risks.

The use of future autonomous technologies will be assessed based on the Technology Readiness Level (TRL) scale which was originally defined by NASA in the 1990's as a means for measuring or indicating the maturity of a given technology. The TRL spans over nine levels as the technology progresses from early R&D concepts at "TRL 1 – Basic principles observed" to the highest level at "TRL 9 – with flight proven technology through successful mission operations.

With the plans to establish a Lunar Orbital Platform-Gateway (LOP-G) in cislunar space, NASA is driving many autonomous systems and technologies, including high-power Solar Electric Propulsion (SEP) systems, on-orbit assembly, refueling and docking, advanced communication strategies, and advancements in autonomy to operate in deep space.

Early adoption and acceptance of autonomous systems can pose challenges when integrating with human space flight systems and operations. The

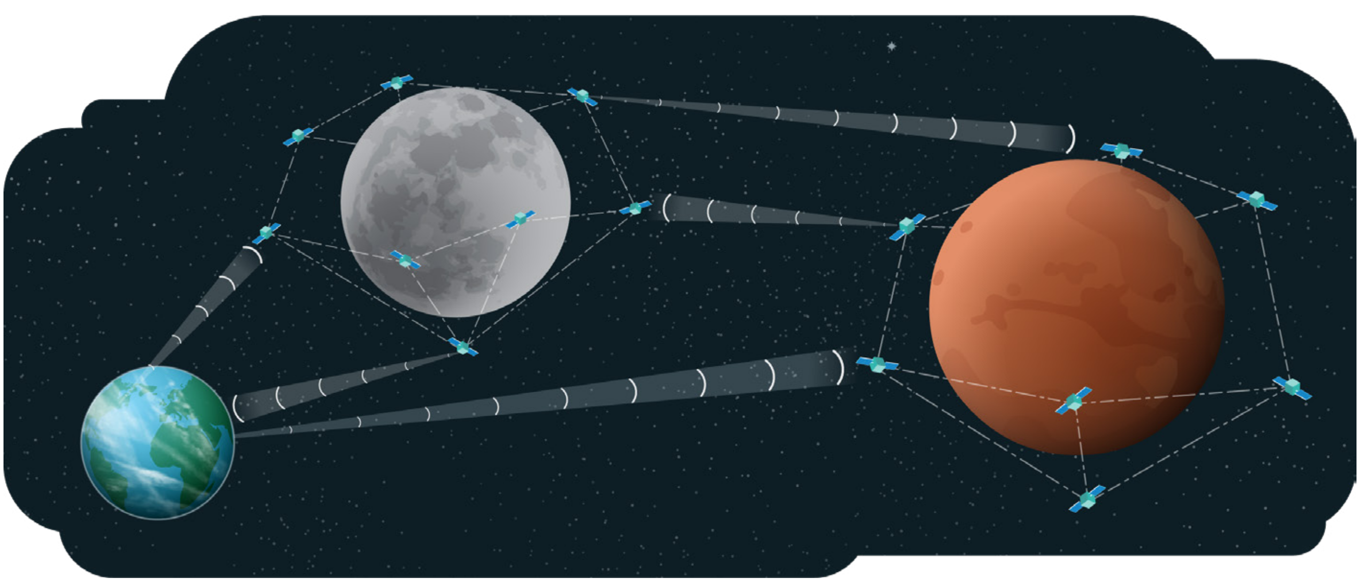

Figure 1: Integrated swarm community of robots providing support for future space exploration

risk posture, acceptance, and use of autonomous systems requires a more deliberate, and slower approval and acceptance process when dealing with “human in the loop” systems. The level of review, redundancy, and fail-safe acceptance criteria are much more critically scrutinized and reviewed when human life is at risk. The failure of critical systems from inappropriate or unsafe autonomous actions and/or systems is a huge concern among the human space organizations. To be successful in the space industry, the integration of autonomy and autonomous systems cannot increase risk to humans.

With the Administration’s objectives in space, NASA and the space industry are poised to propel and utilize autonomous systems to increase efficiency, reduce cost and drive breakthroughs for the betterment of all.

Autonomous systems are not new to the space systems environment. Autonomous systems have been used in robotic rovers canvasing the surface of Mars and with humans on the International Space Station (ISS). As NASA and commercial partners continue to push the boundaries of space, autonomous systems will continue to augment our human capacity—focusing efforts on key mission activities.

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Current and Emerging Technologies

Across the space industry, the investment in and application of autonomy has yielded significant breakthroughs. Research has focused on:

- Mission & flight operations
- On-orbit assembly & docking
- Power systems
- Space structures & habitats
- Fueling, refueling, & power systems
- Communications approaches and systems
- Space launch and space transportation
- Sample return & science/in-situ analysis
- And many more areas of R&D.

Mission, Flight and Ground Operations

Breakthroughs in autonomous missions, flight and ground operations will support the success, safety and crew survival of NASA deep-space missions, including the future LOP-G. Advancements in autonomous operations can significantly reduce operation times and costs and will reduce risks to operations staff and astronauts during hazardous operations such as propellant loading. Additionally, the current and future emphasis on launch vehicle reusability implies a requirement for post-flight vehicle inspections at scale. Emerging, neural-network–based technologies can ingest the massive amounts of data needed to conduct autonomous predictive analysis to identify critical flaws before they adversely impact missions. cause a mission failure or loss of life.

NASA’s Johnson Space Center (JSC) in Houston, Texas, traditionally performs mission operations. It provides mission control for the Orion multi-purpose crew vehicle and numerous advanced human exploration projects. JSC is also NASA's lead for ISS operations and human missions. Autonomous advancements play an important role in NASA's Commercial Crew Program. Early autonomous systems activities conducted here include a co-developed NASA JSC and NASA Ames initiative called the Autonomous Systems and Operations (T2 Treadmill Augmented Reality Procedures). This initiative conducts tests using autonomous augmented reality to help crew members perform inspection and maintenance on the Combined Operational Load Bearing External Resistance Treadmill (COLBERT). This autonomous technology can perform self-guided tasks—instrumental for future space exploration to the Moon, Mars, or wherever significant time delays occur in communications between space and ground. Using autonomous augmented reality to guide astronauts through complex spacecraft maintenance and repair activities can reduce astronaut workload and shorten the time needed for training and general Operations and Maintenance (O&M.)

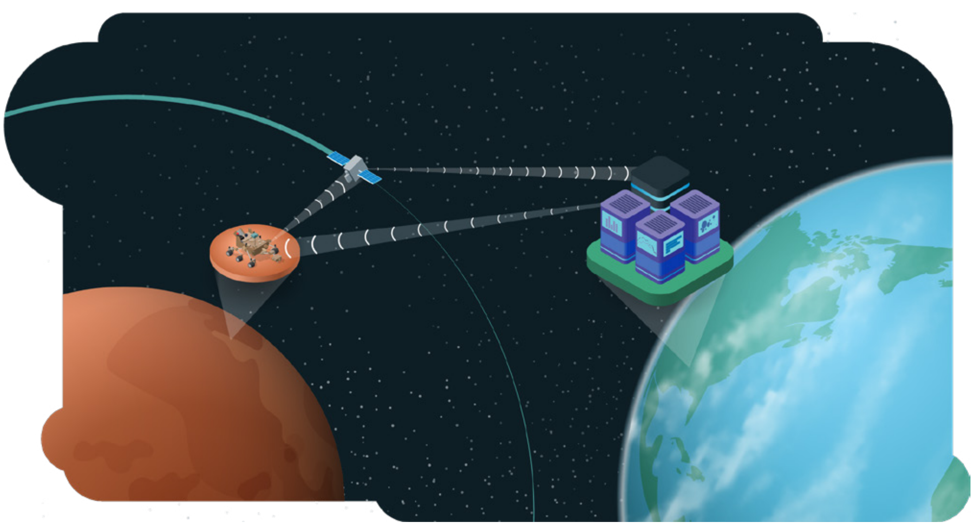

Figure 2: Autonomous communications with explorers on Mars and future planets

Autonomous technology provides the ability to perform needed tasks without assistance from Mission Control.

At NASA's Kennedy Space Center (KSC) in Cape Canaveral, Florida, large specialized teams prepare the spacecraft, payloads, launch and ground systems infrastructure for missions to the ISS and future gateways and planets. Recently, this focus on autonomy has improved the propellant loading process. The newly developed Autonomous Operations System (AOS), a software and hardware solution, can execute cryogenic propellant transfer operations autonomously. This breakthrough is scalable to on-orbit future needs and significantly reduces time, cost, and risk to support personnel and future astronauts.

Marshall Space Flight Center (MSFC) in Huntsville, Alabama, serves as the world leader in propulsion, space transportation and launch vehicles, space systems, and space scientific research. The Autonomous Mission Operations EXPRESS 2.0 Project (AMO-Express-2.0), led by MSFC and in collaboration with Ames and JSC, is an experimental concept to automate payload operations in a single command from an ISS crew member to initiate automatic configuration of a science EXPRESS Rack. Current procedures for turning on and setting up the experimental EXPRESS Racks are complex and require several synchronized steps. This project demonstrates the applicability and benefit of automation of those steps. This advancement, combined with the automation of software procedures, can help future crews manage spacecraft systems with less assistance from Earth, freeing up the crew members' time and allowing for more science exploration.

Space Science on the Edge

Performing science by robotic assistants and instruments that only send back the science, rather than the raw data, is the future for discovery and autonomous science missions. Science-on-the-edge autonomous missions will adapt to the environment and adjust to the mission parameters. The humans involved will be advised of the modifications to the mission and the science. This type of automation will significantly benefit space and space exploration systems by advancing the rate of science and reducing infrastructure systems and their subsequent costs. As we return to the Moon, prepare for longer trips through the solar system, and begin to build servicing stations throughout the solar system, we will need to rely extensively on swarms of autonomous systems to successfully execute the missions and reduce risks and costs.

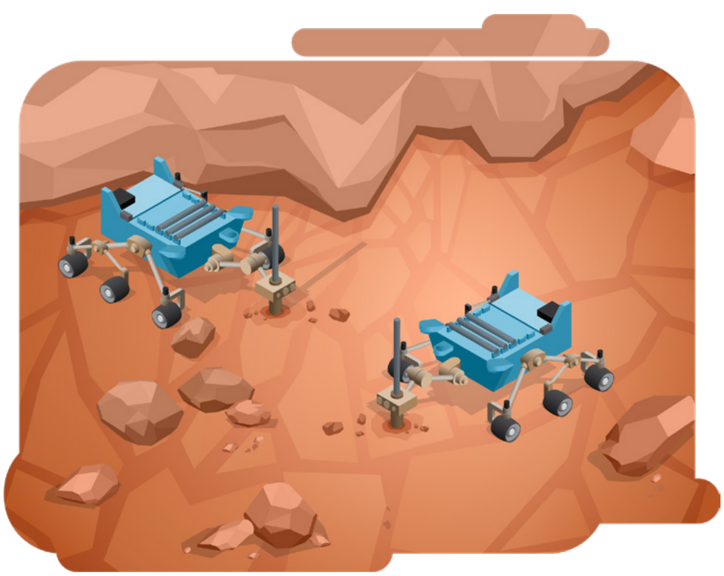

Figure 3: Autonomous robotics working collaboratively

Demonstrating science on the edge, the Air Force Research Laboratory and its partners have created a virtual robotic development and test environment where creative robots can be designed, trained and tested in representative mission environments. Using an application called CSMARRT (Creative, Self-Learning, Multi-Sensory, Adaptive, Reconfigurable Robotics Toolbox), robots can be designed using a newly invented form of Extensible Markup Language (XML) called Robotic Markup Language (RML). With RML, robot designers may specify the structure and mechanics of physical robotic systems as well as their neural networks. Once constructed, these virtual robots can be imported into various learning environments where they can autonomously develop movement strategies, schemes for integrating sensor signals, and creative ways of meeting their mission objectives. Alternate views within the application's Graphic User Interface (GUI) allow users to visualize how individual neural network modules have knitted themselves into complex control architectures. Using CSMARRT, completed designs can be exported to simulate a variety of physical environments. Additionally, efforts are underway to perfect the export of cultivated robotic brains from CSMARRT to a variety of embedded targets such as Field Programmable Gate Arrays (FPGAs) and Graphics Processing Units (GPUs.)

NASA's continued success in space exploration relies on the successful creation and application of low-power, small, lightweight, highly sensitive sensors. A 3D printed sensor technology that uses miniaturization to create a detector platform to fill this need is another example of the value from science on the edge. Using a $2M technology award at NASA's Goddard Space Flight Center, NASA technologist Mahmooda Sultana and team have been advancing this autonomous, multifunctional sensor platform that benefits major scientific efforts to send humans to the Moon and Mars. These tiny platforms can be used on autonomous planetary rovers to detect small quantities of water and methane and monitor biological sensors for astronaut health and safety. The 3D printing will allow technicians to print a suite of sensors on each platform, rather than one at a time, thus simplifying the process.

On-Orbit Servicing and Assembly

Astronauts tethered to the ISS or outside the ISS performing spacewalks to service satellites or the station present one of the most significant safety challenges and high risks to humans in space. Swarms of autonomous systems and robots performing these activities are critically needed and are vital to support planned space exploration expansion initiatives. In the near future, these swarms of robotic on-orbit service agents will reduce risk by performing the space-walking tasks of today's human astronauts.

Many technologies being developed on the ISS seek to determine which maintenance and repairs can be completed satisfactorily while in orbit through the application of autonomy. The growth of low-cost launch vehicles and the expected ease of autonomous rendezvous and docking of small and midsize satellites drives a growing interest in on-orbit servicing and assembly. Autonomous on-orbit assembly overcomes many of the launch limitations on satellite size and mass. Currently, the Defense Advanced Research Projects Agency (DARPA), University of California Berkeley Space Sciences Lab (SSL), Northrop Grumman/Orbital ATK, and others have been evolving modular systems through proof-of-concept designs. Together with the efforts of collaborative standards organizations such as CONFERS, the Consultative Committee for Space Data Systems (CCSDS), and Interagency Operations Advisory Group (IOAG), the work done by these organizations will lay the foundation for the policies and frameworks that will support reconfigurable robotic technology for on-orbit assembly. A set of well-conceived industry standards in this area—currently, established industry standards are missing—could allow emerging space participants to access new markets and allow existing space participants to expand their capabilities.

Figure 4: Autonomous on-orbit docking and assembly

Fueling/Re-Fueling

The advancement of fueling/re-fueling while in orbit will be critical to accomplish extended Moon missions, Mars explorations with humans, and to explore the deepest parts of our solar system and universe.

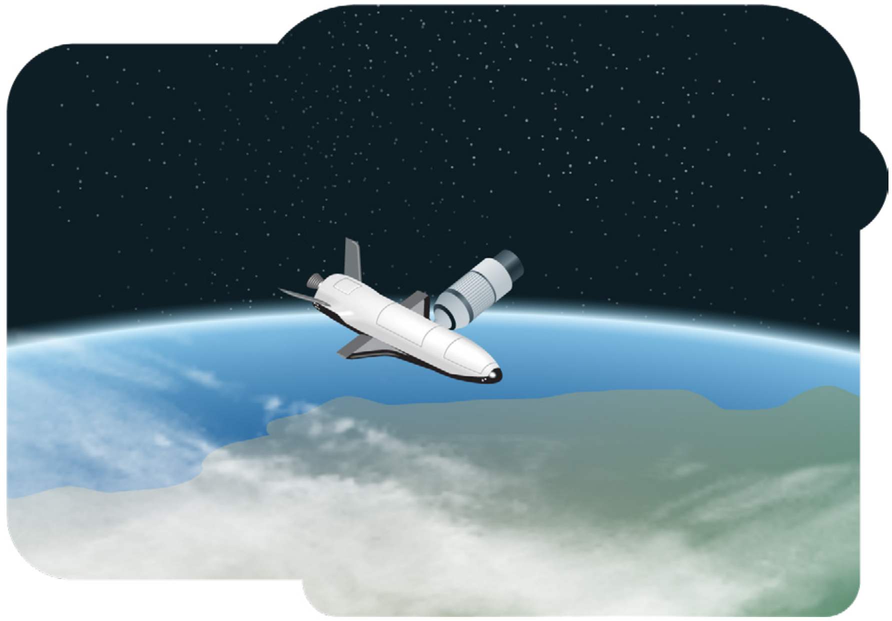

Figure 5: Autonomous on-orbit refueling

Providing autonomous robotic systems with the ability to "see" using a variety of sensors will be critical to a robot's ability to autonomously refuel orbital and interplanetary systems. Proven neural network technologies have demonstrated an ability to use a commercial webcam to replace a $20 million laser guidance system used by NASA. The Robotic Refueling Mission (RRM) investigation, expected to pave the way for future robotic servicing missions in space, uses the ISS's two-armed robotic handyman "Dextre" to show how future robots could service and refuel satellites in space. RRM tests NASA-developed technologies, tools, and procedures to refuel and repair satellites not originally designed to be serviced. The third phase of this investigation will focus specifically on servicing cryogenic fluid and xenon gas interfaces that will support future scientific missions as humans extend their exploration further into our solar system.

As we continue to push to explore Mars and beyond, teams of autonomous systems and rovers will be sent first in preparation for human arrival.

Deep Space Exploration

Preparation is underway to return to the Moon and take humans to Mars long-term. The space industry is currently building the systems that will transport astronauts from Earth to the gateway (i.e., LOP-G) near the Moon. Most of the major manufacturing for the first mission is complete. This year, teams will focus on final assembly, integration, and testing while also performing early work for future missions. NASA plans on launching in 2020 the first mission, Exploration Mission-1, to send an Orion spacecraft on the Space Launch System rocket from the modernized spaceport at KSC. This will be an unmanned test flight before sending crew around the Moon on the second mission, Exploration Mission-2 (anticipated by 2023). As we continue to push to explore Mars and beyond, teams of autonomous systems and rovers will be sent first in preparation for human arrival. These rovers will establish the needed human support systems and infrastructure (e.g., water, oxygen, shelter, communications, power) and assemble habitats for living in very hostile environments. This first phase of support, while very dangerous for humans, is ideal for swarms and teams of autonomous systems capable of making real-time decisions and changes as the environment and inputs change.

SOFTWARE DEFINED NETWORKING (SDN) FOR AUTONOMOUS SPACE COMMUNICATIONS APPLICATIONS

Traditional Internet Protocol (IP) networks are vertically integrated. Within a networking device, the control plane that decides how to handle network traffic is tightly coupled with the data plane that forwards traffic according to decisions by the control plane within a networking device. To implement a high-level network-wide policy, network operators need to configure each individual network device separately using vendor-specific command line interface (CLI) commands. Implementing automatic reconfiguration and failure response mechanisms in the control plane requires complex human expertise, including expertise and knowledge with a complex variety of protocols tightly intertwined with the associated data plane forwarding mechanism.

A new networking paradigm to remove the limitation of existing network infrastructure, SDN allows network operators to control the components of the networking environment via software rather than the traditional hardware approach. It also decouples the data and the control planes' SDN and decouples the logic that decides traffic routing from the underlying systems. SDN replaces the logic layer with a virtualized controller to enable intelligent networking. In this new architecture, network control becomes programmable, flexible, and centralized to allow the network operators to deliver new services or changes on demand. This SDN innovation provides optimized autonomous approaches for connectivity of services between network nodes, which will ensure more robust and cost effective communications and more flexible space operations and activities for next generation space systems.

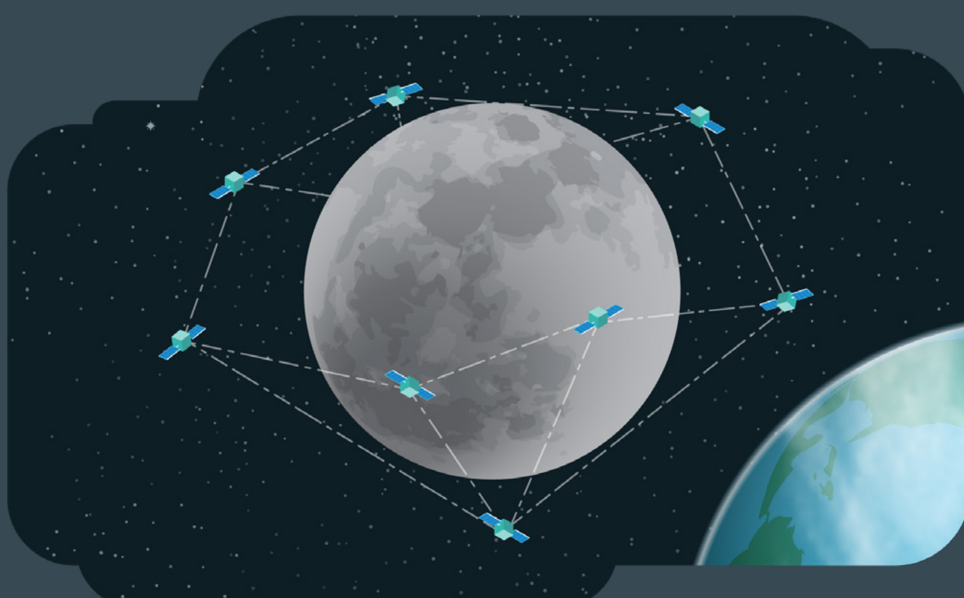

Figure 6: Swarms of autonomous communications systems

Automating SDN for Space

The development process for space systems uses a traditional system design process, involving satellite manufacturing and launch activities susceptible to cost and schedule challenges. The underlying terrestrial networks supporting connectivity between the ground segment infrastructure nodes use inflexible, static, scheduled configurations. Network engineers manually configure these at the design phase and subsequently incorporate the configurations into operating procedures—leading to high operator staffing burden, potential for error, and issues in scaling for large networks to support multi-mission constellations at a ground station. SDN controllers can be employed to apply dynamic re-routing and reconfiguration in terrestrial networks to ensure timely data flows from sources at satellite Mission Operations Control Centers (MOCs) to ground stations. Application Programming Interfaces (APIs) can be developed to communicate autonomously with the SDN controllers and the underlying satellite ground segment networking infrastructure (e.g. switches and/or routers)—automatically adjusting data flow paths from MOCs to ground stations to account for ground path loss/degradation or around unexpected weather events. APIs can override previously scheduled, lower-priority data uploads with higher-priority uplinks to a satellite as needed.

SDN principles can also be applied in the context of site diversity to execute Continuity of Business Operations (COOP) procedures. An SDN controller deployed in a high-availability configuration at a network management site, located independently of satellite ground segment nodes, can devise an effective handover decision algorithm between the primary and backup COOP sites. With SDN-enabled switches deployed at the node site, the SDN controller can automatically execute the handover of satellite engineering and support functions between sites. A handover management API communicates with the SDN controller and with the ground stations or terminals to identify active services and data flows, which maintain a satellite data processing pipeline. After handover, the API can alert the antenna crews at the backup site to change their operating frequencies and antenna alignments if needed.

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Current and future deep space missions involve communications across expansive distances, thousands to millions of miles apart. This makes normal Internet Protocol (IP) communications very complex and challenging, especially regarding delays and associated communications disruption and data loss for Inter Planetary Networking (IPN).

Delay/Disruption Tolerant Networking (DTN) addresses the technical issues related to lack of continuous network connectivity with a suite of protocols that operate in tandem with traditional IP. The DTN architecture implements a store-and-forward message switching by overlaying a new transmission protocol (referred to as the bundle protocol) on top of the IP protocol. The bundle protocol does not alter the IP protocol data; rather, it encapsulates the application protocol data into datagrams referred to as bundles. Bundles received are forwarded immediately, if possible, but are stored for future transmission if forwarding is not possible at the time. The DTN protocol suite also contains network management, security, routing, and quality-of-service capabilities to ensure the next hop is available to forward the packet.

Future deep space exploration missions will involve communications needs and data transfer between many nodes involving multiple hops via relay spacecraft or other intermediate nodes. In the United States, NASA provides communications services to support over 100 NASA and non-NASA missions, including Deep Space Network (DSN), Near Earth Network (NEN), and Space Network (SN). These networks consist of a set of distributed ground stations and space relay satellites. Using DTN routing protocols, they distribute a set of expected future inter-node contacts throughout the network. Each node uses this set to make data-forwarding decisions. All parameters in these networks are pre-determined and reactive when responding to dynamic configuration changes. The current system is planned and orchestrated—it does not know and cannot adapt to what will happen in the future. This opens an opportunity for predictive techniques to provide the first step towards autonomous spacecraft operations that allow for any future scenario.

An SDN controller provides the proactive control plane to initiate a trigger for a specific mission's spacecraft requests for communications services, including science data and payload operations. The SDN controller also provides the central intelligence

To make the leap into fully autonomous operations, the SDN controllers need to be used in combination with Artificial Intelligence (AI) with learning abilities to provide communications services and improve network efficiency while minimizing operator burden at mission control centers.

to alter protocol behavior, including forwarding paths across the multiple network layers and to tune parameters for centralized intelligent routing. In this approach, SDN controllers would be placed on the spacecrafts themselves (a future capability) and terrestrially to control ground station nodes and mission control centers. To make the leap into fully autonomous operations, the SDN controller needs to be used in combination with artificial intelligence (AI) with learning abilities in order to provide communications services and improve network efficiency while minimizing operator burden at mission control centers. There have been successful experiments in geographically distributing the neurons of a neural network, where the inter-neuron communications were done by TCP/IP connections. Future autonomous systems may be composed of distributed networks of neural networks that adaptively configure their own SDN communications in response to unforeseen events.

Considering the computational expense of AI techniques, they may not be appropriate to implement on the spacecraft itself, but rather on other space assets or nodes to support the mission. Neural network training, genetic algorithms, and other AI networking operations can happen offline at the capable nodes, such as terrestrial nodes where the SDN controller is deployed, with the results pushed to the lesser capable nodes. Learning within the network will deliver the needed service outside of the constraints of the pre-coded configurations. With the AI-optimized network strategy output, the SDN controller uses the API interface to send instructions to the affected nodes and may even add new services if desired through the API/SDN controller interface.

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With a combination of SDN and AI, the time-dynamic spatial relationships between objects can be determined. This will better optimize the node-dynamic positions and orientations, along with the modeled characteristics and pointing of sensors, communications, antenna, and payloads aboard both the spacecraft and ground stations—enabling autonomous operations of future spacecraft missions.

Potential Benefits

Advanced autonomous systems significantly improve the state of the art for space systems and can provide potential benefits, including:

- Improved performance through limited human involvement and reduced infrastructure
- Redundancy, efficiency, and ease of design through routine and duplicative systems and application of standards and protocols to ensure optimization and ease of integration
- Reduction of risk to humans in hostile environments by limiting unnecessary human involvement
- Reduced lifecycle costs in infrastructure and systems to sustain human life and operational optimization through autonomous systems working continuously.

Figure 6: Autonomous, mobile machines at scale are poised to transform human activity in a wide range of physical environments.

Challenges

Evolving to an autonomous paradigm with integrated swarms of autonomous systems working cohesively, include the following challenges:

- Human-in-the-loop culture shift and autonomous science on the edge (e.g., new roles, responsibilities and authorities):
  - Relinquishing authority and control in dangerous or hostile environments
  - Increasing reliance on AI systems rather than humans
  - Making corrective real-time decisions and updates via AI results
  - Allowing life and safety decisions to be made by an AI system
- Collaborative development (e.g., acceptance, risk, roles):
  - Accepting commercial companies sharing in exploration
  - Sharing R&D ownership
  - Maintaining an acceptable risk posture, accepting failures and set-backs
- New processes and methods for engineering and development:
  - Allowing creative and innovative approaches and processes not aligned to "traditional" space-accepted practices
  - Increasing reliance on next generation engineering approaches (e.g., MBSE using AI, AI-to-AI system optimization) and trusting the AI
  - Developing autonomous AI industry standards

Figure 8: Future integrated operations on the surface of Mars

Conclusion

Significant investments and breakthroughs have been made across the entire space industry in the application of autonomy. These systems focus on autonomous systems at scale. Examples of research focuses include mission operations, flight operations, on-orbit assembly, power systems, space structures, habitats, fueling/refueling, communications approaches and systems, space launch and space transportation, sample return, science/in-situ analysis, and many more. The space industry stands at the forefront of the autonomy industry to ensure autonomous systems increase efficiency, reduce cost, and drive technology breakthroughs for the betterment of all.

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