Robotic Assembly of Space Assets: Architectures and Technologies
Rudranarayan Mukherjee, Ph.D.
Future In-Space Operations (FISO) Teleconference
June 27, 2018
Recent In Space Assembly Related Talks in FISO

Robotic for Improved Capability, Utilization, and Flexibility on a Cislunar Habitat
Daniel Rey (CSA) & Paul Fulford (MDA)
May 30, 2018

Future Applications for Robotics in Earth Orbit
Gordon Roesler, DARPA
May 2, 2018

Findings and Observations from the November 2017 NASA in-Space Servicing and Assembly Technical Interchange Meeting
Nicholas Siegler, NASA/JPL, Bradley Peterson, OSU & STScI & Harley Thronson, NASA GSFC
Feb 21, 2018

Autonomous In-Space Assembly 'Deja-vu': Leveraging Our Heritage to Enable the Future
Lynn Bowman, NASA LaRC
Sep 27, 2017

On-Orbit Manufacturing and Assembly of Spacecraft: Opportunities and Challenges
Iain D. Boyd & Bhavya Lal, IDA Science and Technology Policy Institute
Sep 6, 2017
Instrument Assembly on the ISS  
Rendezvous and Proximity Operations  
Secondary Launch Vehicles

Commercial Low(er) Cost Launch Vehicles  
NASA Restore-L Mission  
DARPA RSGS

In-space Robotic Manufacturing and Assembly (IRMA)  
Lunar Orbital Platform-Gateway
1990s - High Bandwidth Telerobotic Assembly at JPL

Telerobotic Human Interface
Contour Following
Fluid Coupler Assembly and Ratcheting
Card Insertion
Spinning Body Capture
Dual Limbed Instrument Docking

Picture Credits: Dr. Paul Backes, JPL
Example Manipulation Behaviors in Mars Flight Applications

Single command approach and instrument placement

With 3D target selected on rock, rover autonomously approaches rock, deploys robotic arm, and deploys science instrument at target point on rock.

Autonomous digging: Digging while modifying digging behavior based on sensed hardness of Martian soil.

Terrain model generation using tool placement on grid locations

Autonomous drilling in rocks, force-controlled docking of coring bit with rover.

Drilling into rocks with force controlled feed rate using coring tool at end of robotic arm.

Docking coring tool bit at bit station on rover with force control for bit exchange.
Manipulation for Mars Flight Applications

- On-board autonomy for Mars lander and rover manipulation

- Commands: commands map to autonomous behaviors implemented in on-board flight software.

- Sequences: uplinked sequence of commands to execute, with capability for simultaneous execution of multiple sequences

- On-board behaviors: single state, multi-state, and hierarchical state machines to implement behaviors to change state of robot or environment.

- Anomalies: continuous monitors to ensure robot stays away from dangerous states, or detect and accommodate.

Mars Phoenix lander, 2007-2008

Mars Science Laboratory 2011 - now

Mars 2020 Rover, 2020 - ?
DARPA Robotic Challenge (DRC 2013-15)
Recent Robotic Assembly Efforts at JPL

Optical Testbed and Integration on ISS eXperiment (OpTIIX)

Large Telescope Assembly Architecture with Caltech

DARPA In-Lab Truss Assembly Demonstration

DARPA RSGS Technical Evaluation and Risk Analyses

Persistent Robotic Observation Platform aka Science Station Collaboration with Space System Loral

DARPA Robotic Arms on Cube/SmallSats
Persistent Robotic Observation Platform (Science Station)
Why change the Paradigm?
• Science
• Technical Feasibility
• Cost
Figure 1 | Spatial and temporal synergy of observations and their applications. A pretzel diagram of observations (red text) from each instrument (coloured shapes) and the synergistic physical parameters that can be derived (black text) when observations are taken at synchronous and complementary spatial and temporal resolutions.
SMLS  FTS  
Cloudsat  
Radiometer  IR Sounder  
MSPI  Radiation  
VSWIR Spectrometer  TIR Imager  
Ocean and Coast Imager  FAR IR Spectrometer  

Launch Locks
Rigidly connects pallet and instrument during launch.

Truss Interconnect
Connects pallet and utilities to truss structure.

Delivery Vehicle Interconnect
Connects pallet to delivery vehicle during launch.

Robot Grapple Interface
Physical, electrical, and data connection to robot.

Active Pointing
Allows fine pointing adjustments to achieve accuracy requirements.

Passive Isolation System (Loop Flexure)
Prevents transmission of jitter and disturbances between the instrument and the truss.

Star Tracker
Provides absolute knowledge of instrument position and orientation.

Payload with interconnect

Demo Truss

Fine Alignment Kinematics (x4)

Preload/Utillies

Coarse Alignment Pin/Funnel (x4)

Fluidic Connectors (Refrigerant)

Power/Data Connectors

Robotically Actuated Z-Clamp

Truss Side  
Pallet Side  

1m square
The 100m Robotically Assembled Telescope


jpl.nasa.gov
First, the truss modules are individually deployed and attached. Once the structure is complete, the mirror modules are attached to the underlying truss. A full 100-m primary mirror includes over 300 of each module, requiring numerous repetitive manipulation tasks suitable for a robotic system with supervised autonomy.

The primary mirror assembly is performed by a general-purpose robot that will remain with the telescope and that will also perform servicing tasks throughout its lifetime. This robot, shown in Fig. 3, is a multilimbed robot that can travel over the primary mirror truss structure to perform its assembly and servicing tasks. These tasks include transporting truss and mirror modules across the partially assembled primary mirror structure, positioning and aligning the modules for assembly, and removing and installing components, such as individual mirror segments for servicing.

The following section summarizes prior work related to the RAMST architecture, including a comparison with some of the many concepts developed for large-space telescopes. Section 3 provides an overview of the features and advantages of the RAMST concept and presents some of the trade studies considered. Section 4 explores the 100-m telescope configuration in detail, including the optical, metrology, and structural designs. Section 5 describes the robotic system and assembly sequence. Section 6 summarizes and concludes the paper.
In Space Telescope Assembly Robotics

Stowed truss modules

Truss module deployment

Stowed mirror modules

Truss module assembly

Mirror module attachment

Assembled primary mirror

Unobscured Ritchey-Chretien
FOV 24.5x24.5 arc-sec.
Covers 8K x 8K x 12 micron FPA
DARPA In Lab Telescope Truss Assembly Robotics

Assemble a 3m truss in a “closed kinematic loop” configuration to 1 cm flatness from Deployable Truss Modules (DTMs) using autonomous robotics.

Stowed DTMs

Robotically Deploy

Use adjustable structural and power interconnects

Autonomous mobile manipulation for precision repeated robotic assembly

Assemble 3m closed kinematic truss around a central hub (spacecraft surrogate)

Central Truss

Electromechanical Interconnects

April tags

Floor
Figure 3: Screenshots from a 26 min in-lab demonstration of autonomous assembly with RoboSimian. (3a) shows the build process of a 3 m diameter truss structure in a specific order. Interspersed between the individual truss insertion tasks was a truss deployment and retrieval task shown in (3b). During this sub-task the robot grabs, deploys and retrieves a collapsed truss for assembly.

modules from an astronomical requirements standpoint. In this work, we took a bottom-up approach by designing the simplest possible truss design that was iterated upon via end-to-end testing with a robotic system. This enabled us to balance the cost of manufacturing with those of robotic precision required to achieve the task at hand while keeping costs of actuators and on-board sensors low. We chose the sparse tessellation architecture proposed by Lee et al. (2016) for the truss assembly. The task at hand was to assemble six of these DTM’s, each with a unique set of interconnects that had to be assembled in a specific order. This created a 3 m diameter kinematically closed loop structure to sub-cm accuracy despite the stacking up of tolerance errors in hardware. In addition to the deployable trusses, custom mechanical interconnects were designed with an internal latching mechanism (Figure 4c). Once inserted, the trusses would latch to a fixed central structure. This experimental setup is compatible with the top-down architecture presented in Lee et al. (2016) for a robotically assembled, modular space telescope. However, operational simplifications were made for logistical and cost reasons. In addition, we did not design a custom robot for this task, as we had to adapt the task to an existing robotic system. We relied on Jet Propulsion Lab’s (JPL) RoboSimian Robot which was originally designed for the DARPA Robotics Challenge. A detailed description of JPL’s RoboSimian Robot is discussed in...
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26 min, End-to-End Autonomous 3m Ring Truss Assembly

Position Precision 3.7 mm
Orientation Precision: 0.1 deg

Six visual tags for the central structure

One visual tag for dispenser
https://exoplanets.nasa.gov/internal_resources/837/

Demonstration video link
Position Accuracy 21.5 mm
Position Precision 3.7 mm
Orientation Accuracy: 1.07 deg
Orientation Precision: 0.1 deg
Optical Testbed and Integration on ISS eXperiment (OpTIIX)

3 Mirror Anastigmat Telescope (1.45m aperture)

Fine Steering Tertiary

Coarse Steering Mirror

Robotically assembled and operated at Express Logistics Carrier (ELC3)
OpTIIX Assembly Sequence

1. Gimbal
2. Telescope Core Module
3. Secondary Tower

4.-6. Segment Modules
(no particular order)

Full Deployment of Sunshades

6 launch modules for assembly
Cluster Formation Using CubeSats with Robotic Arms

- Propulsion systems are used to bring CubeSats within 1 meter range
- IR camera and emitter on robotic arm end effectors allows for precise positioning in 2D plane
- Propulsion systems are fired to bring arms together with relative velocity ≤ 10 cm/s

SAR Stripmap mode

Reconfigured Mode
Orbital Debris Mitigation with Robotic Arms on CubeSats
6U Spacecraft
Requirements
• Size: (100 x 226.3 x 340.5) mm
• Mass: 12.0 kg

Functionality
• Accessible launch
• Tracking capabilities
• Rendezvous capabilities
• Limited trajectory alterations

12U Spacecraft
Requirements
• Size: (226.3 x 226.3 x 340.5) mm
• Mass: 24.0 kg

Functionality
• 12U P-POD less mature
• Tracking capabilities
• Rendezvous capabilities
• Trajectory alterations
Technical Evaluation and Risk Analyses for On Orbit Robotic Servicing
Robotically Assembled and Refurbishable Communication Payload
Robotically Assembled 30m Starshade
Robotically Assembled 150m Starshade
Robotically Assembled 150m Starshade
Robotically Assembled 150m Starshade