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Ground-based Demonstration of CubeSat Robotic Assembly

CubeSat Development Workshop 2020

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Motivation: In-Space Small Satellite Assembly

Why not build in space?

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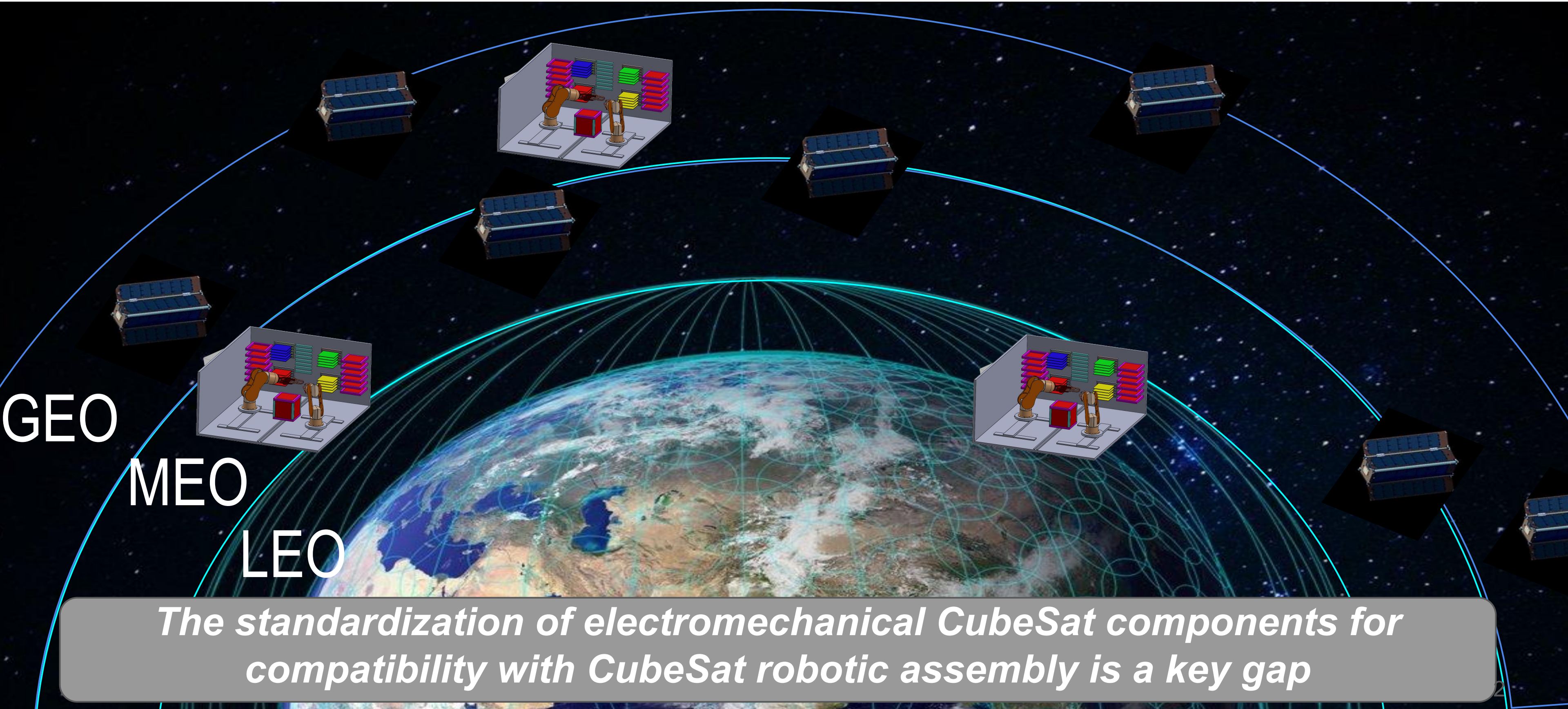

The standardization of electromechanical CubeSat components for compatibility with CubeSat robotic assembly is a key gap

Goal: On-Demand On-Orbit Assembled CubeSats

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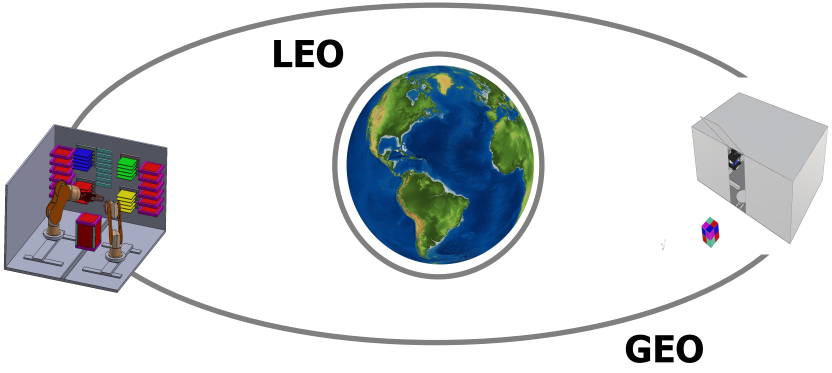

Internal View of 'Locker' Showing Robotic Assembly

IR Sensors · VIS Sensors · RF Sensors · Propulsion

Mission Key Phases

- **Ground Phase:** Functional electro/mechanical prototype
- **ISS Phase:** Development and launch of ISS flight unit locker, with CubeSat propulsion option
- **Free-Flyer Phase:** Development of agile free-flyer "locker" satellite with robotic arms to assemble and deploy rapid response CubeSats
- **Constellation Phase:** Development of strategic constellation of agile free-flyer "locker" satellites with robotic arms to autonomously assemble and deploy CubeSats

Mission Overview

- **Orbit-agnostic lockers deploy on-demand robot-assembled CubeSats**
- 'Locker' is mini-fridge-sized spacecraft with propulsion capability
- Holds robotic arms, sensor, and propulsion modules for 1-3U CubeSats
- Improve response: >30 days to ~hours

Mission Significance

Provides many CubeSat configurations responsive to rapidly evolving space needs

✓ Flexible: Selectable sensors and propulsion

✓ Resilient: Dexterous robot arms for CubeSat assembly without humans-in-the-loop on Earth and on-orbit Build custom-configured CubeSats on Earth or in space saving

✓ Efficient: Assembles CubeSat in 4 hours and saves launch mass for packaging CubeSats by 2x

On-Orbit Robotic Assembly Spacecraft Locker

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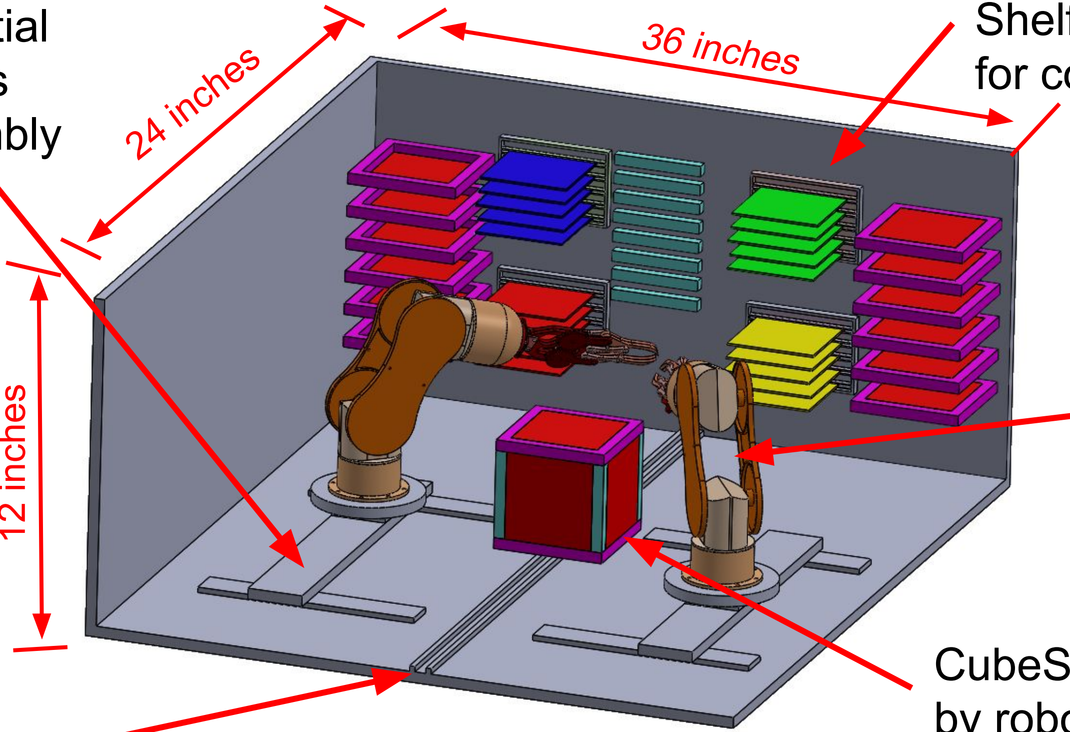
Placement and spatial configuration of rails for arms and assembly platform



Shelf and storage space for components

COTS Robotic Arm(s)

CubeSat being assembled by robotic arms

Location of deployment system for assembled CubeSat

Maximum size of object passing through ISS JEM-EF Airlock is 36.6inx31.4inx22.6in

Concept of Operations in Four Phases

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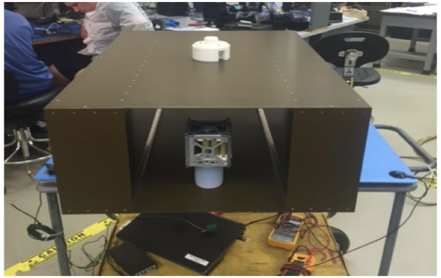
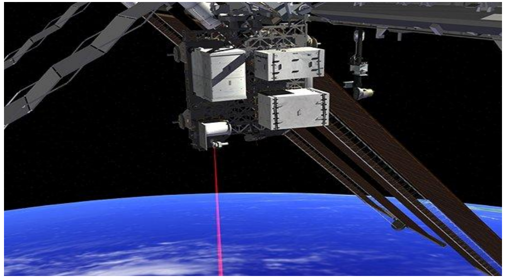
Phase 1: Locker Prototype



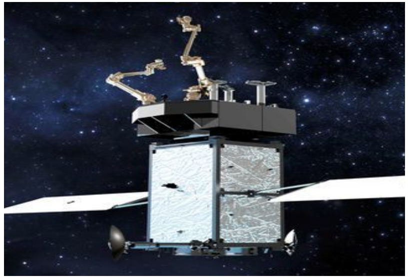
- Lab prototype of locker assembly
- Robotic arms assemble CubeSats
- Different payloads and propulsion options
- Goal to optimize response time and sensing.

Phase 2: ISS Demonstration



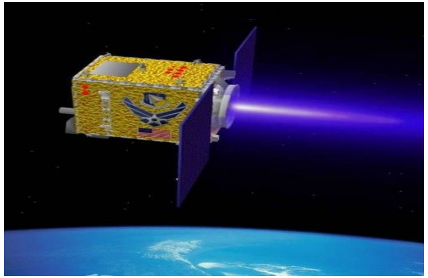
- ISS On-orbit demonstration of locker
- Locker is fixed to the International Space Station
- Assembled CubeSats are deployed and TRL is increased
- Response time is quantitatively assessed.

Phase 3: Free-Flyer



- Free-flyer locker to further reduce response time and reach more orbits
- Consider stand-alone satellite or mount to a GEO comsat
- Demonstrate response time that beats ground-based by 10x.

Phase 4: Constellation



- Autonomous constellation of lockers able to custom assemble CubeSats to incorporate autonomy and swarm coordination
- Demonstrate response that beats ground-based by 100x (from 35 days to 4 hours). Benefits constellation programs.

On-Orbit Robotic Assembly vs. Human-in-the-loop

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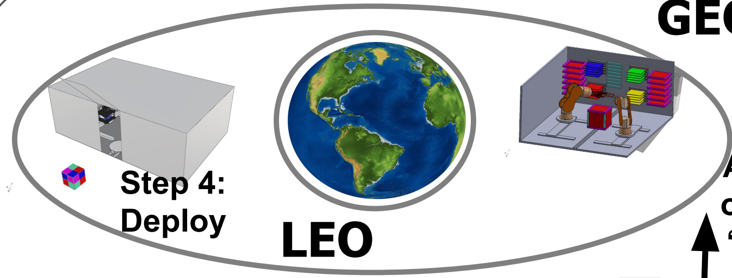
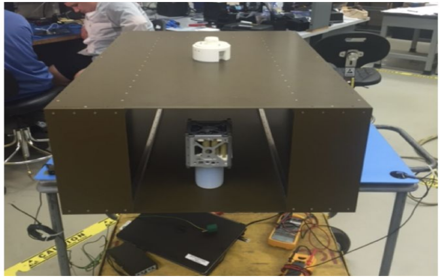
How it will be done in the future



Step 3: Assemble on orbit in "lockers"

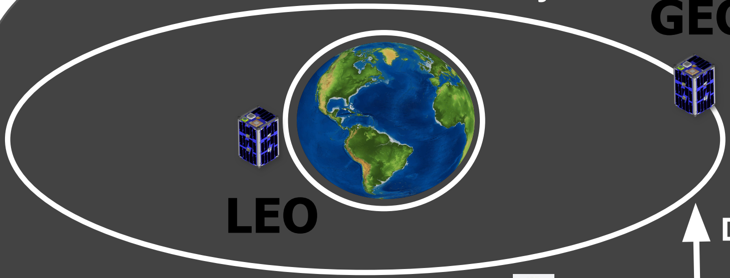


Step 1: Fill "locker" on Earth with parts

Step 2: Launch lockers

One launch manifest per locker per 5-10 CubeSats

How it is done today



Step 3: Deployed in orbit

Step 1: 24-month minimum development

Assuming no launch delays

Step 2: Launch

35-day minimum launch manifest per small satellite

4-hour on-orbit rapid assembly per SmallSat vs minimum 35-day timeline to orbit

Packaging: Deploy-only vs. Robot-Arm Locker

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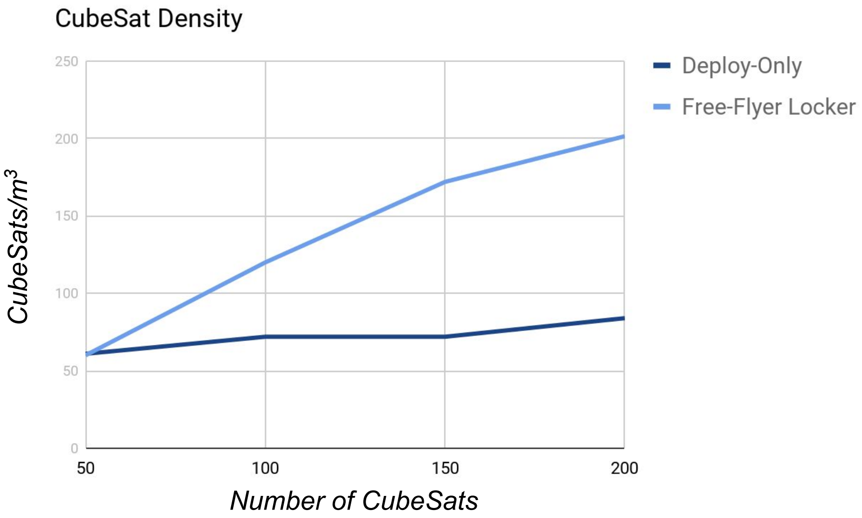
Capability	Free-Flyer Locker (On-Orbit Robotic Assembly)	Pre-assembled Deploy-Only (no Robotic Assembly)
Development Timeline	12-24 months	24-48 months (due to S/C bus contracts, etc.)
Launch Timeline	Minimum 35-day launch manifest (one launch)	Minimum 35-day launch manifest (one launch)
Volume (number of Satellites in 177U)	120 3U CubeSats (shelved/flat packed structures; includes 10U volume for robot arms)	72 3U CubeSats (pre-assembled with structures and rails in upright configuration)
Spacecraft Configurations	Right-sized power and propulsion modules	Limited (determined before launch)
Payload Options	Purpose-driven sensor types and configurations	Limited (determined before launch)
Deployment to Target	Hours (from on-orbit location)	Hours (from on-orbit location)



As locker size grows, can fit more flat-packed CubeSats that are robotically assembled vs. a static deployer with pre-built CubeSats.

Analysis uses conservative flat-pack assumptions. Can be further improved with optimized modules (part of this work).

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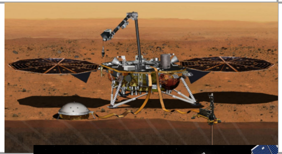
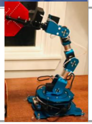
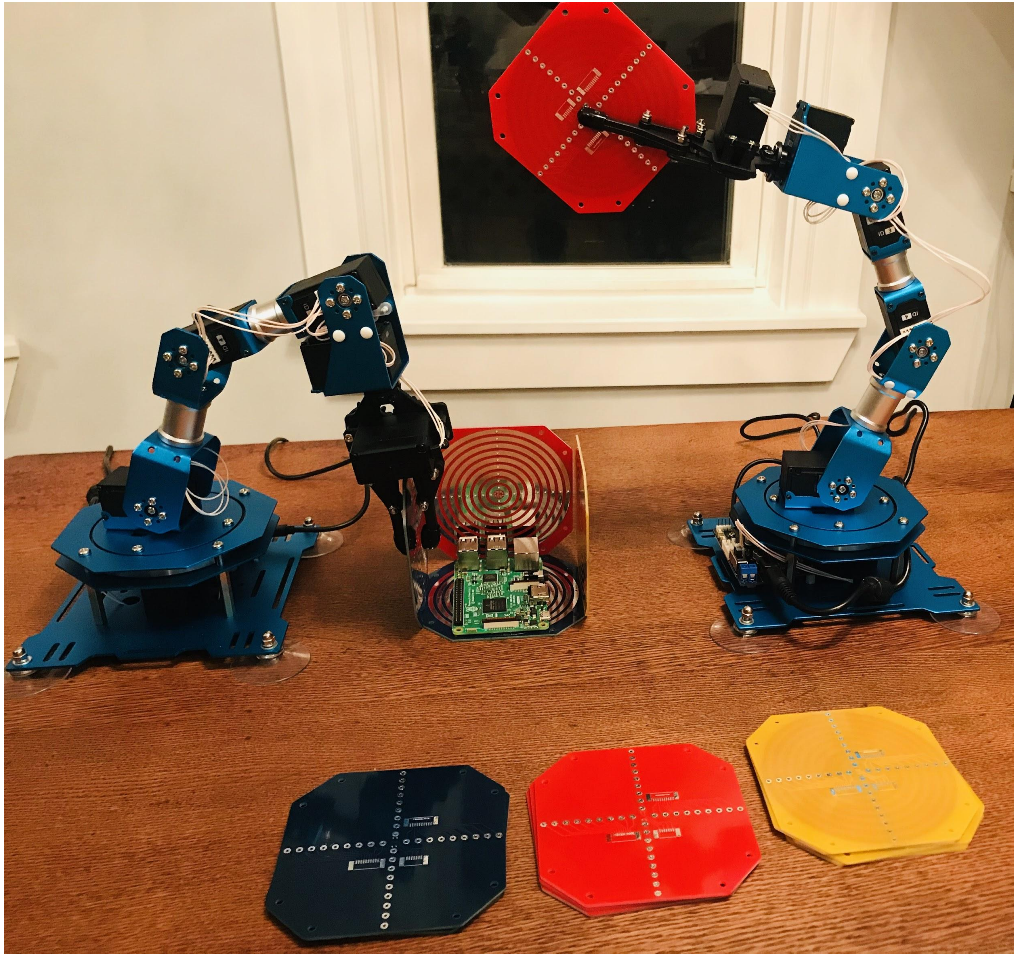
State-of-the-Art: Custom Robot Arms and Servicing Missions

Select List of Relevant Missions	COTS Robot Arm	Standard Modularized Components	Robotic Assembly / Servicing	Mass / Volume Savings
JPL Mars Insight *Custom arms for Mars mission* 	Y	N	**N**	N
NG MEV-1, RESTORE-L *Robotic servicing missions* 	N	N	Y	N
MIS Archinaut *3D printed robotic assembly mission* 	Y	N	Y	N
NASA Ames EDSN *Eight 1.5U CubeSats for Cross-Link Comms* 	N	Y	N	Y
This Work 	**Y**	**Y**	**Y**	**Y**

Concept Phase 1: Laboratory Prototype Development

<u>Objective:</u> Laboratory prototype demonstration and analysis of the robotic assembly of a 1U functional CubeSat by two dexterous COTS robot arms

In an initial test, two LewanSoul robot arms are seen assembling magnetized prototype circuit boards (without a structure)



Concept Phase 1: Laboratory Prototype Approach

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- Conduct Feasibility of Commercial-Off-The-Shelf (COTS) Robot Arms In Space
  - *Can we “buy and fly” robot arms?*
  - *What robot arms and payload sensors must be used?*
  - *How will the robot arms and modular components become space-qualified?*
- Develop Electromechanical CubeSat Components for Lab Prototype
  - *What CubeSats parts could be compatible with robotic assembly?*
- III: Demonstrate Ground-Based 1U CubeSat Assembly
  - *Can two COTS robot arms assemble a functioning satellite without a human-in-the-loop?*

Robot Assembly Block Diagram

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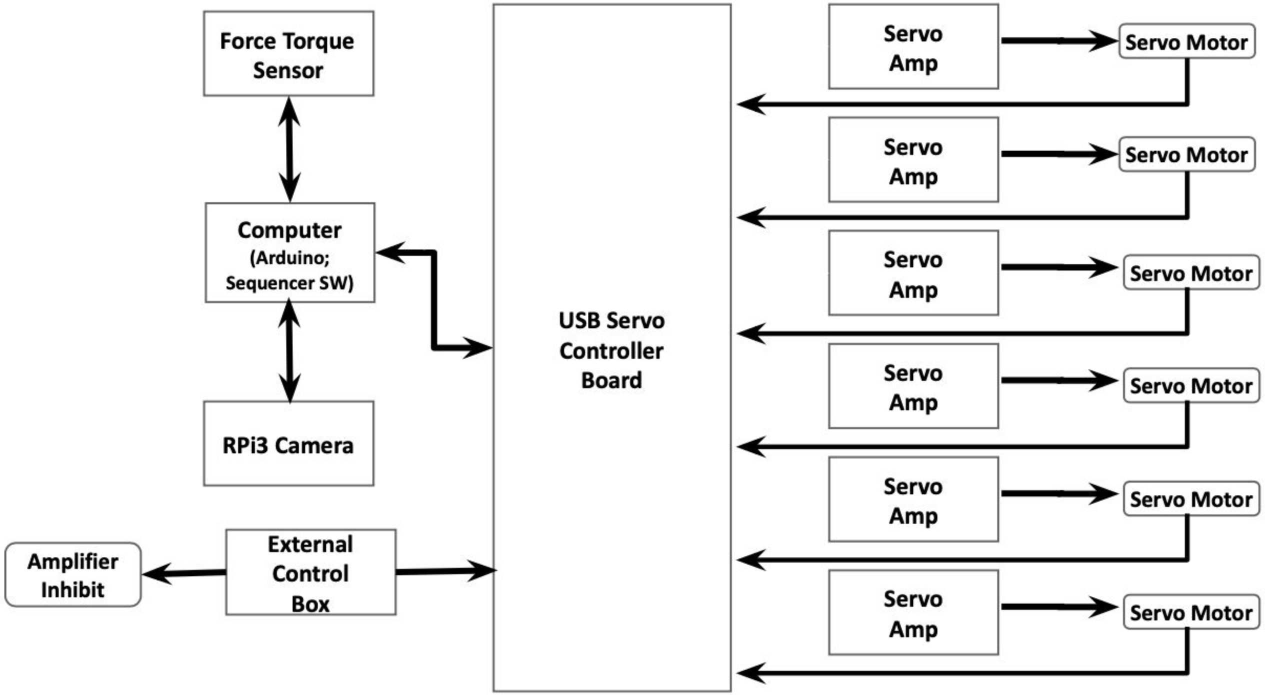

Select Arm and Sensor Specifications

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Robot Arms
Six degree-of-freedom (DOF) arm with a kinematic configuration
Joints are driven by brushless DC motors with a 30:1 gear ratio and 256-count magneto-resistant encoders
Dynamically move a maximum mass of 2 kg, given 1 m arm length using Inverse Kinematics

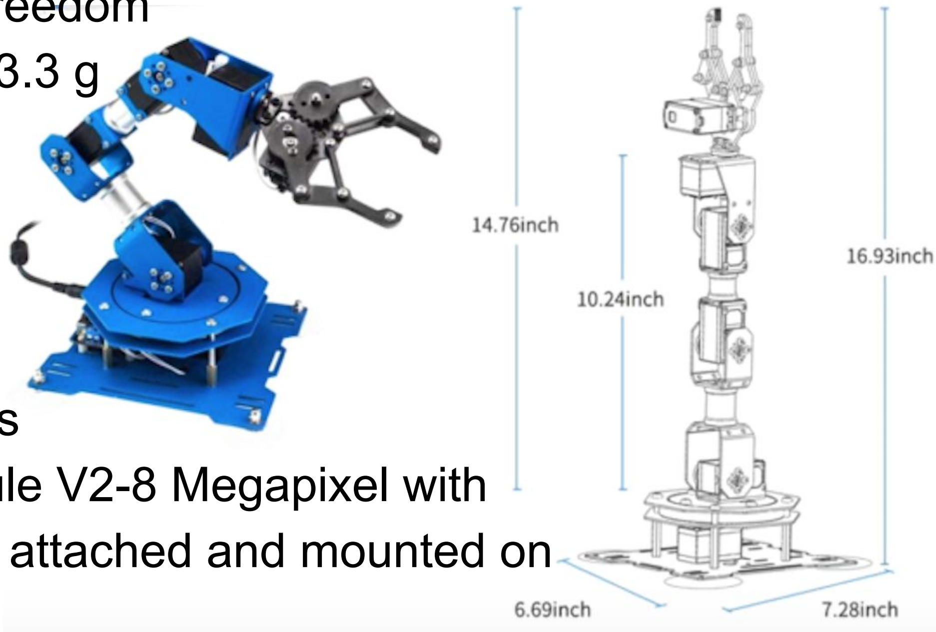
Sensors
One six-axis wrist force torque sensor that measures the wrench (three forces and three torques) at the end-effector
Four joint torque sensors with redundant strain gauge bridges that measure the output torque of each of the joints, attached to the output of each of the first four joints of the arm
Link strain gauges on the two links of the manipulator that measure bending and twist strains for each of the links
One motor current sensor that measures the motor current of each of the six servo motors of the arm with each motor being controlled by a motor controller

CubeSat Characteristics

Volume	1U
Mass	1000 g
Attitude Control	Detumbling
Data bus	I2C/RS-232
Storage	2 x 2 GB
Average payload power	400 mW
Power bus	3.3 V / 5 V (2A max)
Uplink	9.6 kbps (VHF)
Downlink	9.6 kbps (UHF)

Low-Cost COTS Robot Arm Characteristics

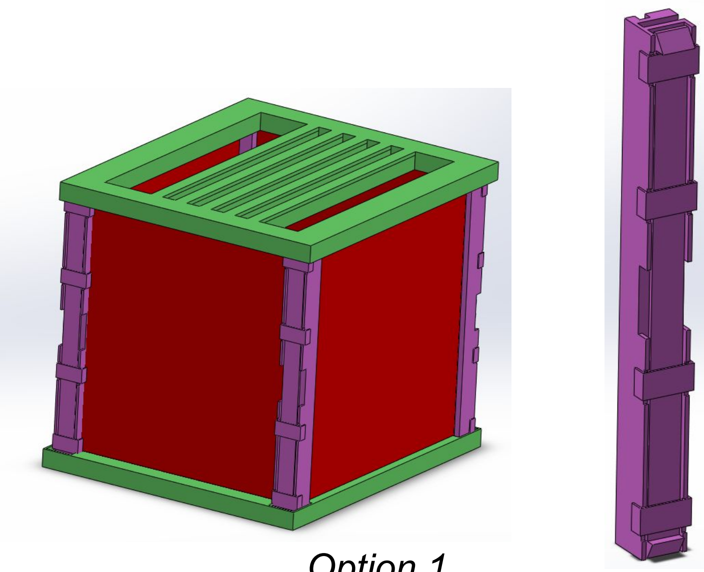
- LewanSoul xArm with 6 Degrees of Freedom
- 6 LX-15D Servo Motors: 8.4 V, 5 W, 43.3 g
- 1 LOBOT Force Torque Sensor, 7.4 V
- Servo Motor Controller



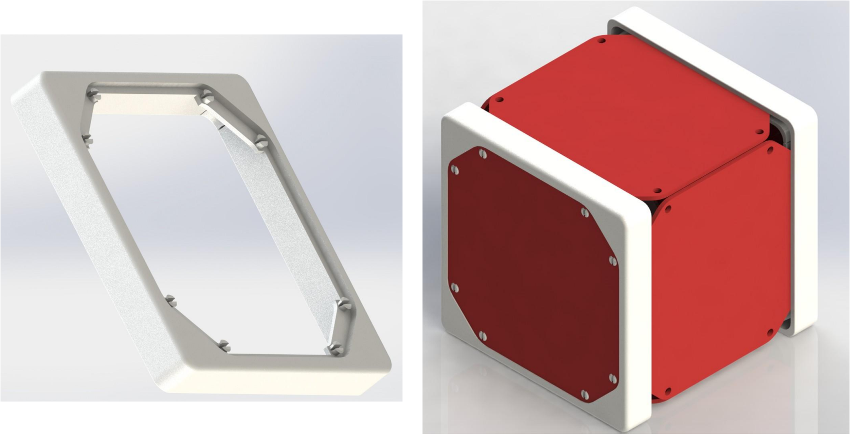
- Programmed using Inverse Kinematics
- We use a Raspberry Pi Camera Module V2-8 Megapixel with an Arduino Uno Microcontroller Board attached and mounted on a 1.5 ft post

Mechanism/Structure Design and Implementation

- Robotically assembled structure does not use fasteners
- Required redesign from previous readily available CubeSat structures
- Several iterations revealed magnets and springs with latches as best options
- 3D-printed for lab prototyping purposes; will be machined for flight



Option 1



Option 2

Current best two structural options: Option 1 with rails and latches and Option 2 without rail support

Modular Component Development

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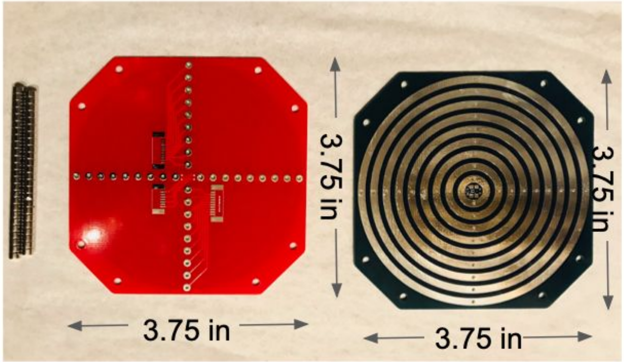
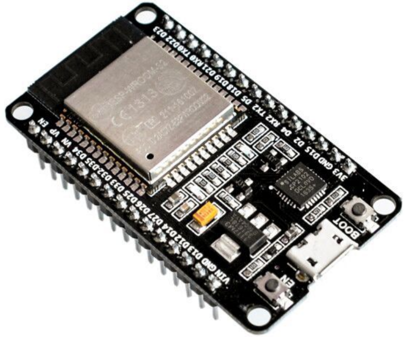
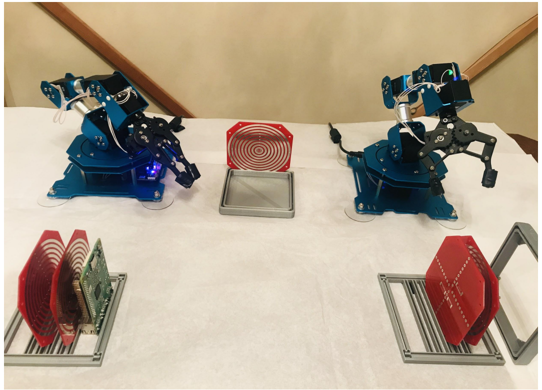
- Standard prototype boards purchased for laboratory prototype
- Customized to include:
  - Photodiode for duplex short-range optical communication for carrying high speed signals
  - Connector pads to connect the round contacts and optical parts to an external PCB
  - Nine round contacts
  - LED pads
  - Through hole pads for pogo pins (for carrying power and low speed signals)
- Made use of ESP32 Microcontroller Board

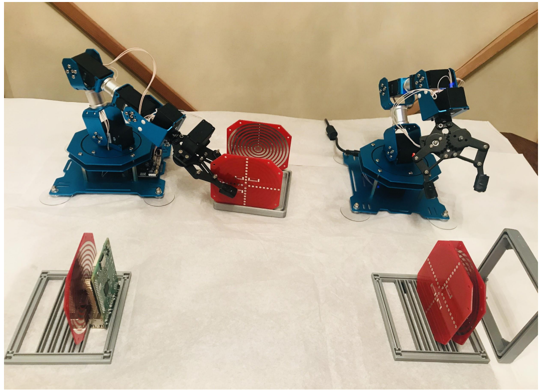




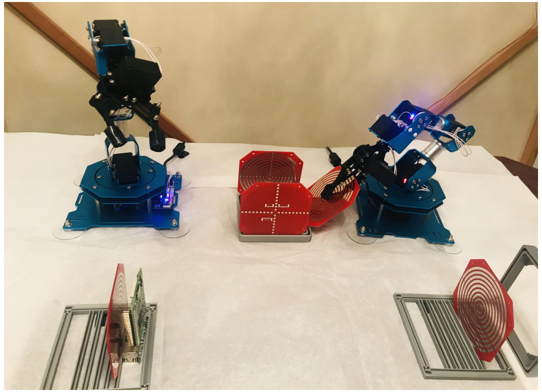
1U CubeSat Robotic Assembly in under 8 minutes



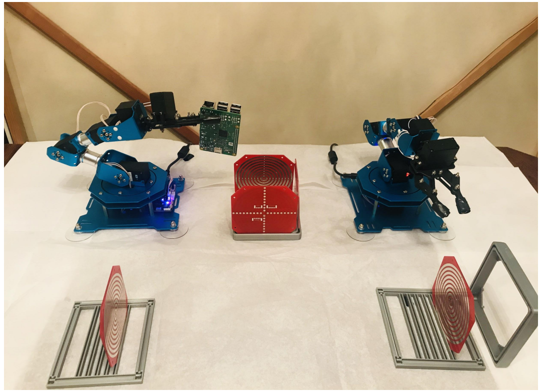
1: Modular board placed by right arm



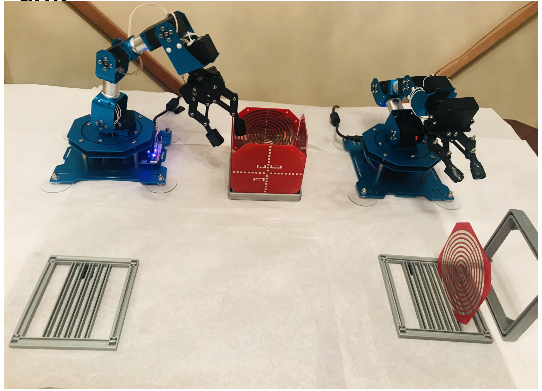
2: Second modular board placed by left arm



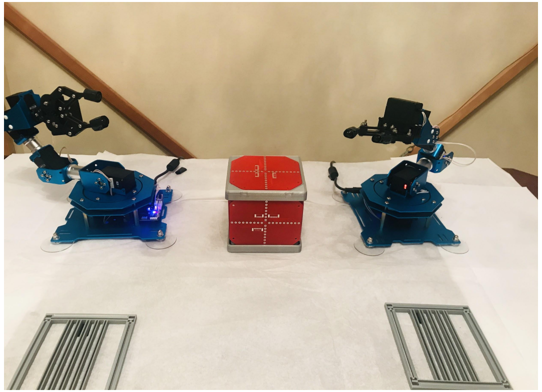
3: Third modular board placed by left arm



4: Processor board placed by left arm



5: Final side panel circuit board is assembled



6: All six modular boards fastened by magnets

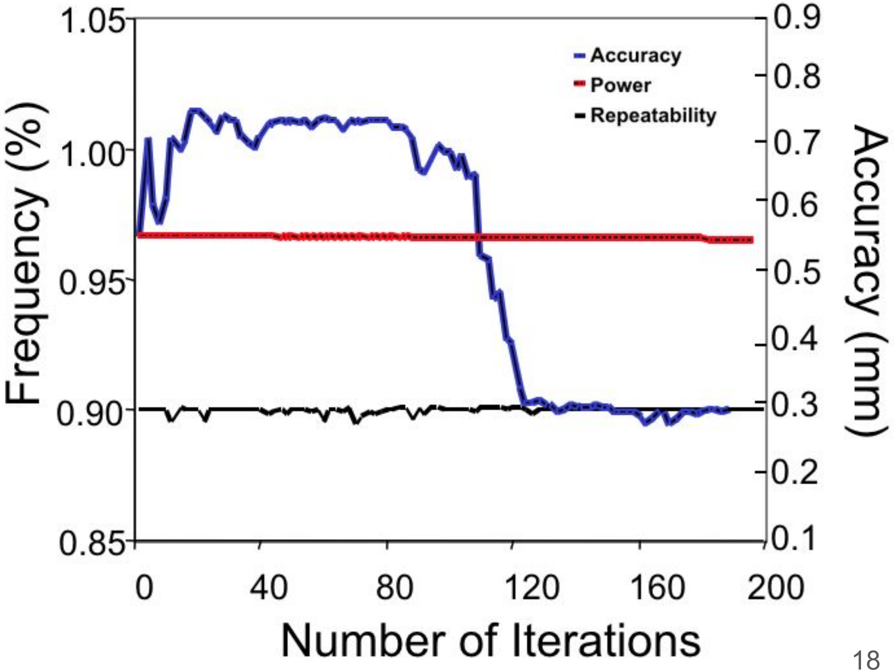
Results

- Robotic assembly of a CubeSat with no humans-in-the-loop in > 8 minutes

- Standardization of electromechanical CubeSat components for on-orbit assembly with magnets and snaps

- Potential for improving the lead time for CubeSat integration and assembly

- Decline in robot arm 95% accuracy requirement after >120 iterations



Lessons Learned

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- Power considerations require improved motors for ISS demonstration as servo motors burnout due to degradation after less than 200 hours of use

- End-effector (gripper) accuracy diminishes with time; therefore, exploration of precision (surgical) robots for flight is a required next step

- Two COTS robot arms and servo motors have shown reliability concerns due to mechanical and degradation issues on the ground; therefore, conducting a future trade study on low-cost offerings for reliable motors and arms is key to moving forward

Future Work: Improved Parts and Space Qualification

- Investigate improved subsystems
  - Consider precise (surgical) robot arms in the same form factor to overcome accuracy issues
  - Explore durable motors for flight demonstration
  - Conduct trade study on low-cost COTS vs surgical robot arms
- Space Qualification of robot arms, components and spacecraft locker
  - Train new robot arms to sense, grasp and assemble CubeSat flight modules
  - Conduct environmental testing of robot arms, assessment of thermal and power budget in addition to lifetime expectation and self-maintenance
- Optimization Analyses for Assembled CubeSats
  - Find optimal CubeSat power requirements and propulsion sizing to enable maneuvers
  - Select CubeSat sensors and payloads best suited for anticipated CubeSat missions
- Propulsion Feasibility Study for Assembled CubeSats
  - Optimization of delta-V maneuvers at the cost of relatively little propellant for CubeSats
  - Simulation of propellant efficiency of electric or chemical CubeSat-sized thrusters
  - Feasibility of miniaturized chemical propulsion modules

Future Work: Space Qualification Tests for ISS Demo

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Space Qualification Tests	Goals
Vacuum Survivability	To ensure that the robot arms can survive vacuum environment
Vacuum Operation (635 nm)	To ensure that the robot arms and locker spacecraft can perform predictably in a vacuum environment
Thermal Vacuum (635nm)	To ensure that the robot arms and locker spacecraft can perform predictably in a vacuum environment across various temperatures (-20C to 60C)
Radiation Testing	To understand the effects of space-like radiation and interrupted assembly on the locker spacecraft and on-orbit robotic assembly
Zero G Testing	To understand how the performance of the locker spacecraft changes and impacts robotic assembly in a microgravity environment

Use Case Scenario 1: Supporting LEO and GEO Assets

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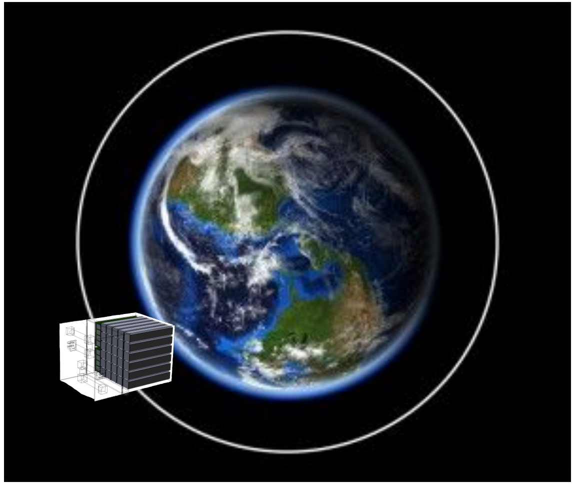
Step 1: *There is a compromised satellite in LEO at 600 km*

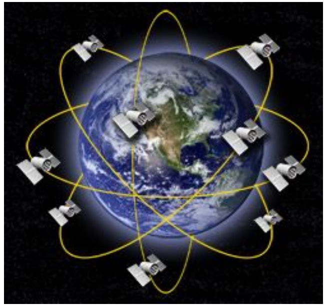


Step 2: *Matrix (at 550 km sun-synchronous orbit) rapidly assembles and deploys a CubeSat for inspection*

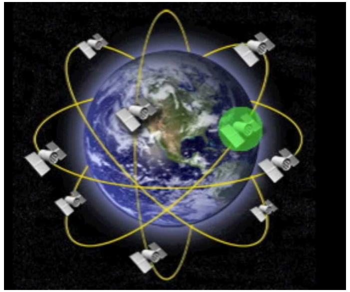
Step 3: *The assembled and deployed CubeSat arrives at the compromised satellite for inspection*

Use Case Scenario 2: Reconstitute Constellations

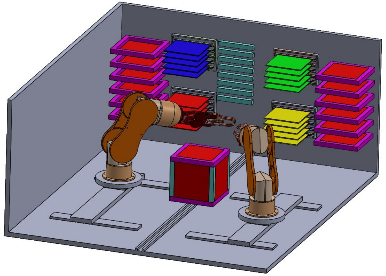
Step 1: *There exists a LEO Constellation with all functioning nodes*



Step 2: *One node loses battery power and becomes unresponsive. Without on-orbit spares, redistributing the constellation will increase the range and decrease the data rate until the node is replaced*



Step 3: *CubeSat is rapidly assembled (in ~6 hours) and a node replacement is deployed (~1 hour) to the LEO Constellation*



Step 4: *The LEO Constellation has been updated with a replacement node. All nodes are functioning as expected*