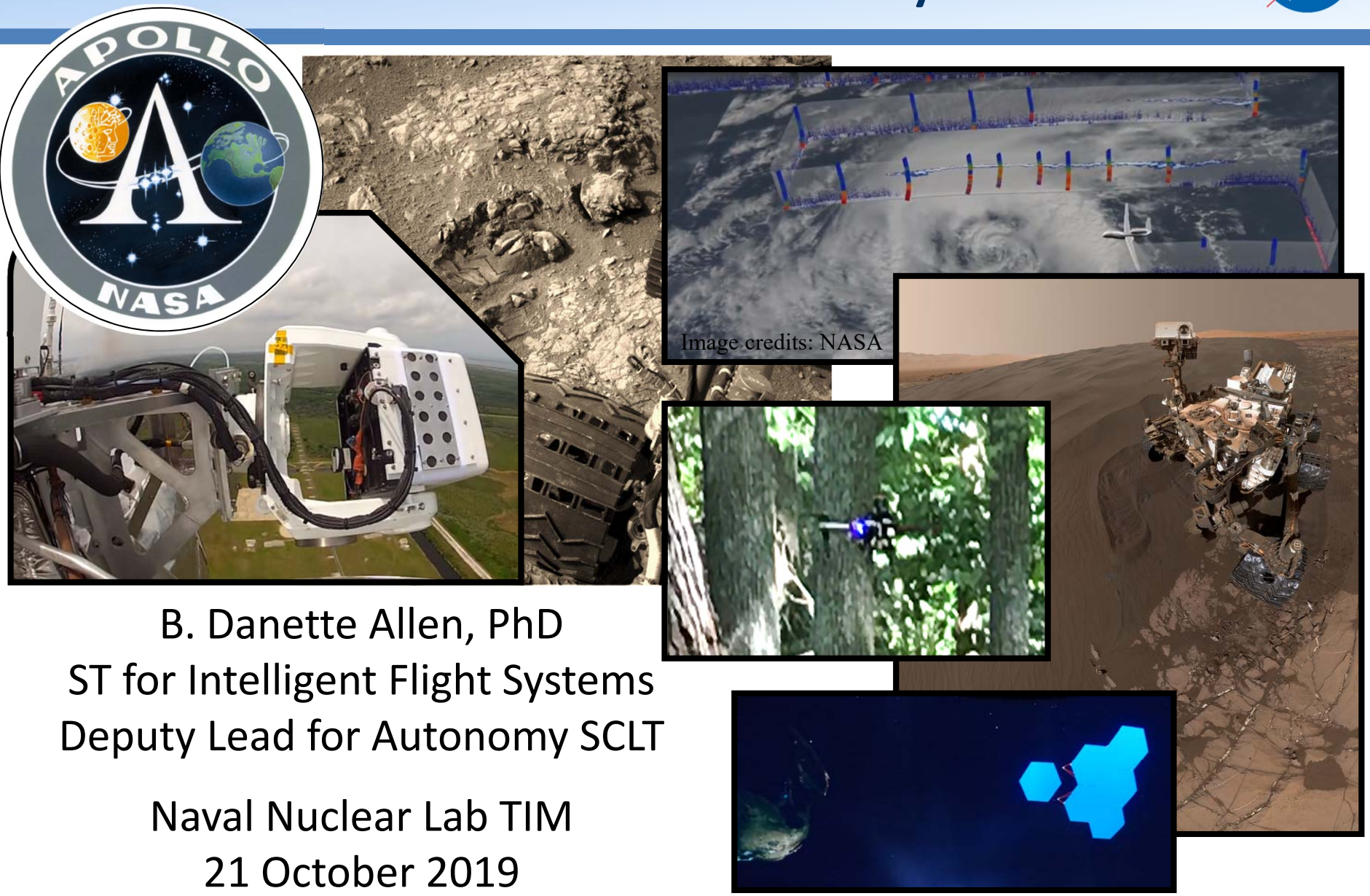
NASA Autonomy



B. Danette Allen, PhD
ST for Intelligent Flight Systems
Deputy Lead for Autonomy SCLT

Naval Nuclear Lab TIM
21 October 2019

Systems Capability Leadership Team

- Charter
  - Serve as a **community of practice** in autonomous systems
  - **Identify barriers** that impact the development and infusion of autonomy capabilities into mission systems
  - Identify and **assess the NASA workforce** and facilities needed to advance autonomous systems
  - **Recommend research and development** in autonomous systems technology for NASA
  - **Recommend investment/divestment** to improve the use of autonomous systems in aeronautics (ARMD), human exploration (HEOMD), science (SMD), and space technology (STMD)
- Team
  - Lead: **Terry Fong**
  - Deputy: **Danette Allen**
  - Members (34): Representatives from all centers and multiple disciplines including computer science, robotics, human factors, etc.

Autonomy is Cross-Cutting

Autonomy is called out in multiple NASA Technology Roadmaps

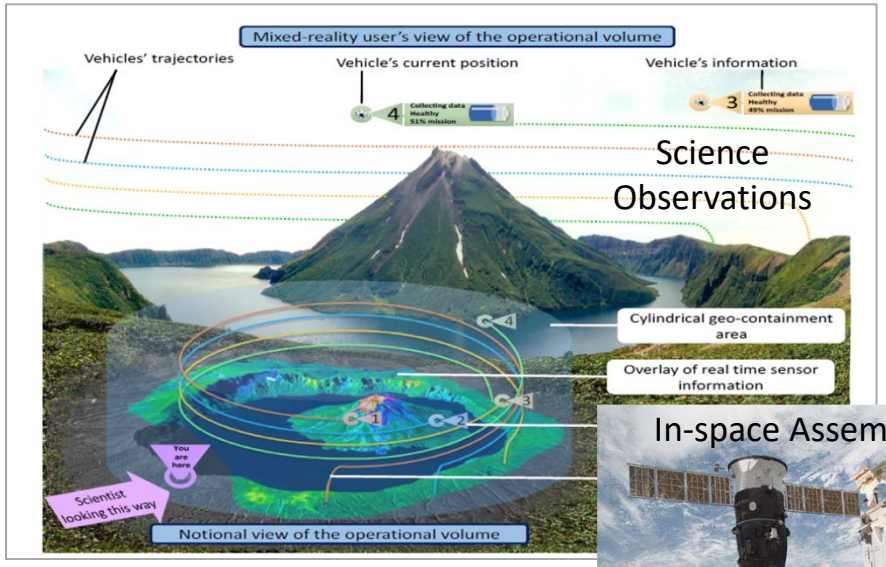




https://www.nasa.gov/offices/oct/home/roadmaps/index.html



NASA's Missions





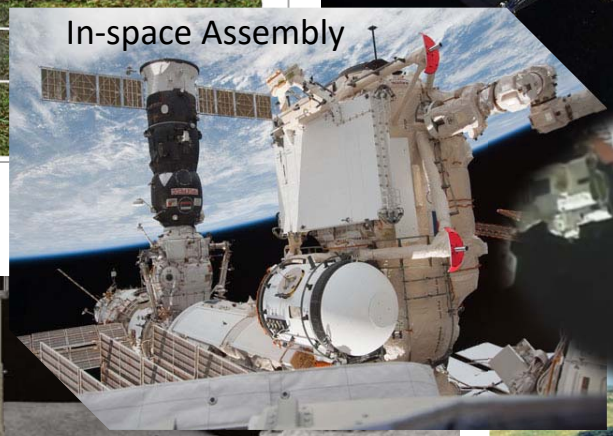
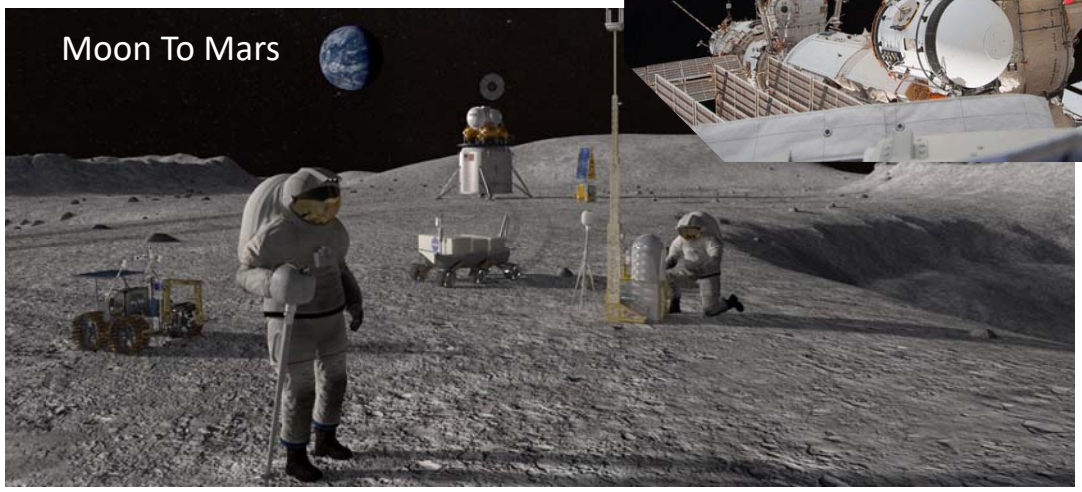
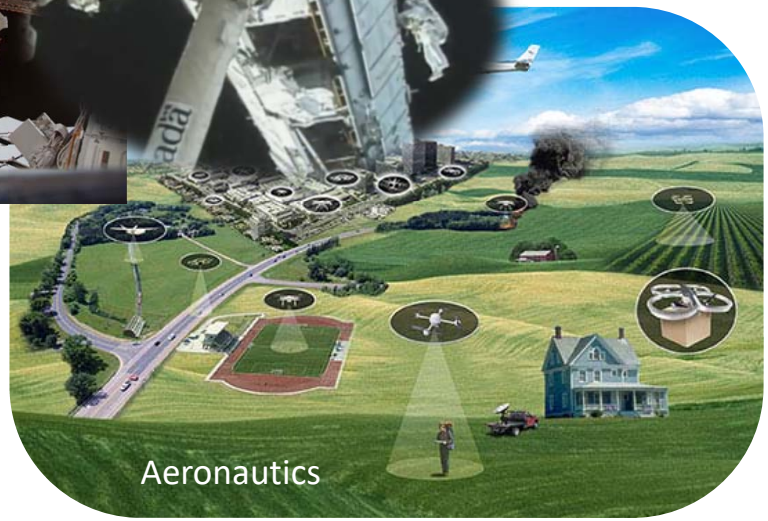


Image credits: NASA

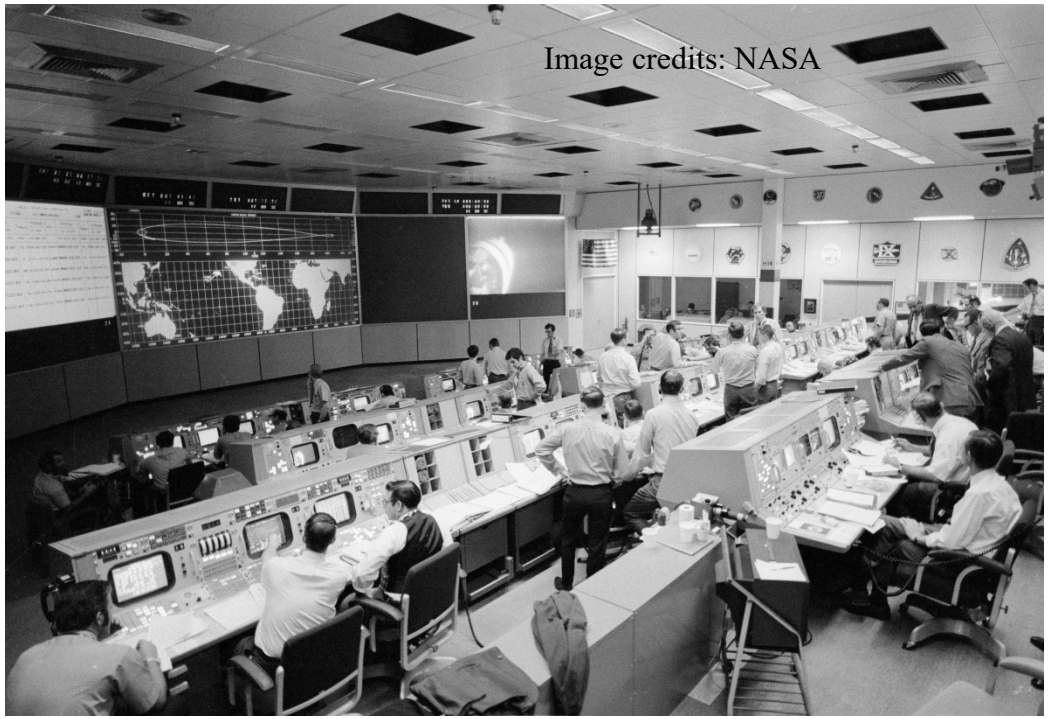




NASA's Manned Missions

- Historic and current ATM and space exploration paradigms are human-centric. Humans are aided by automation to make intelligent decisions and intervene as needed, especially in off-nominal situations.





Five of the seven Apollo missions that attempted to land on the Moon required real-time communications with controllers to succeed.

NASA's Unmanned Missions

- Historic and current ATM and space exploration paradigms are human-centric. Humans are aided by automation to make intelligent decisions and intervene as needed, especially in off-nominal situations.

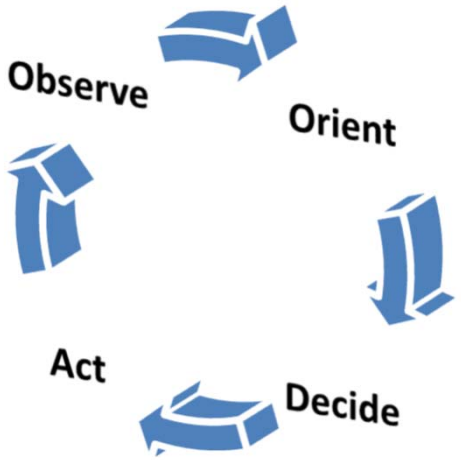

Image credits: NASA



Things have changed but...
humans are still hovering around monitors waiting to intervene.

NASA's Autonomous Missions

- **Human intelligence** applied to supervision, control, and intervention of operations will **no longer** be **viable** due to system/mission complexity, short reaction/decision time, communication delays, distance, or hostile environments.
- Systems with **machine intelligence:** capable of responding to expected and unexpected situations:
  - trusted and certified-safe systems capable of
  - sensing and perception
  - situation assessment/awareness
  - decision-making
  - taking action
  - teaming with humans
  - and knowledge acquisition (**learning**)



- AI is the "capability of computer systems to perform tasks that normally require human intelligence (e.g., perception, conversation, decision making." – Defense Science Board 2016

Machine/Artificial Intelligence

Credit: http://xkcd.com/1425/



Finding the Bird

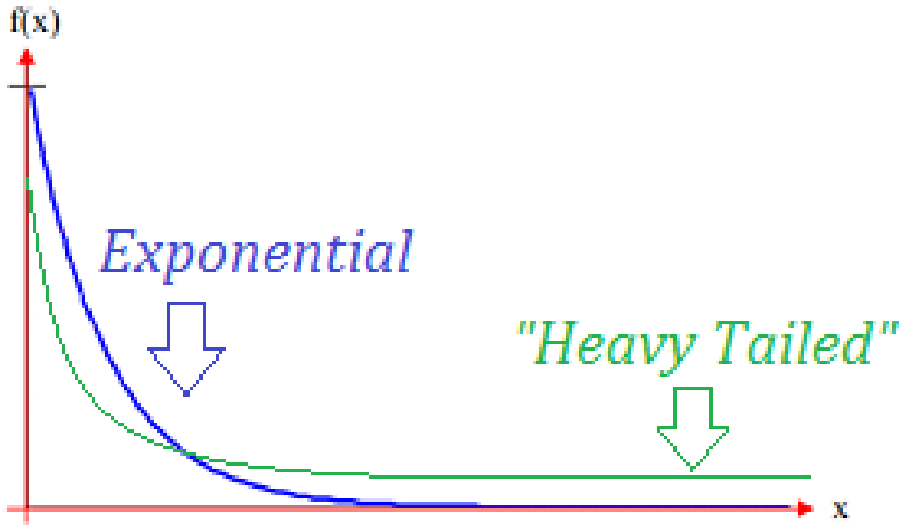


In the 60s, Marvin Minsky assigned a couple of undergrads to spend the summer programming a computer to **use a camera to identify objects** in a scene. He figured they'd have the problem solved by the end of the summer. Half a century later, we're still working on it.

This work [xkcd] is licensed under a Creative Commons Attribution-NonCommercial 2.5 License.

Why Autonomy is Hard

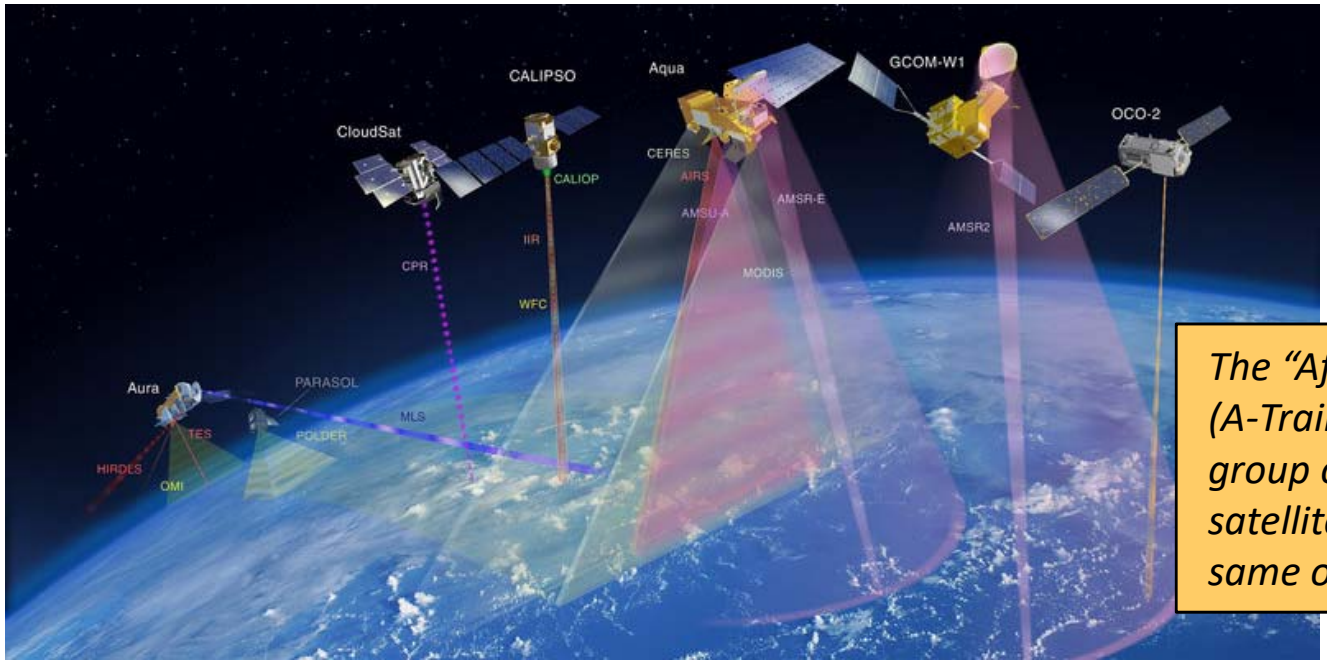
- The real world is highly uncertain and changing
  - "There are **known knowns**. There are things we know that we know. There are **known unknowns**. That is to say, there are things that we now know we don't know. But there are also **unknown unknowns**. There are things we do not know we don't know." – Donald Rumsfeld, 2002
- The real world is a heavy-tailed distribution *
  - High probability of encountering **unexpected events** when operating for a long time or when performing many activities
- All models are approximations
  - Modeling unknowns and uncertainty is really hard
  - Computation is (not yet!) instantaneous and infinite



** thoughts from Reid Simmons*

Automation

- **Automation is the automatically-controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor** *– Merriam-Webster*
- Automation is not "self-directed", but instead requires command and control (e.g., a pre-planned set of instructions)
- A system can be automated without being autonomous

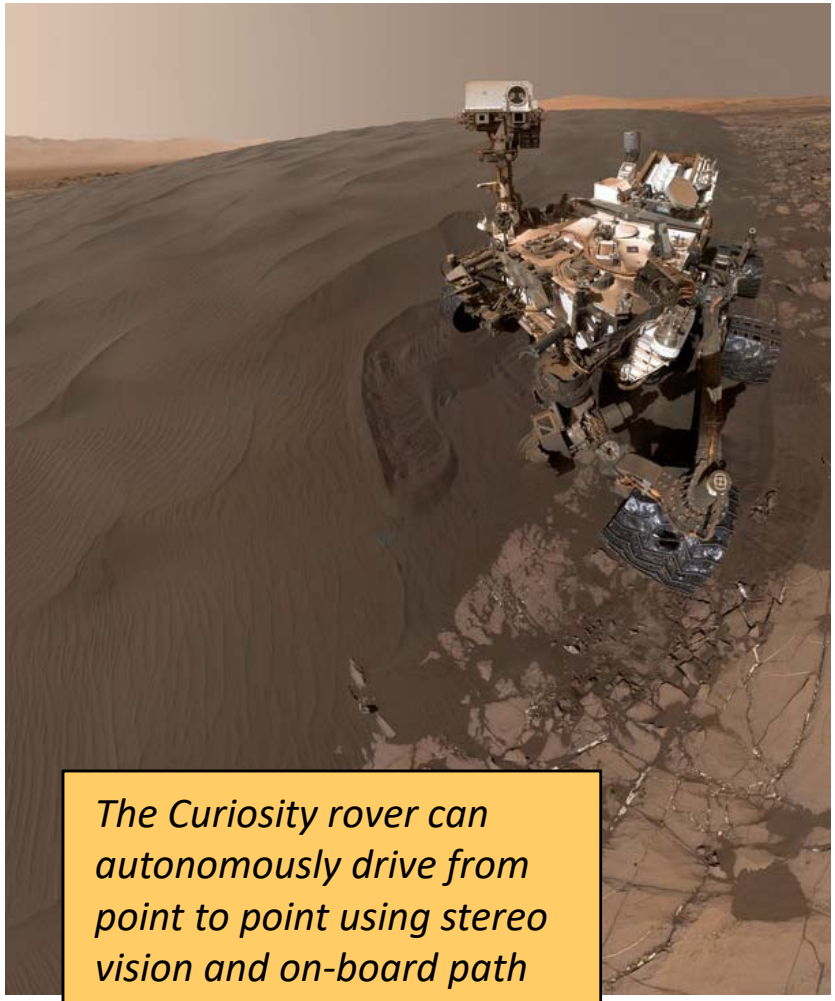


The "Afternoon Train" (A-Train) is a coordinated group of Earth observing satellites that follows the same orbital "track".

Autonomy

- **Autonomy is the ability of a system to achieve goals while operating independently of external control**.
  – *2015 NASA Technology Roadmaps*
  - Requires **self-directedness** (to achieve goals)
  - Requires **self-sufficiency** (to operate independently)

- A **system** is the combination of **elements** that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose.
  – *2016 NASA Sys. Eng. Handbook*



The Curiosity rover can autonomously drive from point to point using stereo vision and on-board path planning.

Autonomy !≡

Automation, but often relies on automation

- Most robotic space missions rely on automation
- Command sequencing (event, order, time triggered)

Artificial Intelligence, but may use AI

- Machine learning (deep learning, reinforcement learning, etc.)
- Perception (object recognition, speech recognition, vision, etc.)
- Search, probabilistic methods, classification, neural networks, etc.

“adaptive”, “intelligent”, “smart”, or “unmanned / uncrewed”

- Autonomy is about making systems **self-directed** & **self-sufficient**
- Systems **can include humans** as an integral element (human-system integration / interaction, human-autonomy teaming, etc.)
- Decision support can make **humans more independent** from other humans, systems, etc. (air traffic control, mission control, etc.)

The Automation-Autonomy Gap

Sheridan Scale

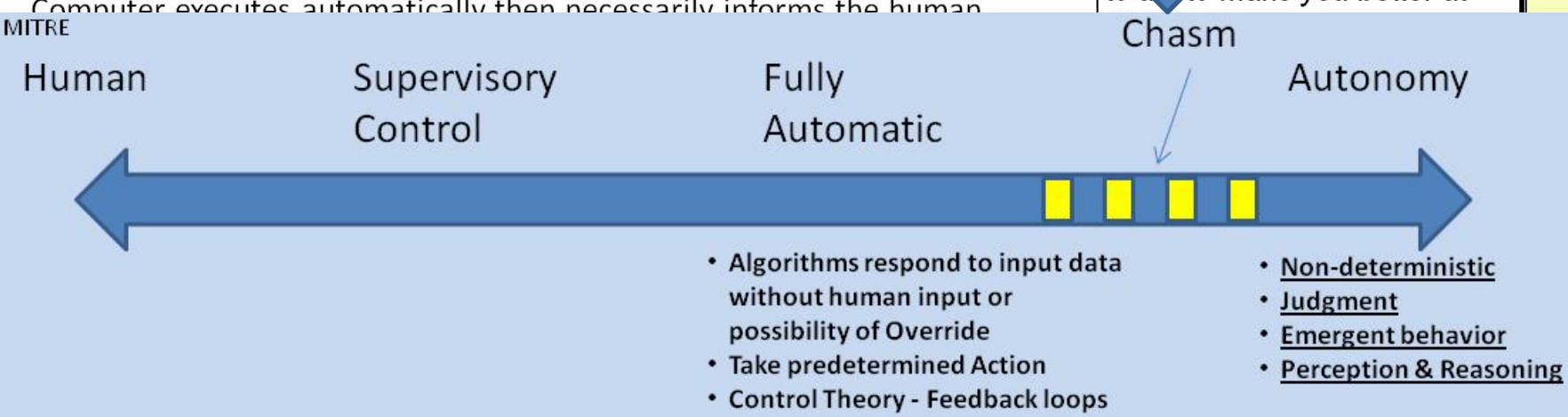
- Computer offers no assistance; human does it all
- Computer offers a complete set of action alternatives
- Computer narrows the selection down to a few choices
- Computer suggests a single action
- Computer executes that action if human approves
- Computer allows the human limited time to veto before automatic execution
- Computer executes automatically then necessarily informs the human

Decide	Act
computer performs ranking	Computer executes ...atically and does not ... any human interaction.
	...uter executes ...atically and only ...ns the human if required ...ntext. It allows for

We Are Here

to a... to *make you better* at

Credit: MITRE



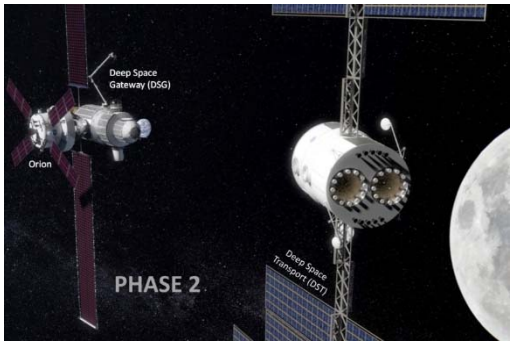
trade spaces) auton...
assist program mana...
officers and developers i...
systems. It would also ...
impact of a particular au...
are discussed further in t...

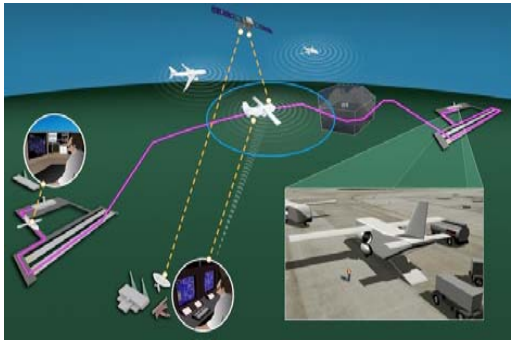
2	Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies.	Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data.	The human performs all ranking tasks, but the computer can be used as a tool for assistance.	Human is the prime source of execution, with computer shadow for contingencies.
1	Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data.	Human is responsible for analyzing all data, making predictions, and interpretation of the data.	The computer does not assist in or perform ranking tasks. Human must do it all.	Human alone can execute decision.

Autonomy is Needed…

- When the cadence of decision making exceeds **communication constraints** (delays, bandwidth, and communication windows)
- When **time-critical decisions** (control, health, life-support, etc) must be or are better made on-board the system, vehicle, etc.
- When decisions can be better made using **rich on-board data** compared to limited downlinked data (e.g., adaptive science)
- When local decisions **improve robustness** and **reduce complexity** of system architecture
- When autonomous decision making can **reduce system cost** or **improve performance**
- When **variability in training, proficiency**, etc. associated with manual control is unacceptable







Aeronautics (ARMD) Strategic Thrusts

U.S. leadership for a new era of flight

6 Strategic Thrusts



Safe, Efficient Growth in Global Operations



Transition to Alternative Propulsion and Energy



Innovation in Commercial Supersonic Aircraft



Real-Time System-Wide Safety Assurance



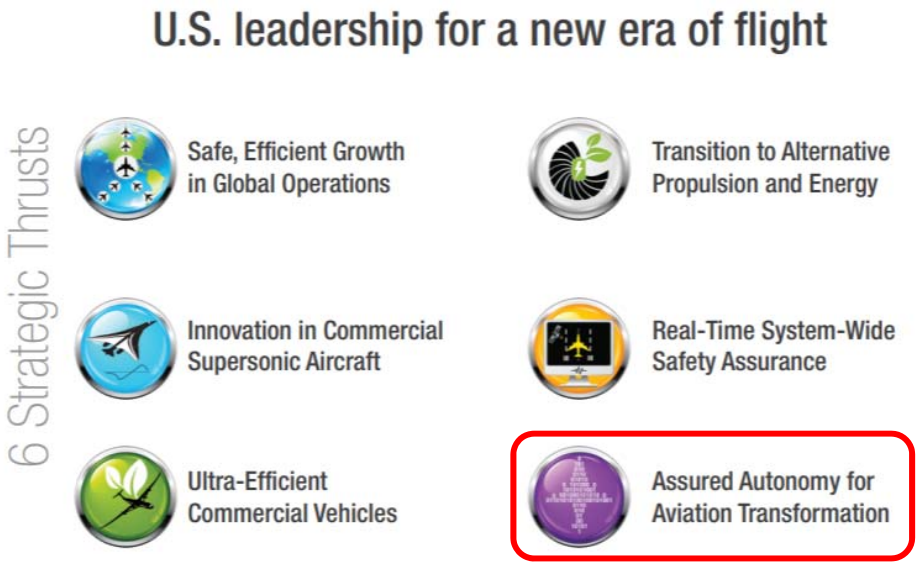
Ultra-Efficient Commercial Vehicles



Assured Autonomy for Aviation Transformation

https://www.nasa.gov/aeroresearch/strategy

Aeronautics Strategic Thrust 6







Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Ever-increasing levels of automation and autonomy are transforming aviation, and this trend will continue to accelerate. ARMD will lead in the research and development of intelligent machine systems capable of operating in complex environments, including the safe integration of UAS in the NAS. Complementary methods will provide safety assurance, verification, and validation of these systems. To pave the way for increasingly autonomous airspace and vehicles, ARMD will explore human-machine teaming strategies, and advanced metrics, models, and testbeds will enable the effective evaluation of autonomous systems in both laboratory and operational settings.

Aeronautics Strategic Thrust 6

	2015	2025	2035
Outcomes	Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals	Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals	Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals



Advanced Air Vehicles Program (AAVP)



Airspace Operations and Safety Program (AOSP)



Integrated Aviation Systems Program (IASP)



Transformative Aeronautics Concepts Program (TACP)

https://www.nasa.gov/aeroresearch/strategy

National Space Strategy

President Donald J. Trump is Unveiling an America First National Space Strategy

INFRASTRUCTURE & TECHNOLOGY | Issued on: March 23, 2018

★ ★ ★

Space Policy Directive – 1
The National Aeronautics and Space Administration (NASA) to return American astronauts to the moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.

National Space Strategy 2018
(U) **On-orbit Servicing and Manufacturing**. Explore new capabilities to **service, manufacture, and assemble space systems.**
Develop and demonstrate satellite servicing technologies to support a nascent commercial satellite industry, as well as application by NASA, DOD, and Other government agencies. Enable an industry-led consortium to establish publicly available standards and operational safeguards for commercial satellite servicing using rendezvous and proximity operations.
(U) **Lead: NASA** and DOD
(U) Supporting DOS and DOC
(U) Resources/Authorities required: NASA FY 2018 budget request of $74.0 million, **With outyear funding** / Covered under existing authorities in Title 51.
(U) Timeline: Continuous program
(U) Measure of Performance: Number of technologies developed and transferred between the government and industry; demonstration ff on-orbit mission extension, servicing, assembly, and manufacturing; and as appropriate, defined voluntary standards and operational practices for on-orbit servicing capabilities.

NASA CALLED TO LEAD IN TWO AREAS

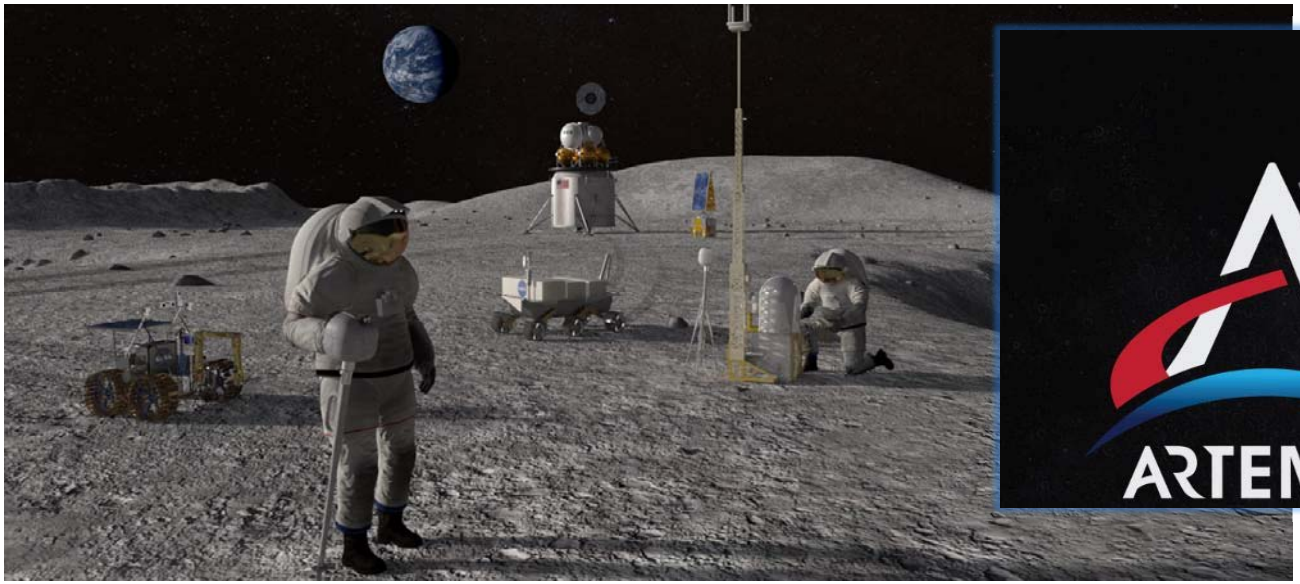
Artemis



OSAM



Exploration: Forward to the Moon and Mars

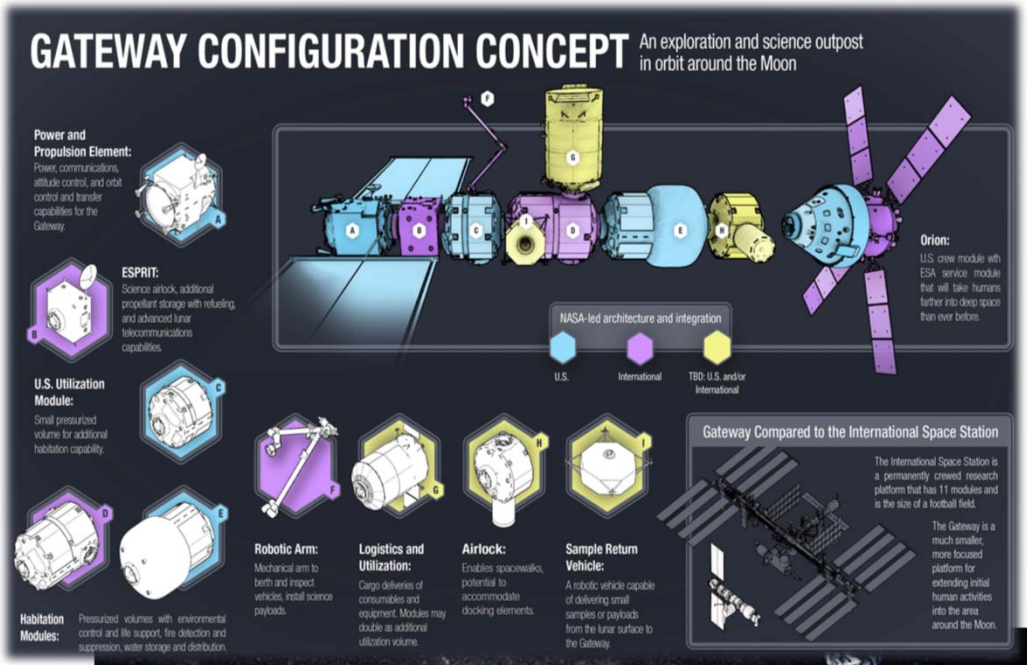






- Return astronauts to the lunar surface by 2024
  - human landing system will be launched in advance and assemble together in lunar orbit and dock to the Gateway as a single unit, ready to take astronauts down to the lunar surface.
- Establish a sustainable human lunar presence by 2028
  - autonomous rovers and robots will move around the surface.
  - print, manufacture and build with materials found on the Moon.
- Prove out the technologies that will take us to Mars (2030s) and beyond

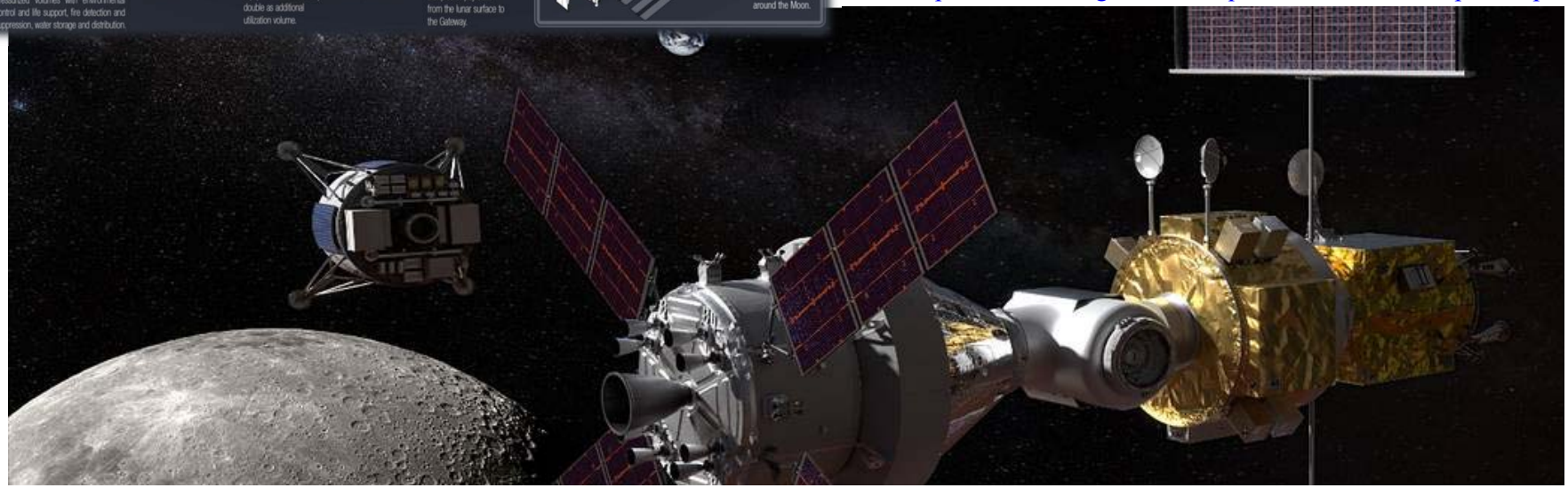
Exploration: Forward to the Moon and Mars



Gateway

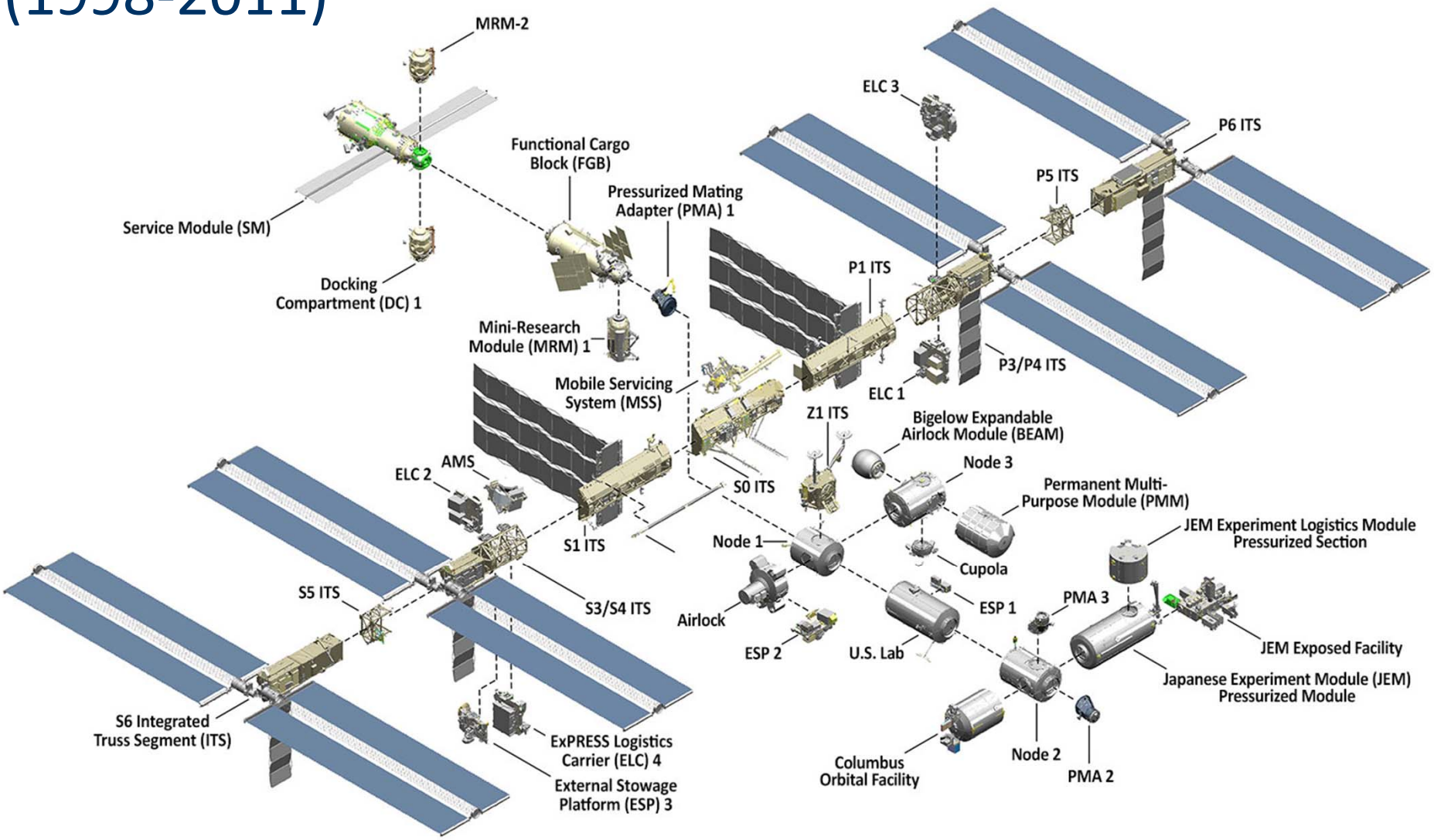
- enable a sustained presence around and on the Moon and to develop and deploy critical infrastructure required for operations on the lunar surface and deep space destinations
- requires multiple launches for assembly in space

https://www.nasa.gov/feature/questions-nasas-new-spaceship



ISS Assembled in 30+ Flights

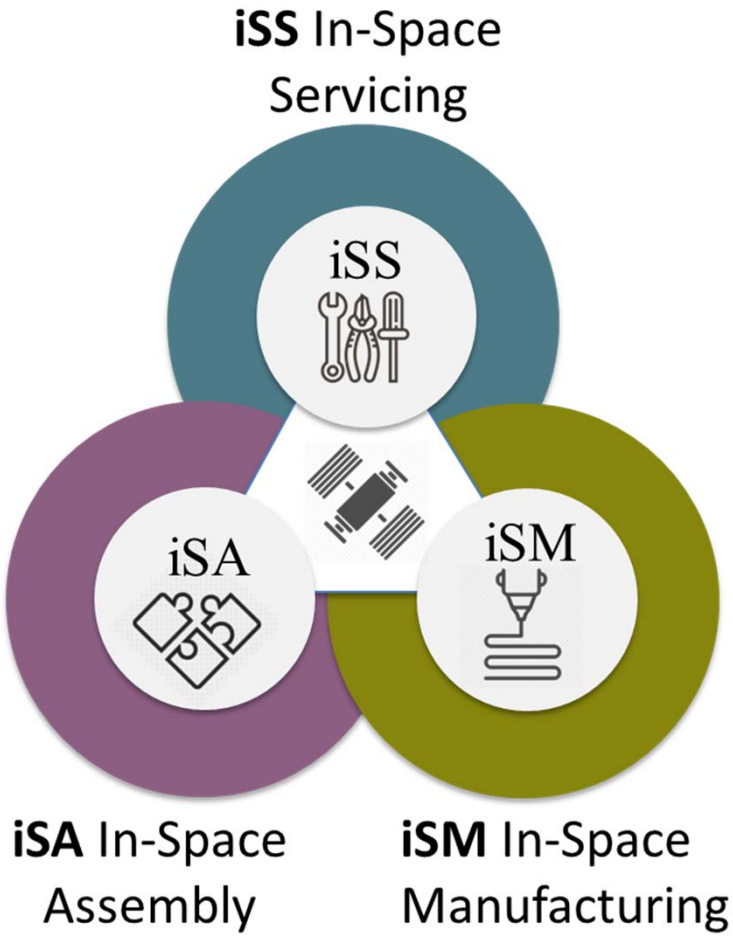
(1998-2011)



On-Orbit Servicing, Assembly, & Manufacturing

OSAM is an emerging set of capabilities that enables servicing, repair, upgrade, modular assembly, and inspection of space assets

- ***Servicing* is the on-orbit alteration** of a satellite after its initial launch using another spacecraft
- ***Assembly* involves on-orbit aggregation of components** to constitute a spacecraft into a shape or configuration that cannot be achieved with traditional deployment methods and available launch vehicles
- ***Manufacturing* involves on-orbit transformation of raw materials** into usable spacecraft components



OSAM capabilities combine multiple technologies to enable new missions previously considered impossible… and demand autonomy!

OSAM: In-Space Assembly (ISA)

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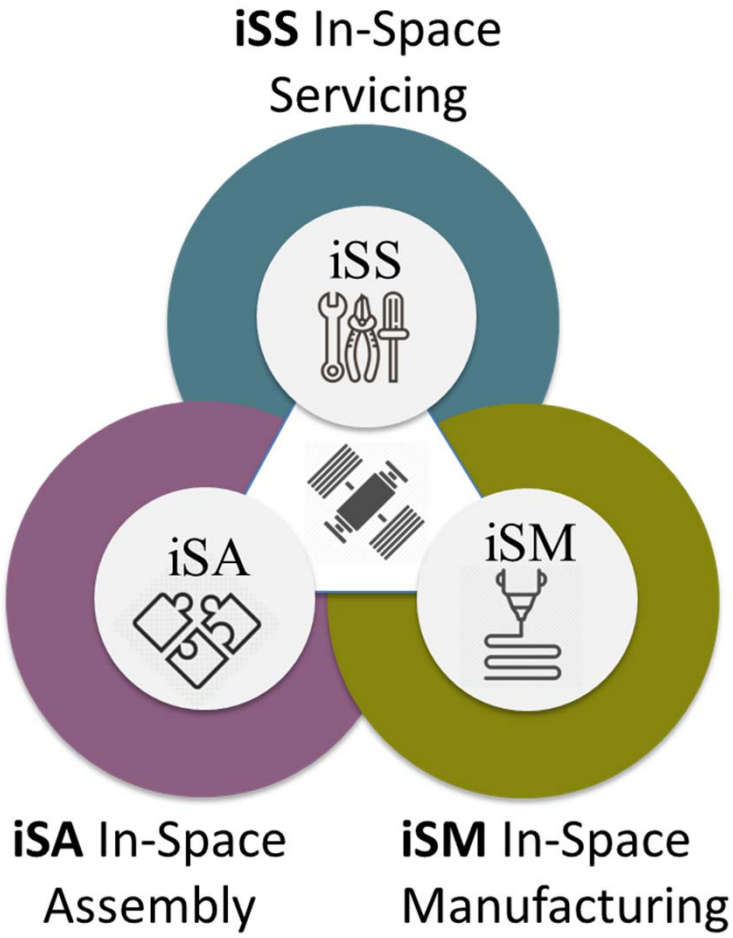

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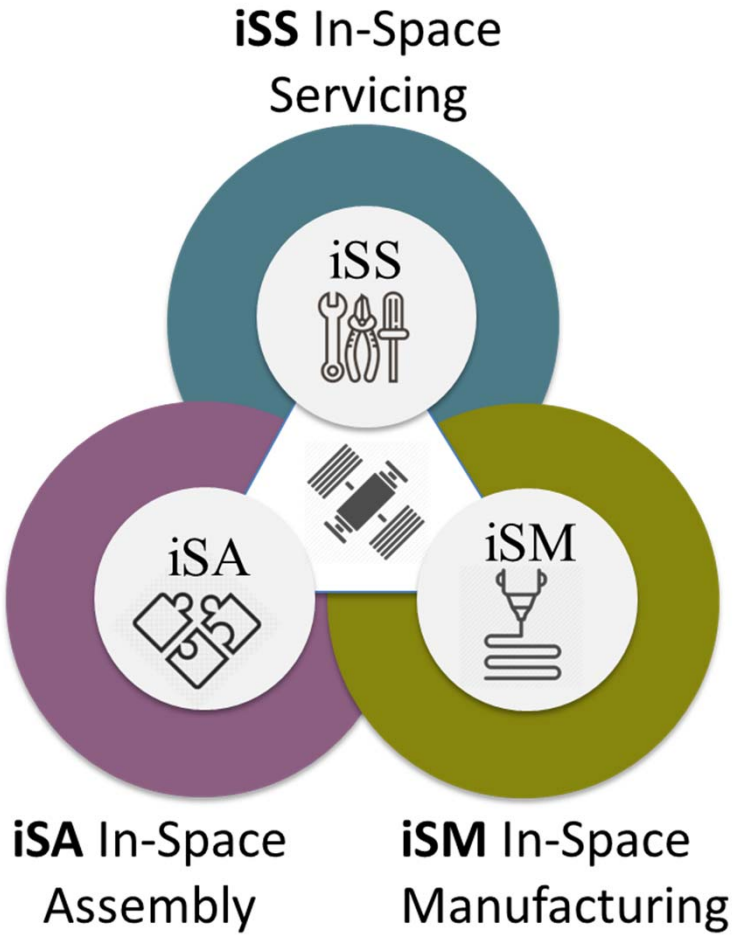

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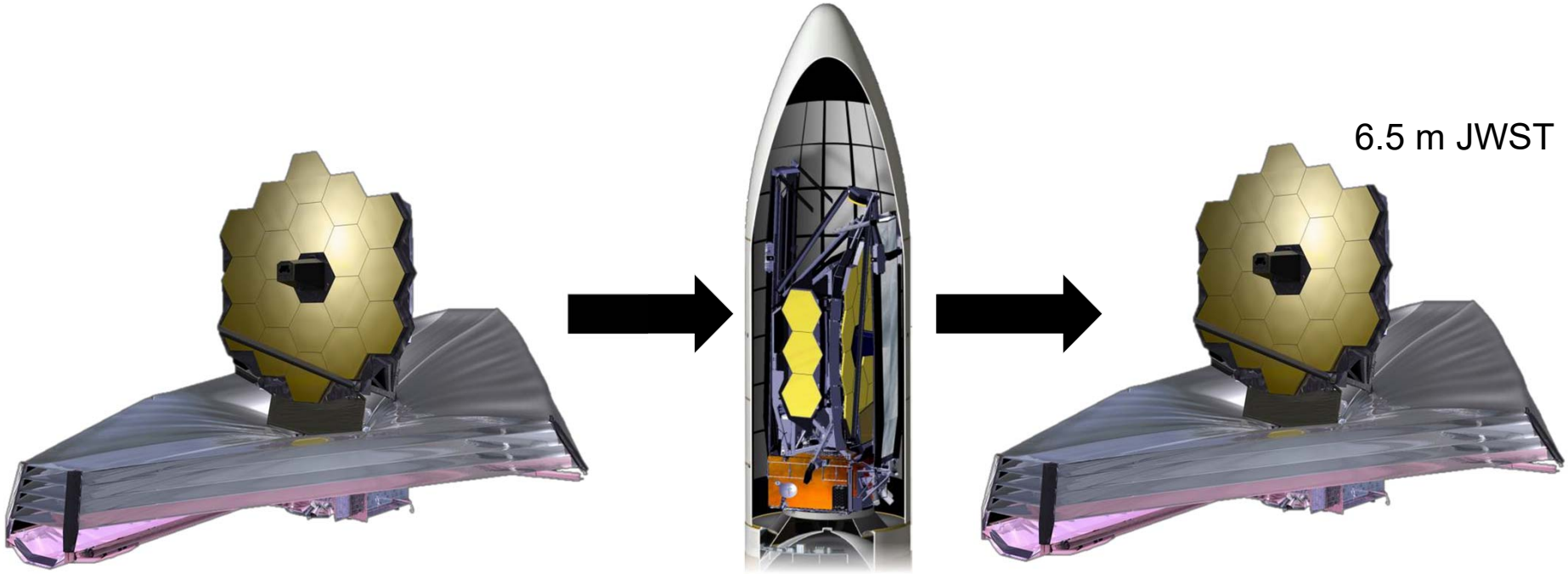
The Current Telescope Paradigm

In-Space Deployment



volume and mass constraints

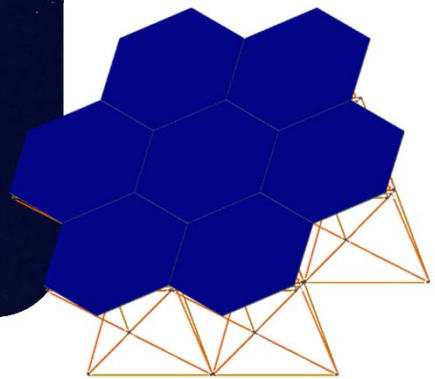
$$$

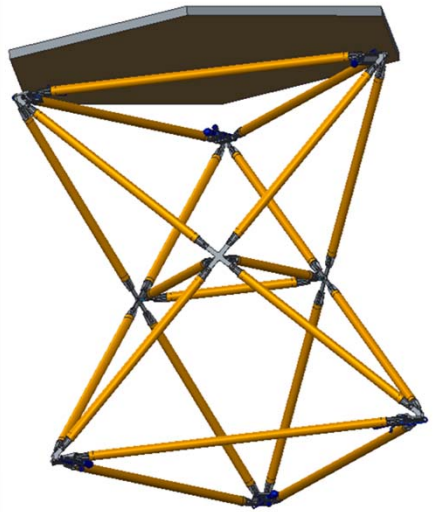
Currently, no existing LV to fly an 8 m segmented telescope

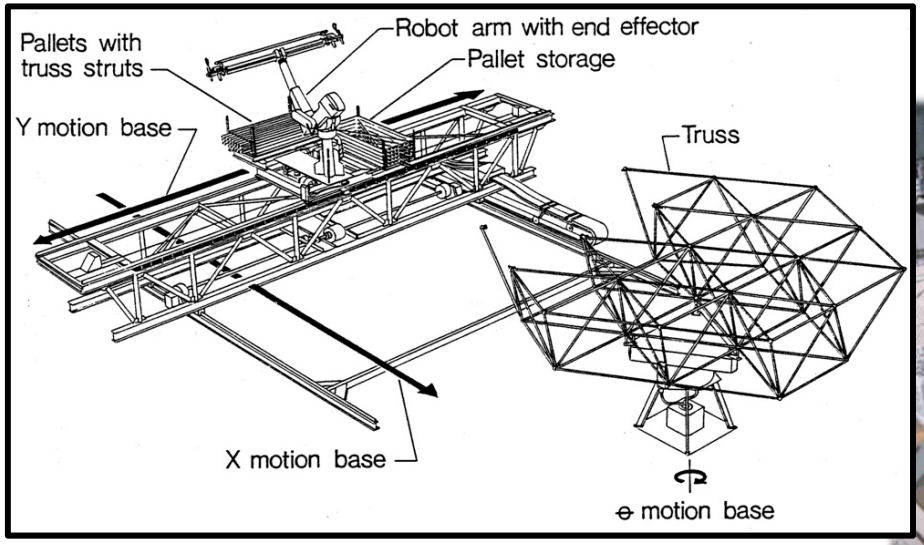
- **20 deployable events**
- **40 deployable structures**
- **178 release mechanisms**

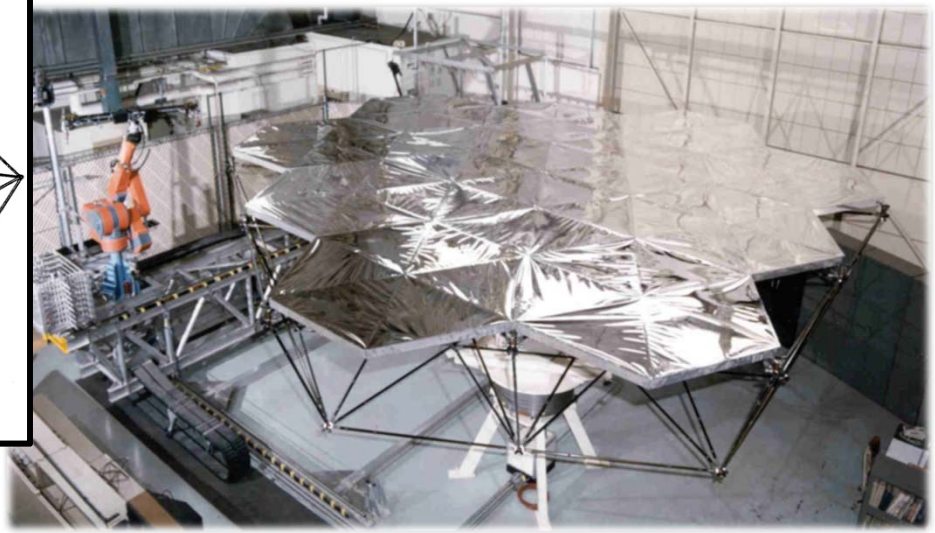
In-Space Assembly (ISA)











ISA S&T Partnership and OSAM

On-orbit Servicing, Assembly, & Manufacturing

Science and Technology (S&T) Partnership Forum

- Established in 2015
- Interagency collaboration NASA/USAF/NRO
- Focus
  - In-Space Assembly
  - Trusted Autonomy



https://www.nasa.gov/offices/oct/science-and-technology-partnership-forum.html

National OSAM Initiative

- Mission:
  - Serve as NASA's and the nation's steward for OSAM capability development and mission execution, and as a central hub for engaging the broader OSAM stakeholder community
- Objectives:
  - Facilitate Relationships
  - Develop and Share Technology
  - Advance New Concepts and Capabilities
  - Serve as a Knowledge Center

ISA Capability Needs

1. Deployable modules
2. Structural assembly
3. Connecting utilities
4. Ability to disjoin
5. Sensing, Modeling, Simulation, and Verification
6. Interoperability
7. Automation/Autonomy
8. Precision
9. Adaptive correction
10. Design
11. Tunability
12. Stability
13. Standard interfaces
14. Docking/berthing

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1.1 Deployable su

1.2 Inflatable com

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2.9 Ability to asse (e.g. Moon, Mars)

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2.11 Conductive he

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3.1 Ability to route assembled joints

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4. Ability to disjoin

4.1 Ability to rever and fluid connections.

4.2 Ability to disconnect structural, electrical, and fluid connections without propagating damage to other system components.

alter a build-up in errors.

arts capable of s spectrum of design

tries, systems, and mensional or mass

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power and data with active

TBD sensors for metry.

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approaches with well-characterized properties.

8. Precision

8.1 Jigging and joining processes capable of achieving a high level of precision open-loop.

8.2 Known precision limits of any and all assembly agent elements across the assembly site's environmental envelope

14. Docking/Berthing

14.1 Soft docking / berthing of modules

https://www.nasa.gov/sites/default/files/atoms/files/snt_partnership_1_-_aiaa_space_2018.pdf

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Autonomy-enabling capabilities across other Capability Needs

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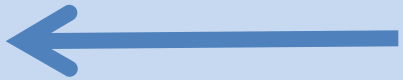
13. Standard interfaces
14. Docking/berthing



1. Deployable modules

1.1 Deployable su

1.2 Inflatable com

2. Structural Assembly

2.1 Robotic assem

2.2 Long-reach ma

2.3 Ability to asse

2.4 Ability to asse

2.5 Ability to asse

2.6 Ability to asse joints

2.7 Ability to asse stability

2.8 Ability to asse control

2.9 Ability to asse (e.g. Moon, Mars)

2.10 Ability to depl fabrication proces

2.11 Conductive he

3. Connecting utilities

3.1 Ability to route assembled joints

3.2 Ability to route

3.3 Ability to route

3.4 Ability to route

4. Ability to disjoin

4.1 Ability to rever and fluid connections.

4.2 Ability to disconnect structural, electrical, and fluid connections without propagating damage to other system components.

alter a build-up in errors.

arts capable of s spectrum of design

tries, systems, and mensional or mass

e structural control.

power and data with active

TBD sensors for metry.

passive vibration

ndard mechanical, connection

approaches with well-characterized properties.

8. Precision

8.1 Jigging and joining processes capable of achieving a high level of precision open-loop.

8.2 Known precision limits of any and all assembly agent elements across the assembly site's environmental envelope

14. Docking/Berthing

14.1 Soft docking / berthing of modules

https://www.nasa.gov/sites/default/files/atoms/files/snt_partnership_1_-_aiaa_space_2018.pdf

ISA Capability Needs

1. Deployable modules
2. Structural assembly
3. Connecting utilities
4. Ability to disjoin
5. Sensing, Modeling, Simulation, and Verification

7. Automation / Autonomy	Ability to perform tasks and assess situation for decision making with minimal or no human input
7.1 Intelligence to make stereotyped decisions correctly without human input	Software to automate assembly operations short of full autonomy, minimal adaptability to unexpected situations
7.2 Intelligence for full autonomy	
7.3 Fail-safe modes of behavior on failure detection	Ability to detect problems and move into "safe mode" to foreclose additional problems
7.4 Multi-agent autonomy (distributed situation assessment & coordinated control)	Ability of multiple autonomous agents to develop common situation state estimate & develop appropriate cooperative plans of action w/out requiring massive real-time data links between agents

14. Docking/berthing

Autonomous System Capability Taxonomy

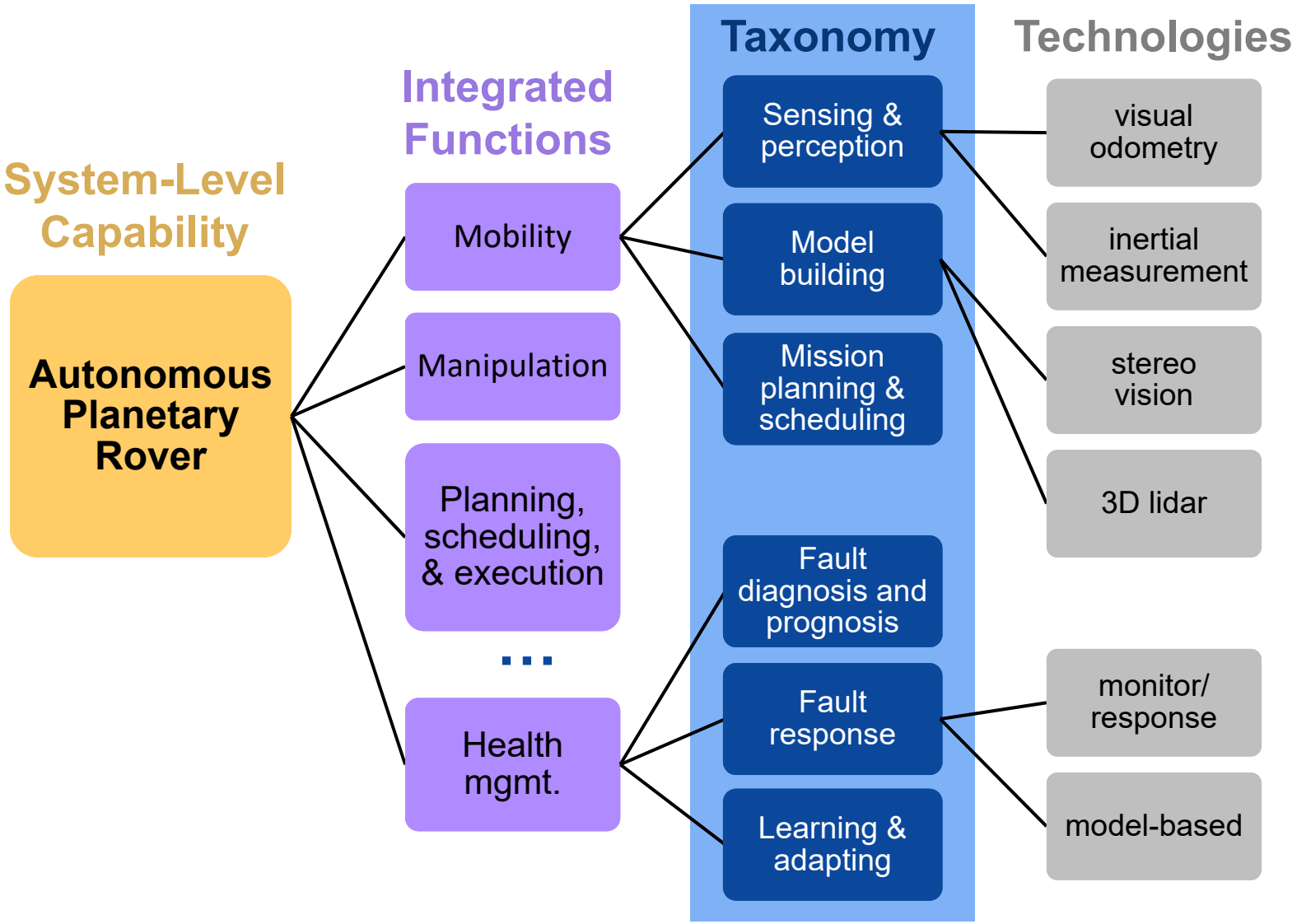


- **1.0 Situation and Self Awareness**
  - 1.1 Sensing and Perception
  - 1.2 State Estimation and Monitoring
  - 1.3 Knowledge and Model Building
  - 1.4 Hazard Assessment
  - 1.5 Event and Trend Identification
  - 1.6 Anomaly Detection
- **2.0 Reasoning and Acting**
  - 2.1 Mission Planning
  - 2.2 Activity and Resource Planning and Scheduling
  - 2.3 Motion Planning
  - 2.4 Execution and Control
  - 2.5 Fault Diagnosis and Prognosis
  - 2.6 Fault Response
  - 2.7 Learning and Adapting
- **3.0 Collaboration and Interaction**
  - 3.1 Joint Knowledge and Understanding
  - 3.2 Behavior and Intent Prediction
  - 3.3 Goal and Task Negotiation
  - 3.4 Operational Trust Building
- **4.0 Engineering and Integrity**
  - 4.1 Verification and Validation
  - 4.2 Test and Evaluation
  - 4.3 Operational Assurance
  - 4.4 Modeling and Simulation
  - 4.5 Architecture and Design

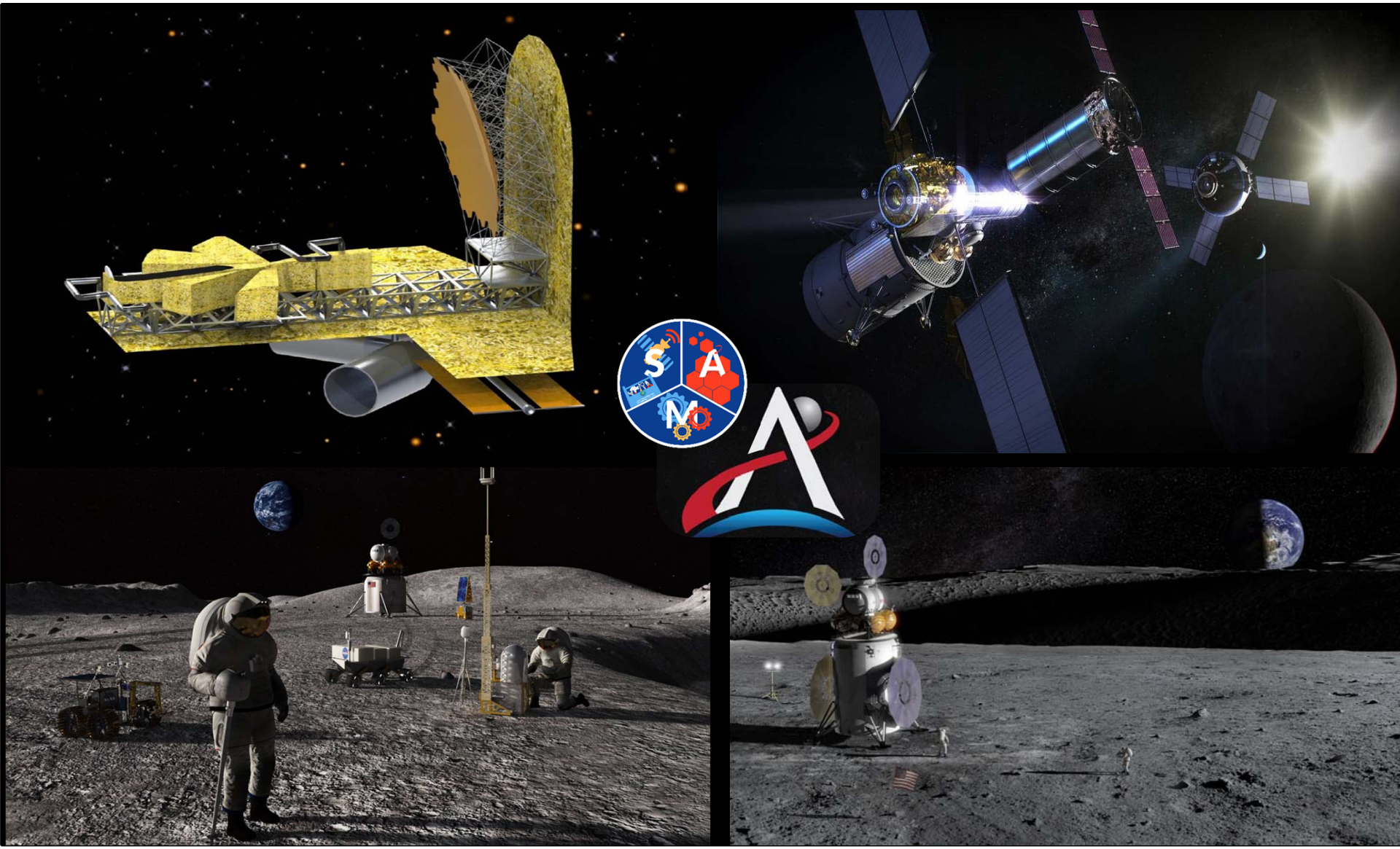
Released 2018-04-26

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180003082.pdf

Mapping Capability to Taxonomy



Performance, Pace, & Persistence In Space



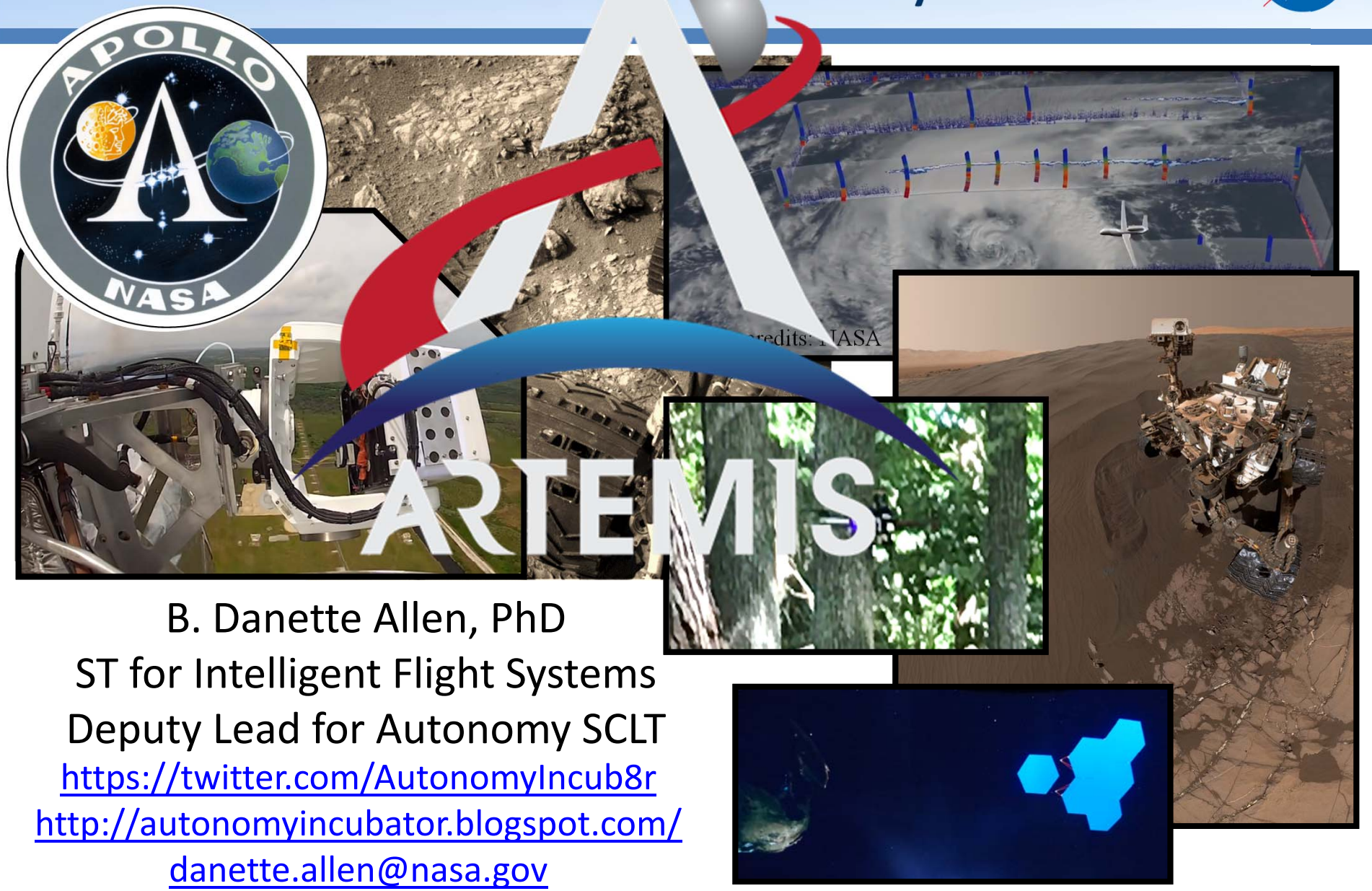
Trusted Autonomy S&T Partnership Forum

- Trusted autonomy refers to self-sustaining and reliable technologies that are certified for mission use. Autonomous technologies will
  - perform mission tasks
  - run spacecraft systems and make changes to operations

  without input from humans or computers.
- Trusted Autonomy necessary to enable
  - crewed missions to Mars because of communications delays, making Earth-based decision-making impractical.
  - advanced technologies such as in-space assembly and satellite servicing.
- NASA's Office of the Chief Technologist (OCT) and the U.S. Air Force Space Command hosted a technology interchange meeting at NASA HQ on Oct. 8-9, 2019

https://www.nasa.gov/offices/oct/feature/Trusted_Autonomy_for_the_Moon_and_Mars

NASA Autonomy



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