National Aeronautics and Space Administration

On-orbit Servicing Assembly and Manufacturing (OSAM)
Technology Transfer Workshop

Journeying Longer and Seeing Farther

Sept 22-23, 2020

OSAM Autonomy

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ST for Intelligent Flight Systems
Deputy Lead for Autonomous Systems SCLT

National Space Strategy 2018

NASA CALLED TO LEAD IN TWO AREAS

The National Space Strategy identifies NASA/DOD as the OSAM leads for the Nation

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

INFRASTRUCTURE & TECHNOLOGY | Issued on: March 23, 2018

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.

1. Exploration

2. OSAM

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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

Courtesy of Keith Belvin, NASA LaRC

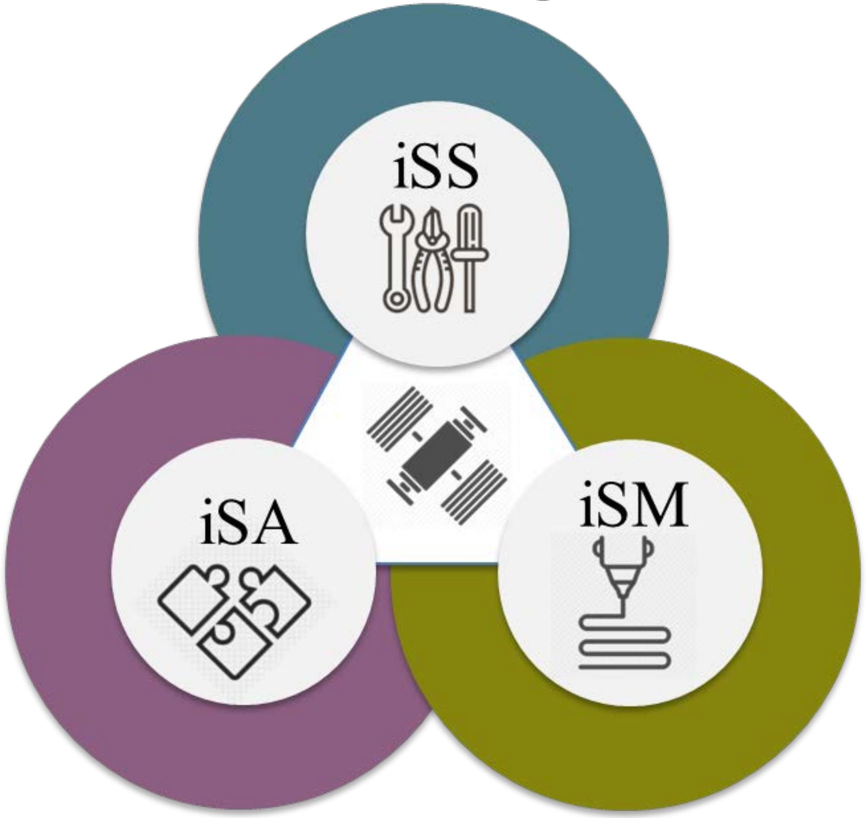
OSAM

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…

iSS In-Space Servicing



iSA In-Space Assembly

iSM In-Space Manufacturing

OSAM: In-Space Assembly (ISA)

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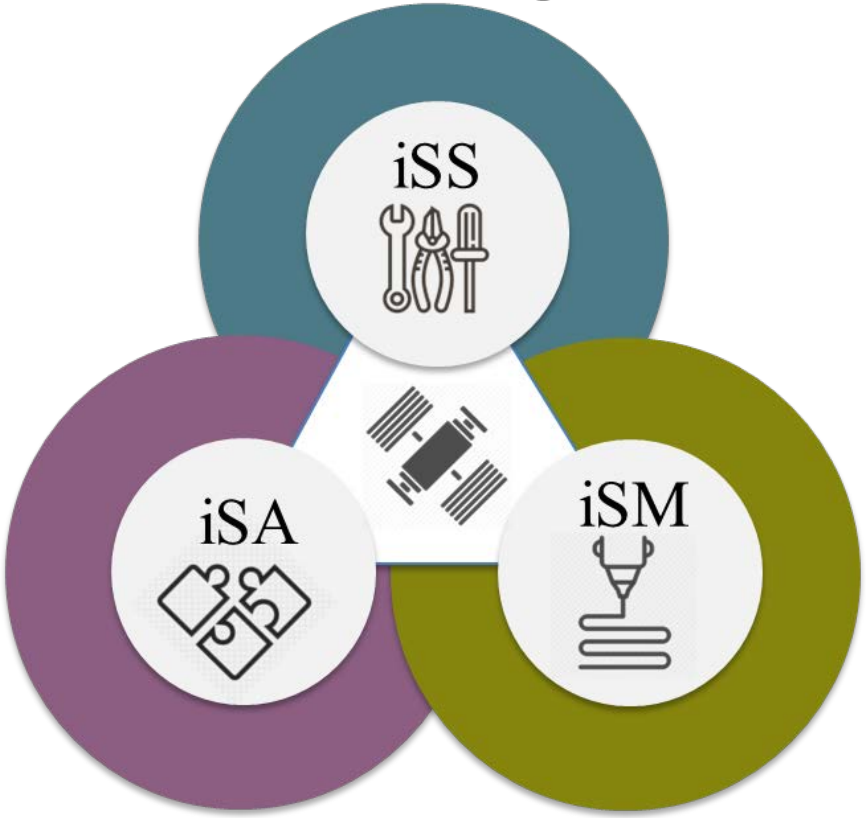

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OSAM: AUTONOMOUS In-Space Assembly (ISA)

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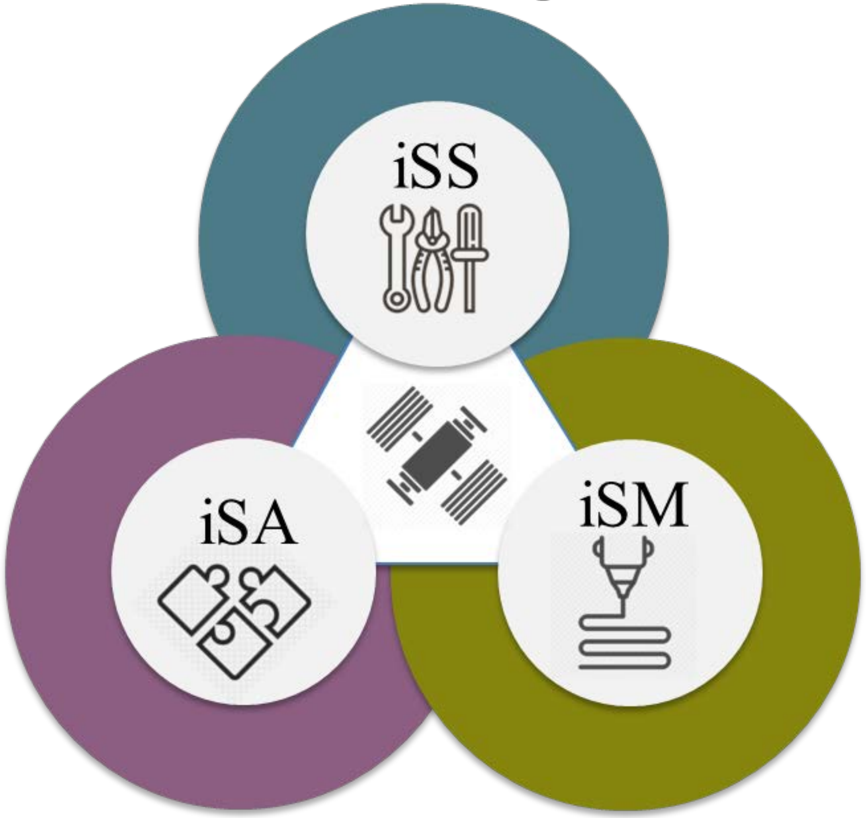

iSA In-Space Assembly

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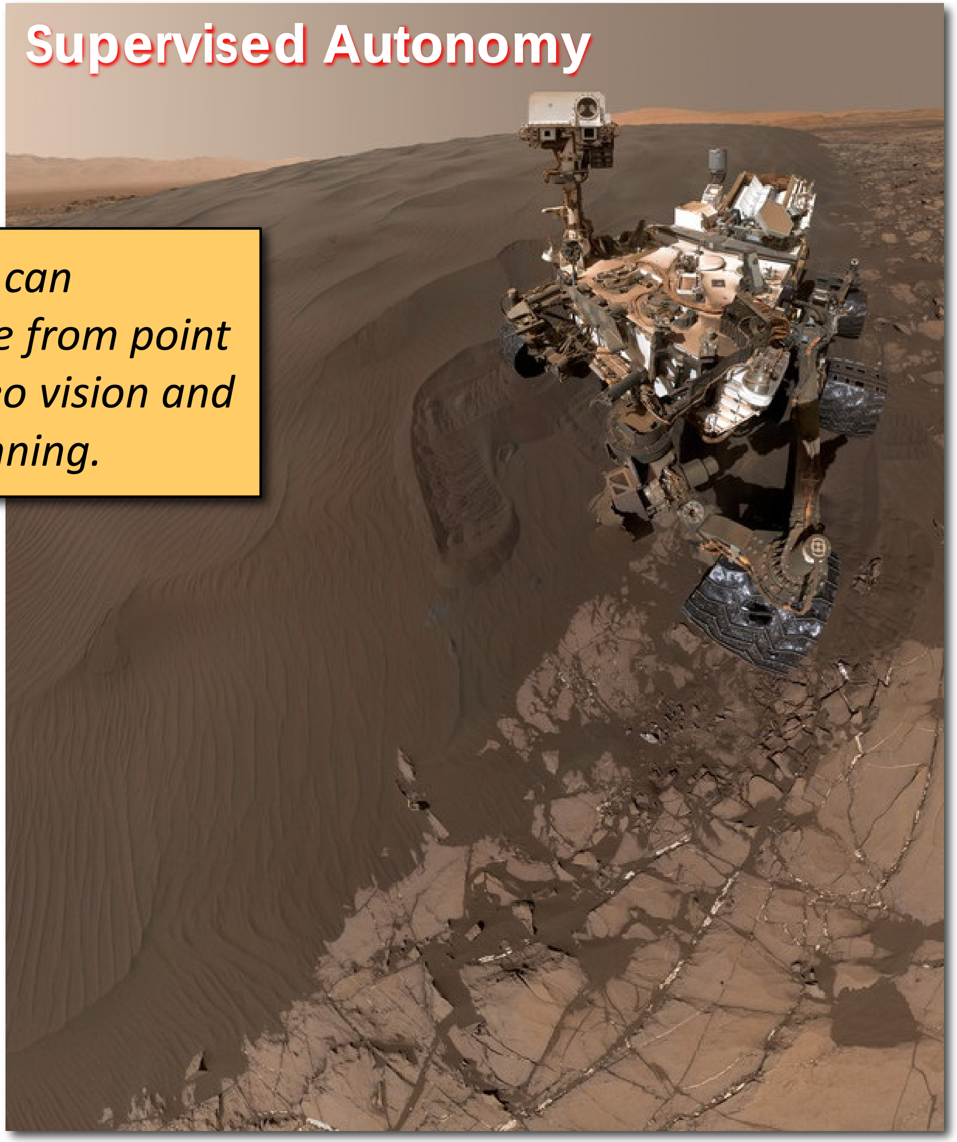
Autonomy in Decision-Making

- **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.



Autonomous Systems are Cross-Cutting

TX01 Propulsion Systems
- 1.1 Chemical Space Propulsion
- 1.2 Electric Space Propulsion
- 1.3 Aero Propulsion
- 1.4 Advanced Propulsion

TX02 Flight Computing and Avionics
- 2.1 Avionics Component Technologies
- 2.2 Avionics Systems and Subsystems
- 2.3 Avionics Tools, Models, and Analysis

TX03 Aerospace Power and Energy Storage
- 3.1 Power Generation and Energy Conversion
- 3.2 Energy Storage
- 3.3 Power Management and Distribution

TX04 Robotic Systems
- 4.1 Sensing and Perception
- 4.2 Mobility
- 4.3 Manipulation
- 4.4 Human-Robot Interaction
- 4.5 Autonomous Rendezvous and Docking
- 4.6 Robotics Integration

TX05 Communications, Navigation, and Orbital Debris Tracking/Characterization Systems
- 5.1 Optical Communications
- 5.2 Radio Frequency
- 5.3 Internetworking
- 5.4 Network Provided Position, Navigation, and Timing
- 5.5 Revolutionary Communications Technologies
- 5.6 Networking and Ground Based Orbital Debris Tracking and Management
- 5.7 Acoustic Communications

TX06 Human Health, Life Support, and Habitation Systems
- 6.1 Environmental Control and Life Support Systems and Habitation Systems
- 6.2 Extravehicular Activity Systems
- 6.3 Human Health and Performance
- 6.4 Environmental Monitoring, Safety, and Emergency Response
- 6.5 Radiation
- 6.6 Human Systems Integration

TX07 Exploration Destination Systems
- 7.1 In-Situ Resource Utilization
- 7.2 Mission Infrastructure, Sustainability, and Supportability
- 7.3 Mission Operations and Safety

TX08 Sensors and Instruments
- 8.1 Remote Sensing Instruments and Sensors
- 8.2 Observatories
- 8.3 In-Situ Instruments and Sensors

TX09 Entry, Descent, and Landing
- 9.1 Aeroassist and Atmospheric Entry
- 9.2 Descent
- 9.3 Landing
- 9.4 Vehicle Systems

TX10 Autonomous Systems
- 10.1 Situational and Self Awareness
- 10.2 Reasoning and Acting
- 10.3 Collaboration and Interaction
- 10.4 Engineering and Integrity

TX11 Software, Modeling, Simulation, and Information Processing
- 11.1 Software Development, Engineering, and Integrity
- 11.2 Modeling
- 11.3 Simulation
- 11.4 Information Processing
- 11.5 Mission Architecture, Systems Analysis, and Concept Development
- 11.6 Ground Computing

TX12 Materials, Structures, Mechanical Systems, and Manufacturing
- 12.1 Materials
- 12.2 Structures
- 12.3 Mechanical Systems
- 12.4 Manufacturing
- 12.5 Structural Dynamics

TX13 Ground, Test, and Surface Systems
- 13.1 Infrastructure Optimization
- 13.2 Test and Qualification
- 13.3 Assembly, Integration, and Launch
- 13.4 Mission Success Technologies

TX14 Thermal Management Systems
- 14.1 Cryogenic Systems
- 14.2 Thermal Control Components and Systems
- 14.3 Thermal Protection Components and Systems

TX15 Flight Vehicle Systems
- 15.1 Aerosciences
- 15.2 Flight Mechanics

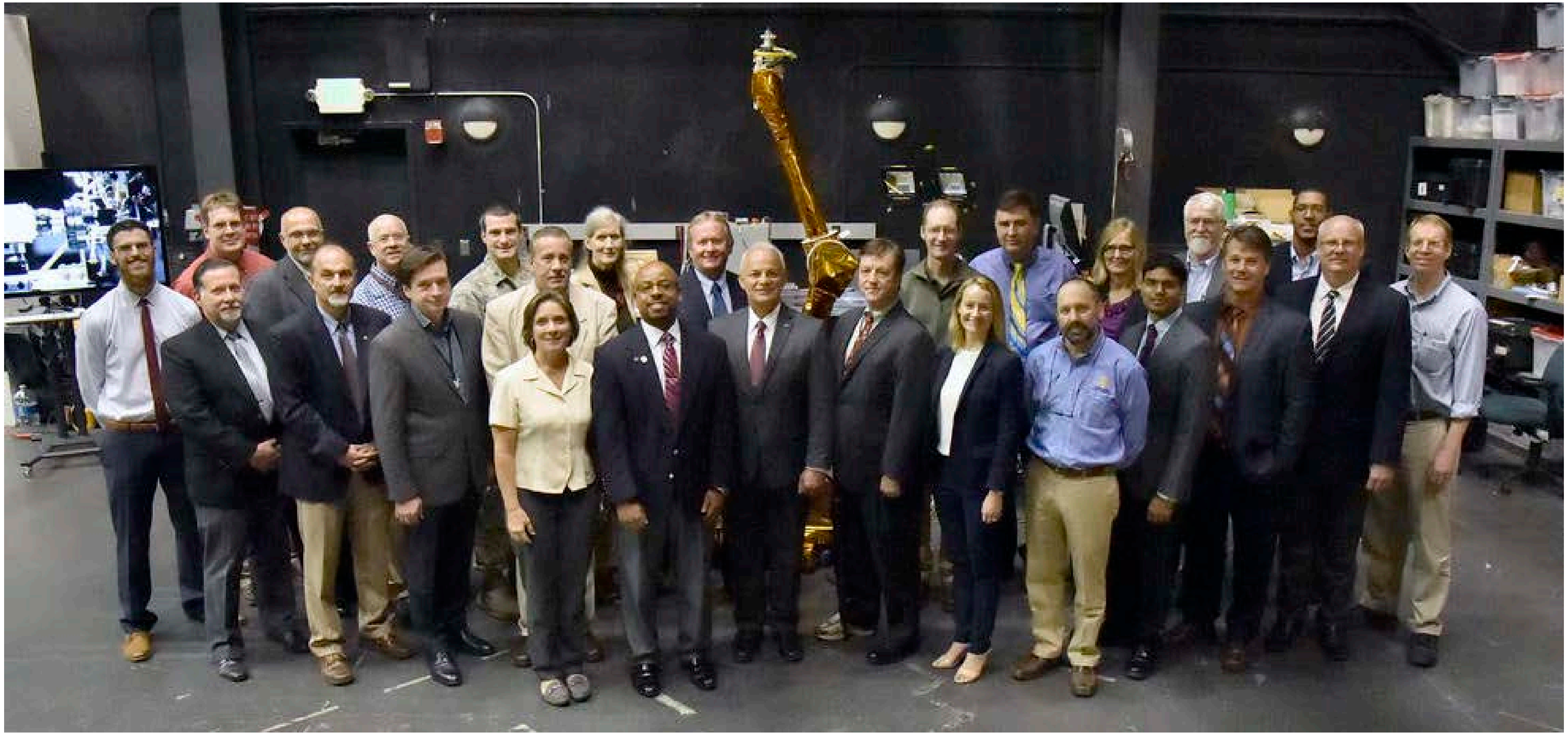
TX16 Air Traffic Management and Range Tracking Systems
- 16.1 Safe All Vehicle Access
- 16.2 Weather/Environment
- 16.3 Traffic Management Concepts
- 16.4 Architectures and Infrastructure
- 16.5 Range Tracking, Surveillance, and Flight Safety Technologies
- 16.6 Integrated Modeling, Simulation, and Testing

TX17 Guidance, Navigation, and Control (GN&C)
- 17.1 Guidance and Targeting Algorithms
- 17.2 Navigation Technologies
- 17.3 Control Technologies
- 17.4 Attitude Estimation Technologies
- 17.5 GNC Systems Engineering Technologies
- 17.6 Technologies for Aircraft Trajectory Generation, Management, and Optimization for Airspace Operations

Autonomy is pervasive throughout the 2020 NASA Technology Taxonomy and called out specifically in multiple NASA Technology Roadmaps

https://www.nasa.gov/offices/oct/taxonomy/index.html

ISA S&T Partnership Forum



- Working together to identify common needs and capabilities for ISA
  - Opening the doors to assembling habitats away from the safe harbor of low-Earth orbit and building large telescopes

In-Space Assembled Telescope (iSAT) Study

- Enabling the next generation of large space telescopes in space
- iSAT asked "When is it worth assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from a single launch vehicle?"

When is it Worth Assembling Observatories in Space?
Astro 2020 APC Whitepaper, R Mukherjee et al. 2019

Step 1	Step 2	Step 3	Step 4	Step 5
Reference Telescope Architecture & Modularization Selection	Trade Space Analyses and Concept of Operations Selection	Qualitative Cost and Risk Analysis of ISA	Grass Roots Concept Project Planning	Quantitative Analyses of ISA Costs

The Five Steps of the NASA iSAT Study

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The Five Steps of the NASA iSAT Study

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

1. Deployable modules
1.1 Deployable su
1.2 Inflatable com
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2.2 Long-reach ma
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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.

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

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.
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 - Autonomy

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Autonomy-enabling capabilities across all Capability Needs

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ISA Capability Needs – Automation / Autonomy

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document approved for public release

ISA Capability Needs – Automation / Autonomy

1. Deployable modules
2. Structural assembly
3. Connecting utilities

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

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NASA's Autonomous Systems Capability Taxonomy

1. 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. Reasoning and Acting

- 2.1 Mission Planning & Scheduling
- 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. 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. Engineering and Integrity

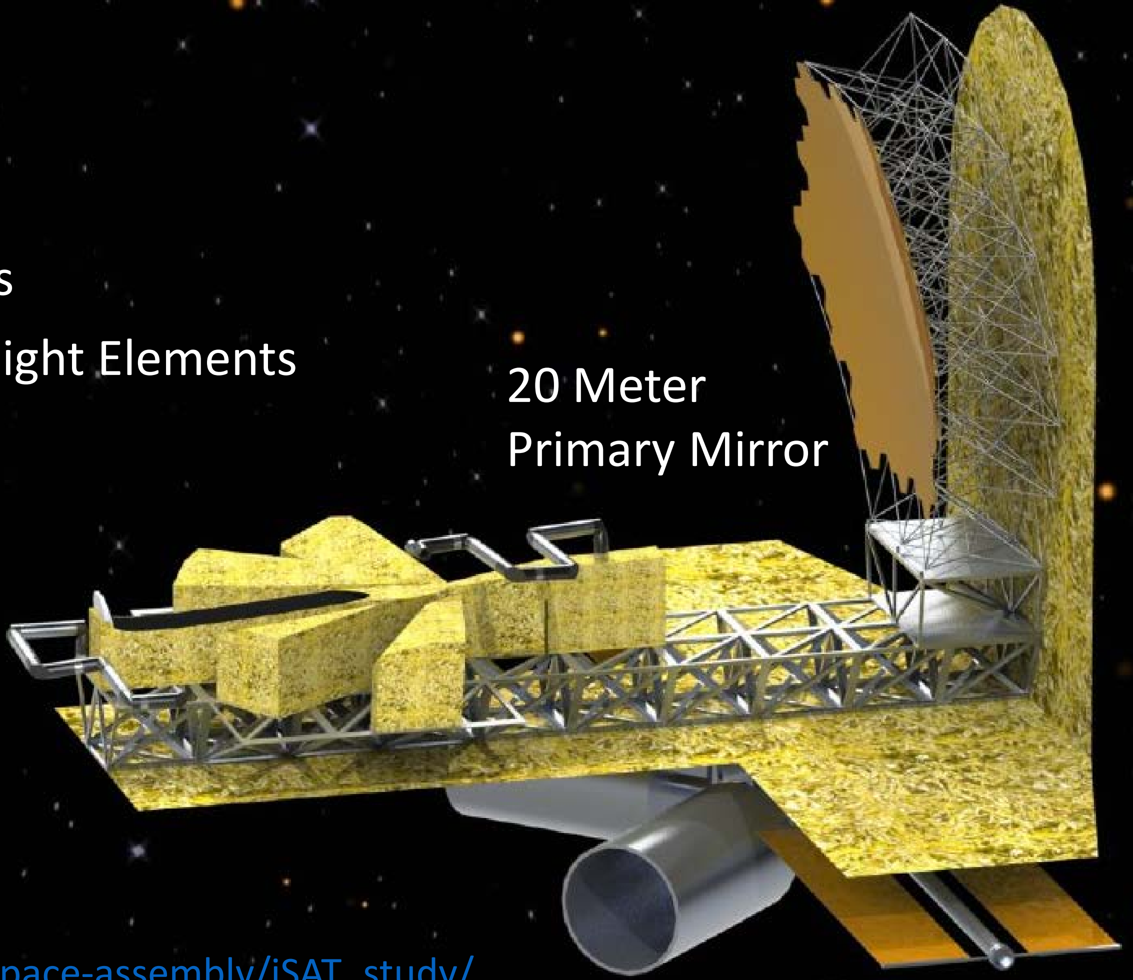
- 4.1 Verification and Validation
- 4.2 Test and Evaluation
- 4.3 Operational Assurance
- 4.4 Modeling and Simulation
- 4.5 Architecture and Design

Updated 2019-06-21

iSAT: 20 m Segmented UV/V/NIR Telescope

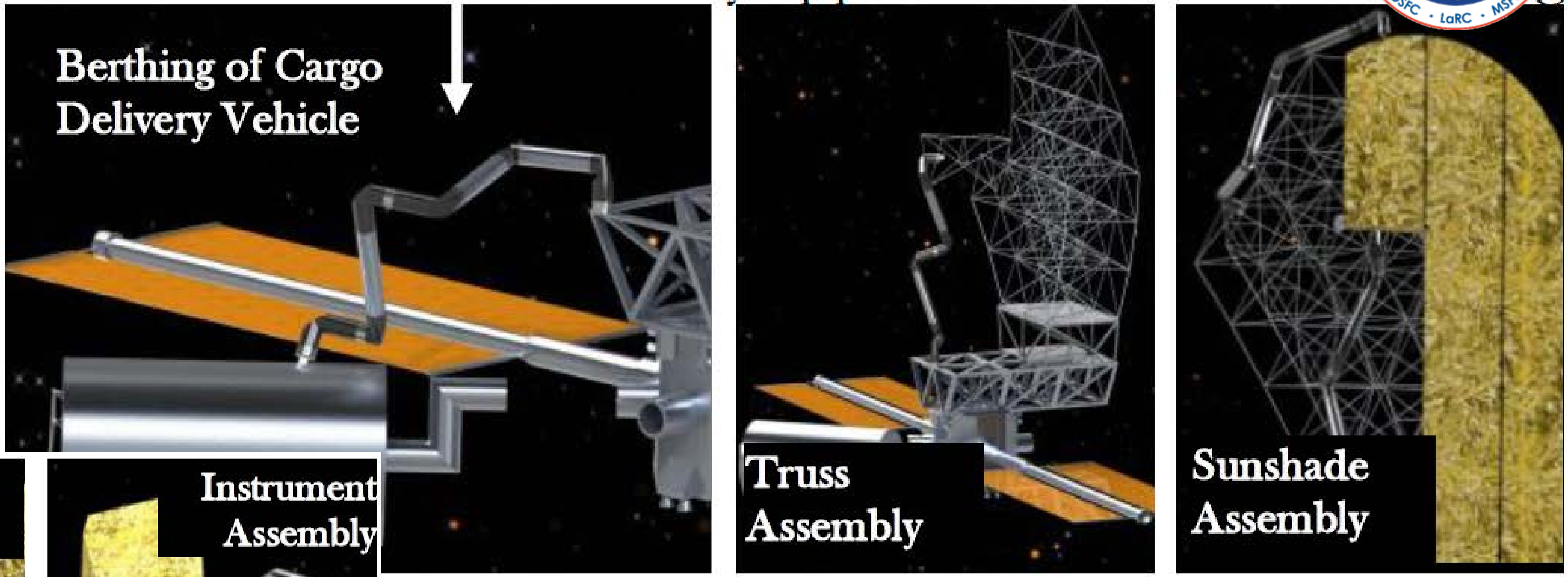
Key Design Features

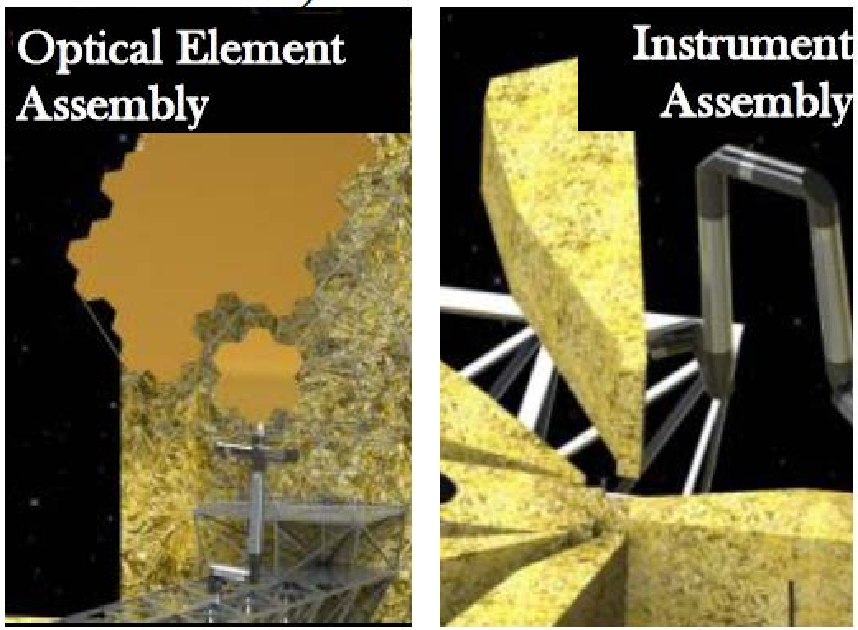
- Modularized Flight Elements
- Multiple Launches
- Relaxed Mass and Volume Constraints
- In-Space Assembly and Servicing of Flight Elements



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

iSAT ConOps: Major Steps





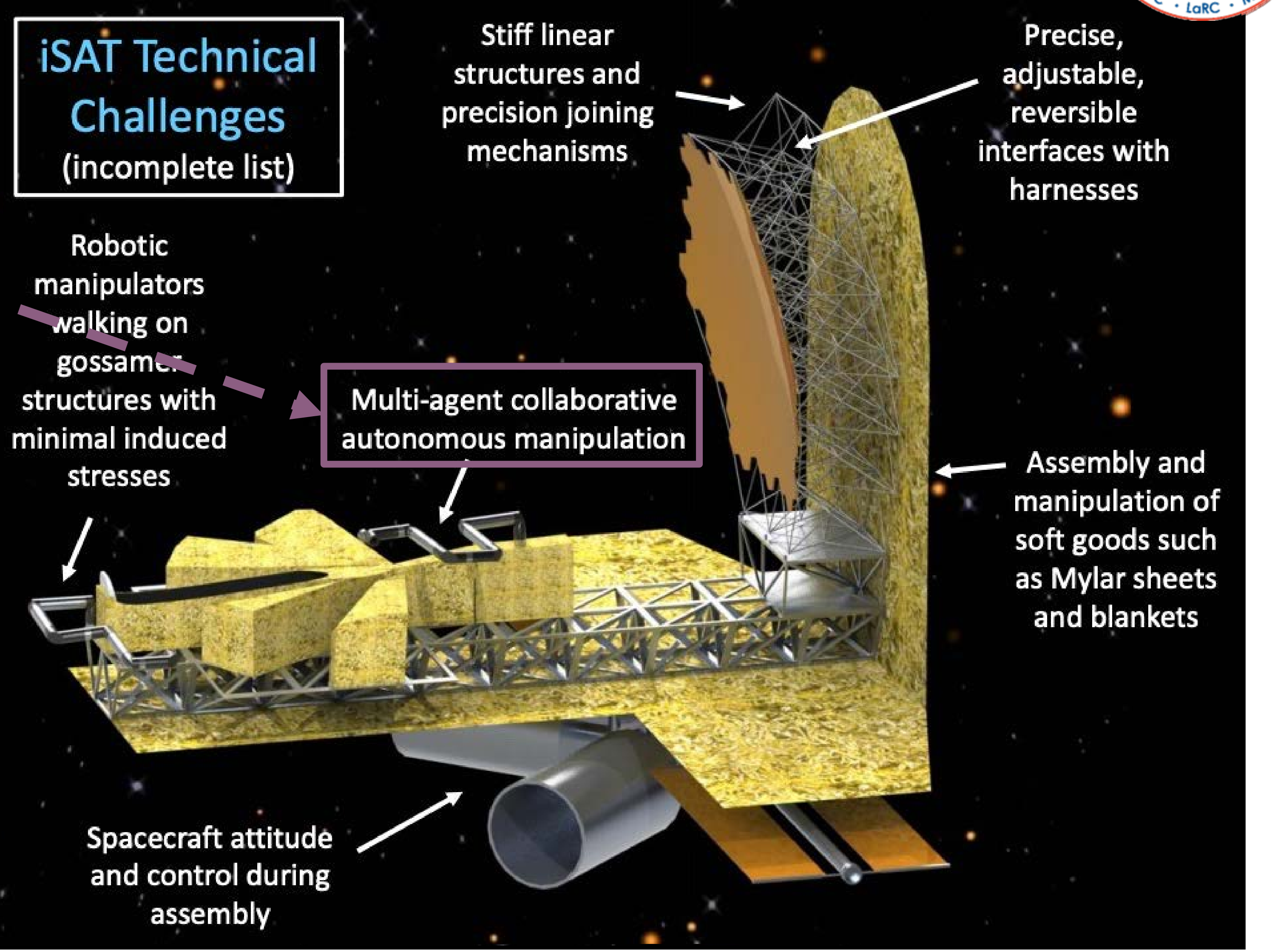
Artistic rendition of representative robotic assembly steps for the Study's iSAT reference concept

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

iSAT Technical Challenges

Autonomous Robotic Ops

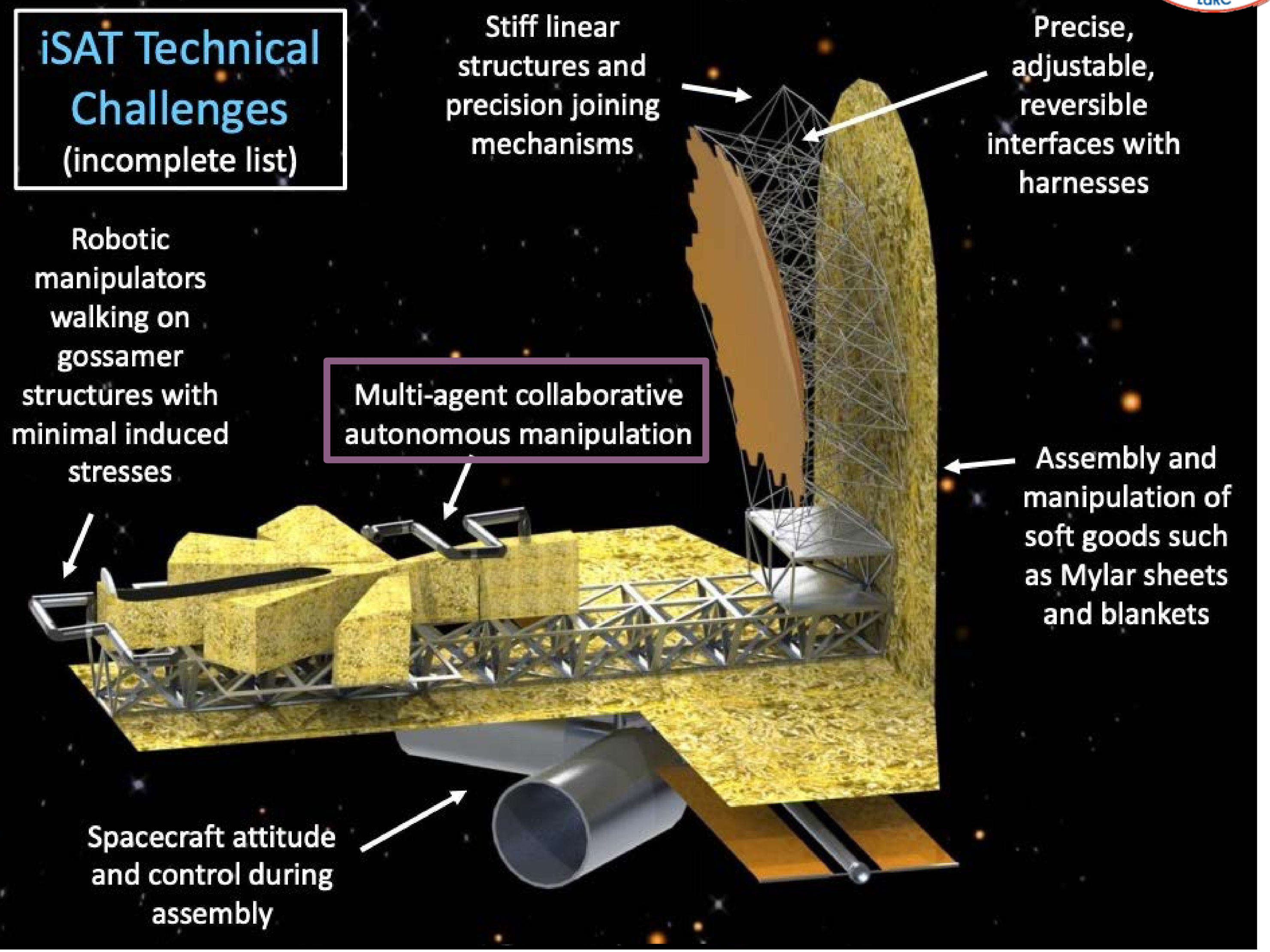
- Multi-agent collaboration
- Autonomous manipulation



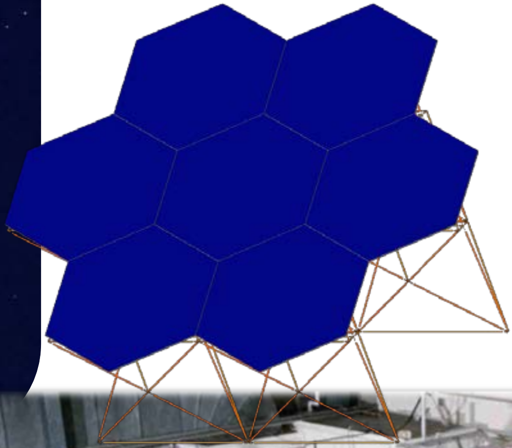
iSAT Technical Challenges

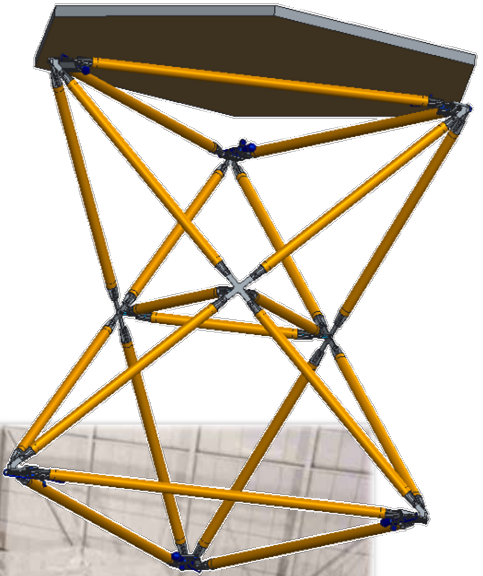
Autonomous Robotic Ops

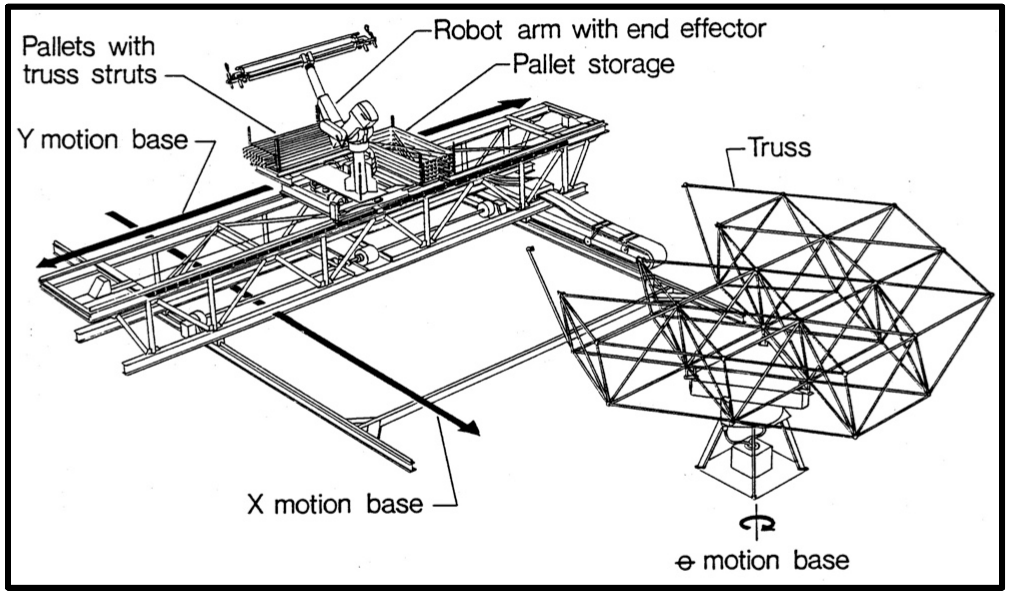
- Multi-agent collaboration
- Autonomous manipulation
- Walking on
  - Gossamer structures
  - …
- Assembly and manipulation of…
  - Soft goods
  - …
- Spacecraft attitude and control

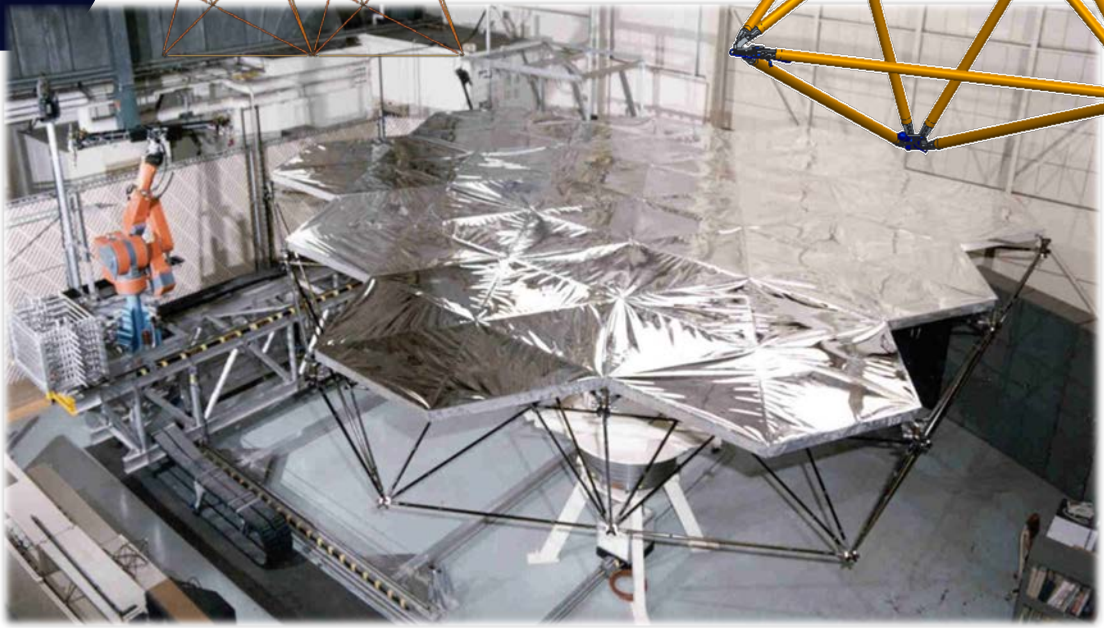


ISA at NASA Langley Research Center (LaRC)



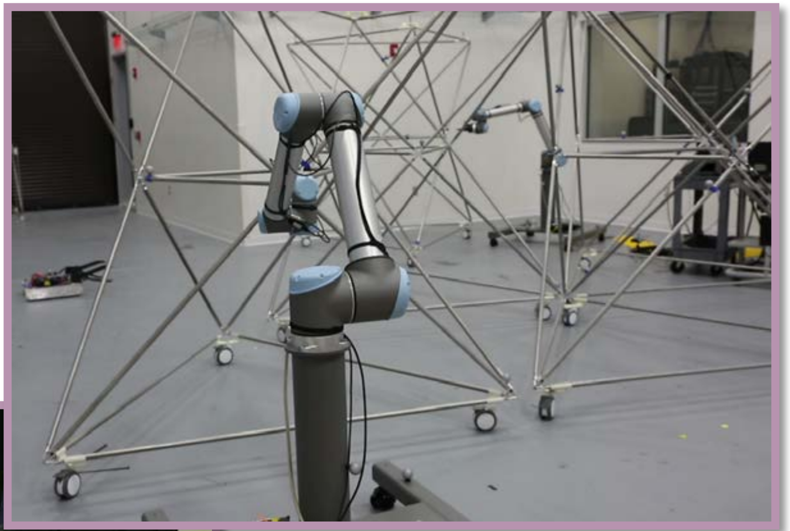






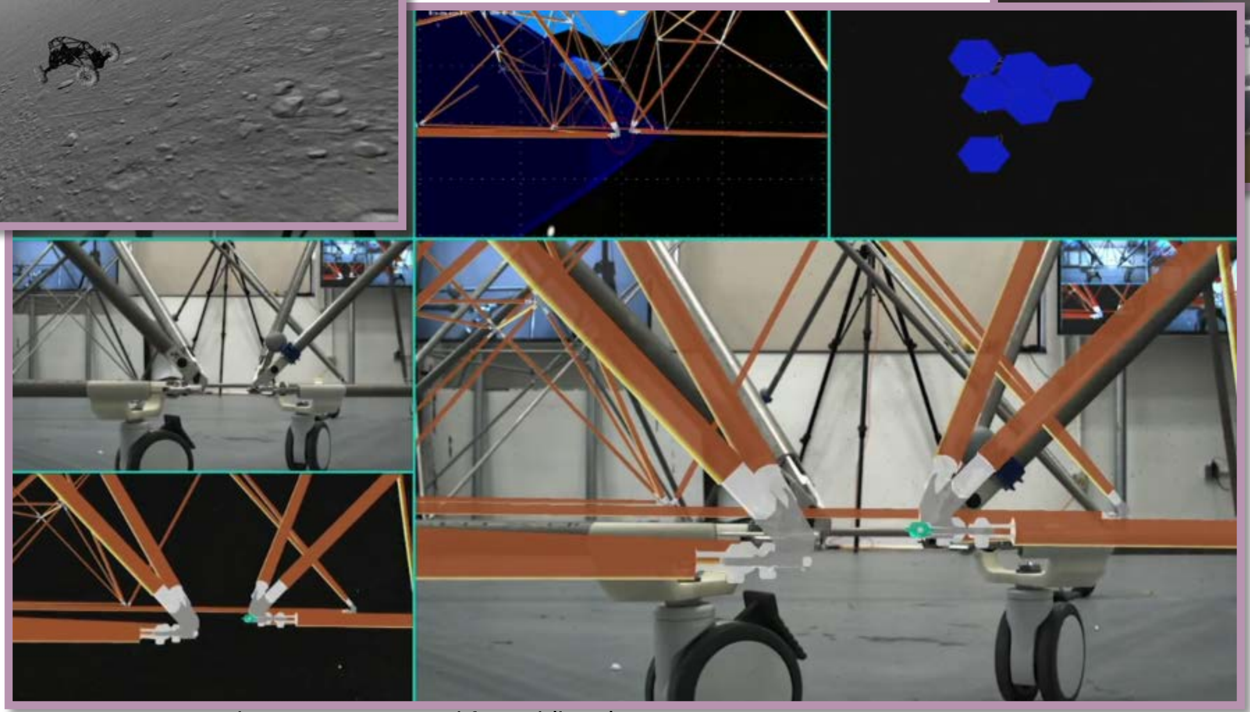
Autonomous ISA at NASA LaRC

- Autonomously assemble tri-truss to coarse alignment
  - Predefined structure with truss placement task
  - Identify, Seek, Grasp, Transport, Deliver, Join, Retreat
- Multi-Agent Collaboration
- Test & Evaluation (T&E)



T&E for Autonomous ISA – Modeling & Simulation

- Development, Test, and Evaluation via simulation
- Hardware In The Loop
- Data Distribution Service (DDS)
- Distributed
- Full Scale
- Subscale
- VR/AR/MR

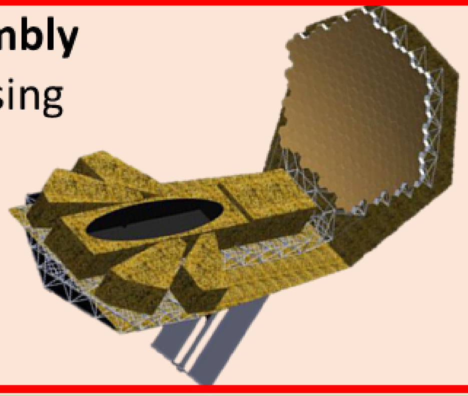


OSAM: Performance, Resilience, Persistence

NASA: Telescope – stable, large space platform that is enabled by on-orbit assembly

Telescope iSAT study: "The consensus finding of the SMEs in this Study was that closing the gaps and demonstrating them is achievable with today's capabilities."

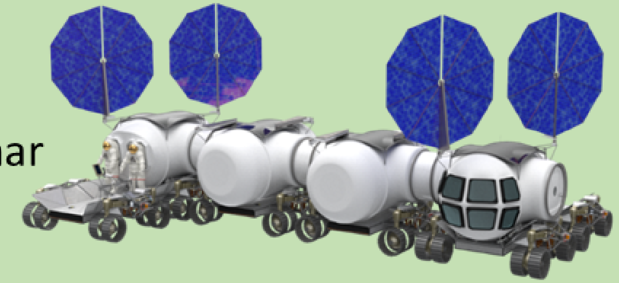
- Very large structure robotically assembled with erectable units
- Essentially no increase in complexity with increasing size
- Efficient packaging (launch mass limited – not volume limited)
- Inherently serviceable, expandable, repairable with predictable structural performance



NASA: Lunar Surface (Artemis) – persistent architecture for lunar infrastructure

Artemis maps manufacturing toward ISRU; assembly to construction

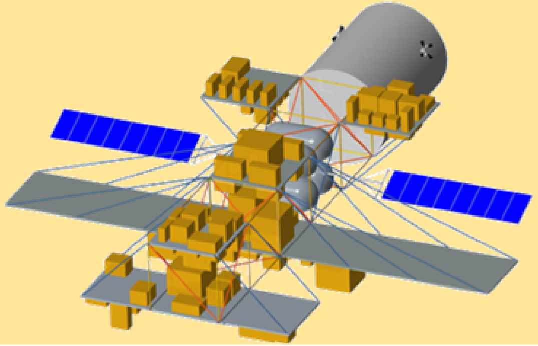
- Logistics need low cost ($/kg) landed mass
- Drive toward persistent architecture – every lander/payload adding to lunar infrastructure – sustainable and resilient
- Surface power for demanding ops and lunar night



DOD: Persistent Platform – instantiation of a persistent infrastructure

Persistent Platform reusable infrastructure pushing mission affordability

- Move from building spacecraft around payload toward providing service to payload
- Connector based service: mechanical, power, data, thermal, fluid
- Complete end-to-end service to payload developer/customer



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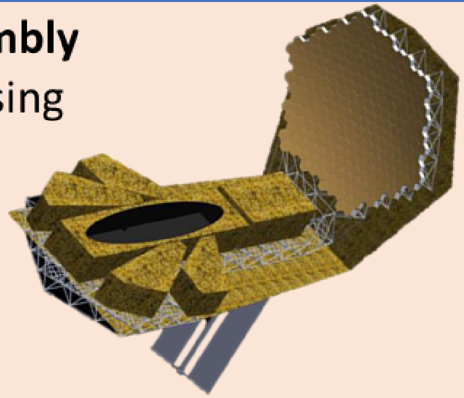

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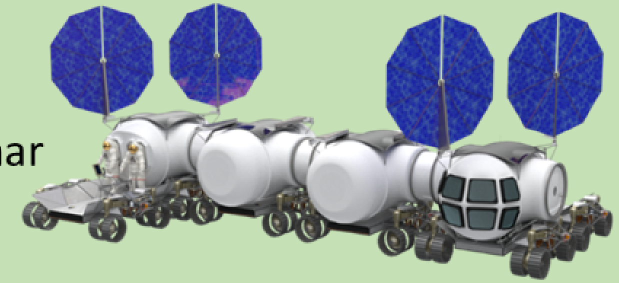

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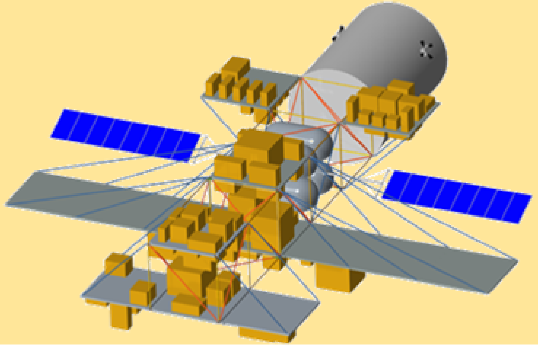

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A Rich History

NASA LaRC’s Legacy in Automated and Autonomous Systems

(Timeline circa 2015)

Space Trusted Autonomy (STA) S&T Partnership Forum

Trusted autonomy refers to self-sustaining and reliable technologies that are certified for mission use. In the future, these autonomous technologies will be reliable enough to perform mission tasks, run spacecraft systems and make changes to operations without input from humans or computers.

Mars missions will require trusted autonomy to keep astronauts and hardware safe on the Red Planet where comm delays with Earth can be up to 24 minutes one way.

NASA's Gateway will rely on autonomous technologies to keep the orbiting outpost functioning and in good health when NASA astronauts are not aboard.

In addition to spacecraft and habitat operations, trusted autonomy will enable other advanced technologies such as in-space assembly and satellite servicing.

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

National Aeronautics and
Space Administration

On-orbit Servicing Assembly and Manufacturing (OSAM)

Journeying Longer and Seeing Farther

Robots are poised to make what was once thought to be impossible in space a reality. From extending the lifespan of satellites, to assembling massive life-seeking telescopes in space, to refueling and repairing spacecraft on journeys to distant locations, the possibilities are endless. Key to these endeavors is demonstrating the foundational capabilities – servicing, assembly, and manufacturing.

To arrange further discussion of on-orbit servicing technologies contact Patrick Cosgrove (Patrick.a.cosgrove@nasa.gov)

Background Graphic: OSAM technologies continue the legacy of the Hubble Space Telescope (HST) Servicing Missions, and will be implemented to assist astronauts span and expand orbiting stations like the International Space Station (ISS). OSAM technologies will also support lunar surface and orbiting operations.