ISSRDC

Astrobee: Completed, Current, and Future Research using Free Flying Robots on the International Space Station.

Aric Katterhagen

Astrobee Operations Lead

AIRBUS

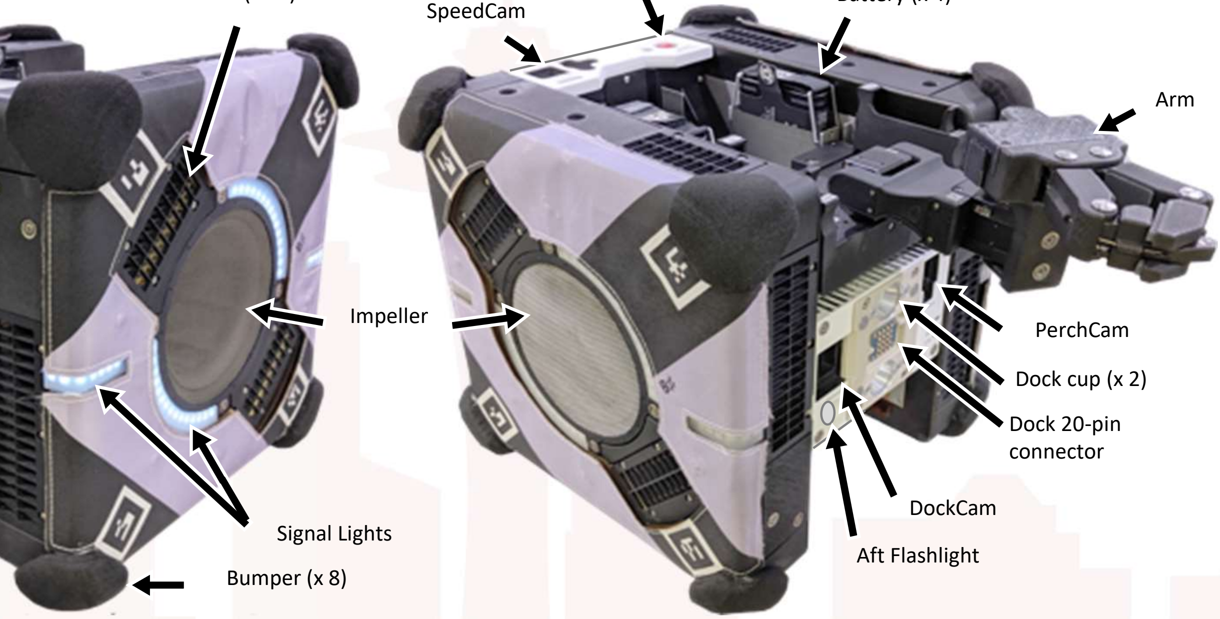
Technical Session Sponsor

Four Years of Free Flying on the ISS.

Astrobee Presentation Agenda

- Astrobee Overview
- Highlights of completed Payload Developers & Guest Researchers
- Highlights of Current Payload Developers & Guest Researchers
- Highlight of Future Payload Developer

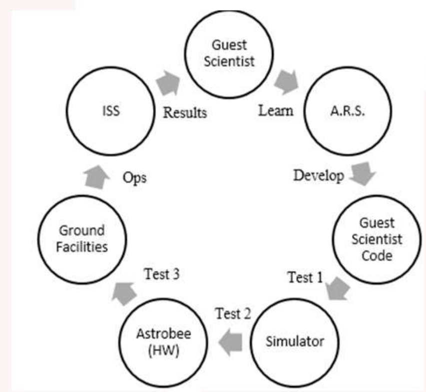
Astrobee HW Overview



- Free flying robot inside the ISS
- 32 cm wide, ~9.1kg (2 batt., no arm)
- All electric + fan-based propulsion
- Robot arm for "perching", ~1kg
- Three smartphone computers
- Three payload bays for expansion
- Microphone not currently enabled
- More: www.nasa.gov/astrobee

Astrobee Wingspan

- Payloads in ISS Integration or Operational
  - Astrobatics (NASA-DoD/Naval Postgraduate School)
  - CLINGERS (ISS NL/JPL-USC)
  - Gecko (NASA STMD/Stanford)
  - ISAAC (NASA STMD-GCD/ARC)
  - Multi-Resolution Scanner (MRS) (ISS NL/CSIRO)
  - JAXA Kibo-RPC (JAXA)
  - RFID Recon (NASA AES/REALM-2)
  - SOARS (ISS NL/Zero-g Horizons)
  - Zero Robotics (ISS NL/MIT)
- Completed Investigations:
  - Astroporter (NASA-STMD/Tethers Unlimited)
  - REGGAE (ISS NL/NanoRacks-Braunschweig)
  - ROAM (ISS NL/MIT-DLR)
  - ReSWARM (ISS NL/MIT)
  - SVGS (NASA STMD/FIT)
  - SoundSee (ISS NL/Astrobotic-Bosch)



Astrobee Utilization Stats

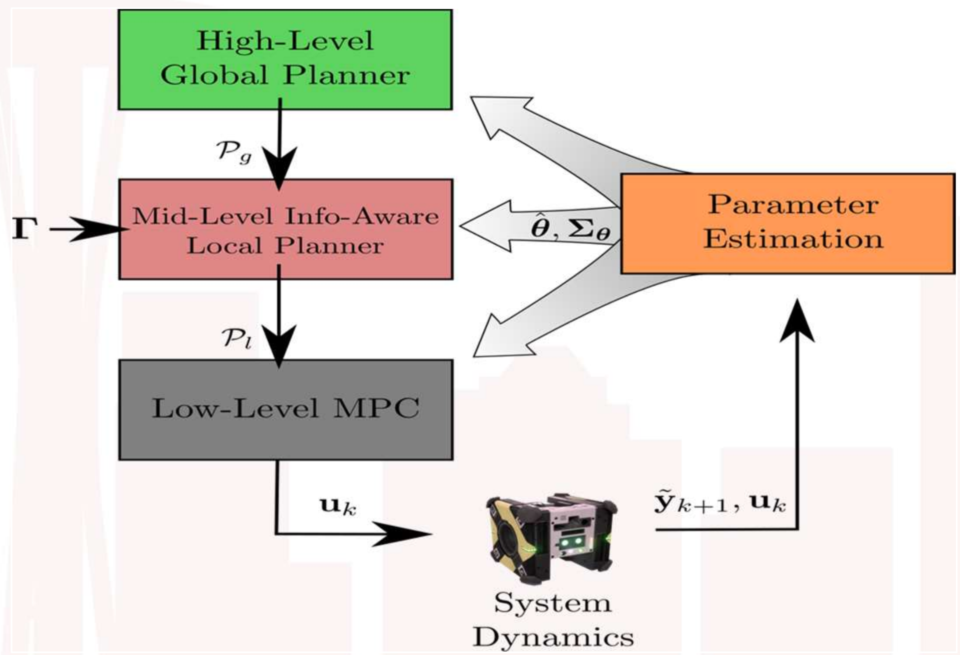
Utilization Stats to date	
Number of on orbit operations:	146
Number of on orbit REMOTE* Test Sessions	104 (71% of total operations)
Unique Crew Members trained and who have operated Astrobee on the ISS:	28
Number of on-console hours:	1030+
Crew hours	~239

Payload Developers – Guest Scientist Intro Slide

• ReSWARM & ROAM	MIT – Massachusetts Institute of Technology
• SVGS	FIT – Florida Institute of Technology
• Zero Robotics	MIT
• Astrobtics	NPS – Naval Post Graduate School & New Mexico State University
• MRS	CSIRO – Commonwealth Scientific and Industrial Research Organisation & Boeing

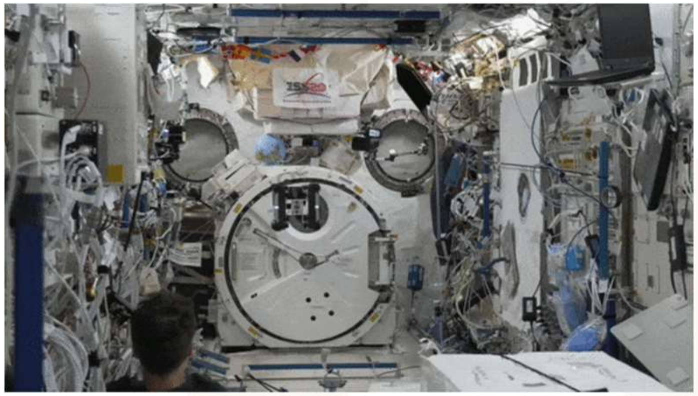
MIT/IST ReSWARM
Motion Planning that Gains Information

- ReSWARM: **R**elative **SW**arming and **A**utonomous **R**obotic **M**aneuvering
  - How to handle uncertain payloads during on-orbit maneuvering?
  - On-orbit validation of robotic planning algorithms for on-orbit assembly and informative trajectory planning
- Solution: RATTLE: **R**ealtime information-**A**ware **T**argeted **T**rajectory planning for **L**earning via **E**stimation
  - Incorporation of information-awareness explicitly in the motion planning: learn model unknowns on-the-fly
  - Multi-level framework to balance computational feasibility of robustness, model updating, and information-aware replanning



MIT/IST ReSWARM

RATTLE On-Orbit Results: Info-Aware Trajectory Generation



No information weighting

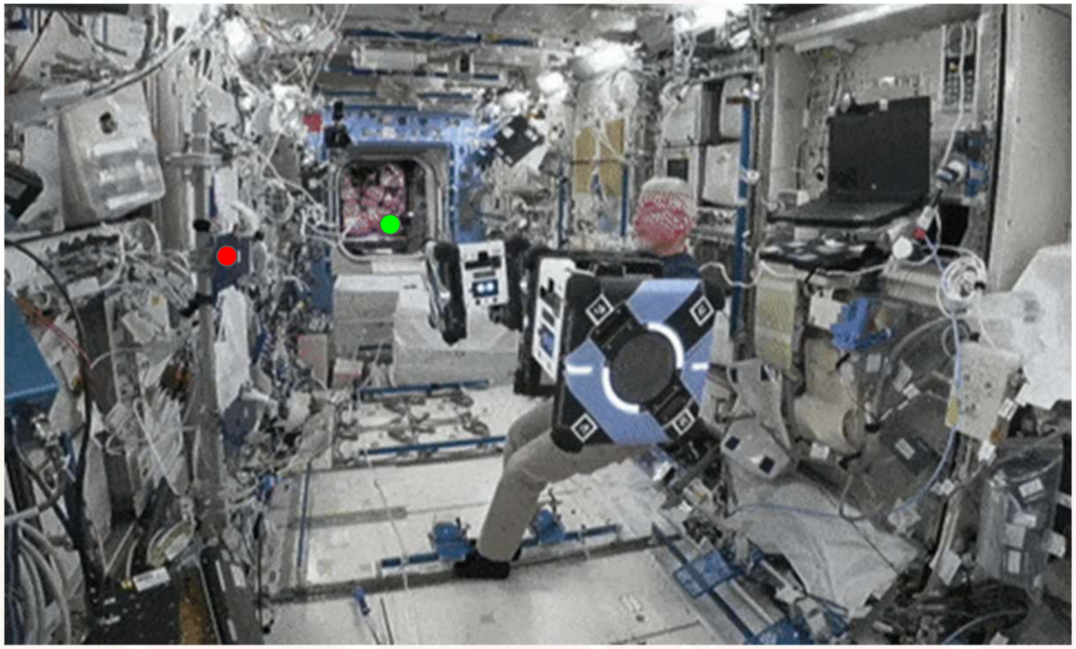
With mass and moment of inertia information weighting

RATTLE can be operated in different ways: no information weighting ignores planning for parameter learning (left). Information weighting (right) intentionally adds information-gathering maneuvers.

MIT/DLR ROAM
Envisat: A High Priority Target

- ROAM/TumbleDock
  - ➢ ROAM: **R**elative **O**perations for **A**utonomous **M**aneuvers
  - ➢ Collaboration between MIT/DLR for autonomous rendezvous with non-cooperative tumbling targets
- There is significant **uncertainty** in how these targets tumble!
  - ➢ Inertia tensor
  - ➢ Attitude/angular velocity
- Cannot know precisely until observation time
- Solution: TRACE: **T**umbling **R**endezvous via **A**utonomous **C**haracterization and **E**xecution
  - Autonomously determine tumble, plan solution, and robustly track

MIT/DLR ROAM
TRACE: Full Pipeline Rendezvous



Goal: reach an offset mating point in the Target's body frame.

MIT/DLR ROAM
Robust Control Comparison used in TRACE

Standard MPC

Robust tube MPC (same tuning)

Comparing standard and robust tube MPC reference trajectory tracking used in TRACE.

MIT Team Credits

ROAM

- K. Albee, C. Oestreich, C. Specht, R. Lampariello, R. Linares, "Autonomous Rendezvous with an Uncertain, Uncooperative Tumbling Target: the TumbleDock Flight Experiments," ESA ASTRA, 2022.
- K. Albee et al., ``A Robust Observation, Planning, and Control Pipeline for Autonomous Rendezvous with Tumbling Targets," Frontiers in Robotics and AI, vol. 8, p. 234, 2021.
- C. Oestreich, A. Teran, J. Todd, K. Albee, and R. Linares, ``On-Orbit Inspection of an Unknown, Tumbling Target using NASA's Astrobee Robotic Free-Flyers," Conference on Computer Vision and Pattern Recognition, Virtual, 2021.
- A. Teran, H. Hettrick, K. Albee, A. C. Hernandez, and R. Linares, ``End-to-End Framework for Close Proximity In-Space Robotic Missions," International Astronautical Congress (IAC), Washington, D.C., 2019.

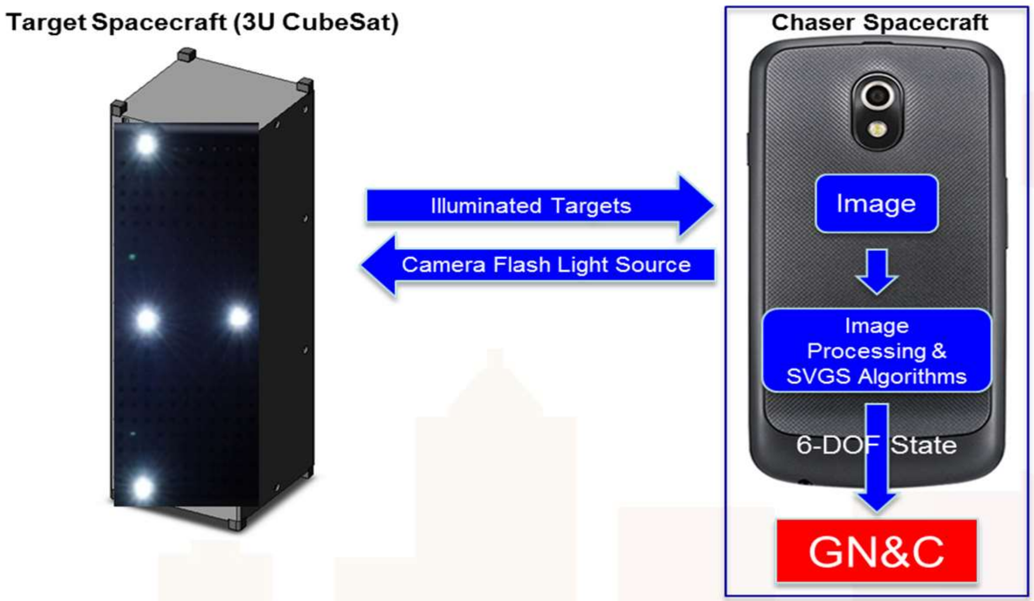
ReSWARM

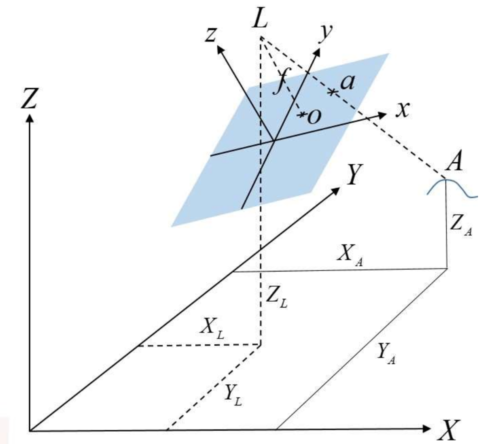
- B. Doerr, K. Albee, M. Ekal, R. Ventura, R. Linares, ": The ReSWARM Microgravity Flight Experiments: Planning, Control, and Model Estimation for On-Orbit Close Proximity Operations," Journal of Field Robotics, 2022. (Submitted).
- K. Albee, M. Ekal, B. Coltin, R. Ventura, R. Linares, D. Miller, "RATTLE: A Real-Time Information-Aware Motion Planning Framework for Online Parametric Model Learning," Robotics and Automation, Letters (IROS), 2022.
- M. Ekal and K. Albee, B. Coltin, R. Ventura, R. Linares, and D. W. Miller, ``Online Information-Aware Motion Planning with Inertial Parameter Learning for Robotic Free-Flyers," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2021
- W. Parker, K. Albee, and R. Linares, ``Spacecraft Dynamics Model Learning and Control with Gaussian Process Regression," AAS/AIAA Astrodynamics Specialist Conference, 2021
- B. Doerr, K. Albee, M. Ekal, R. Linares, and R. Ventura, ``Safe and Uncertainty-Aware Robotic Motion Planning Techniques for Agile On-Orbit Assembly," AAS/AIAA Astrodynamics Specialist Conference, 2021
- K. Albee and A. C. Hernandez, ``The Case for Parameter-Aware Control of Assistive Free-Flyers," AIAA SciTech GNC, 2021
- K. Albee and M. Ekal, R. Ventura, and R. Linares, "Combining Parameter Identification and Trajectory Optimization: Real-Time Planning for Information Gain," ESA Advanced Space Technologies for Robotics and Automation (ASTRA), Noordwijk, The Netherlands, 2019

Vision-Based Navigation for Formation Flight on the ISS SVGS

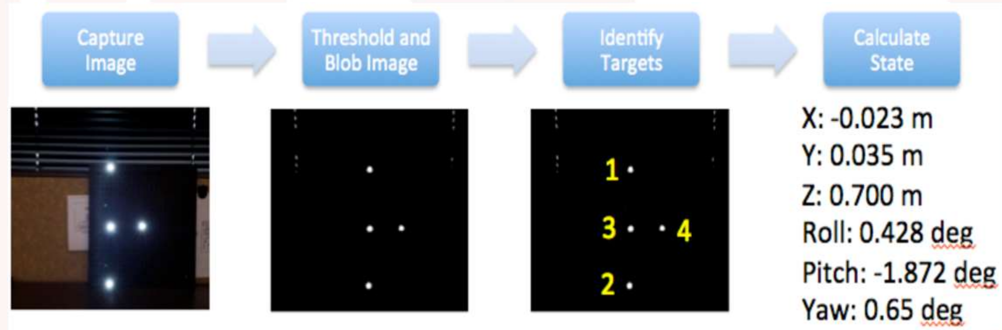
HECTOR GUTIERREZ
FLORIDA INSTITUTE OF TECHNOLOGY - AEROSPACE SYSTEMS AND PROPULSION LAB

SVGS: Smartphone Video Guidance Sensor





Object and Camera Frame Geometry in SVGS



Smartphone captures images of SVGS beacon

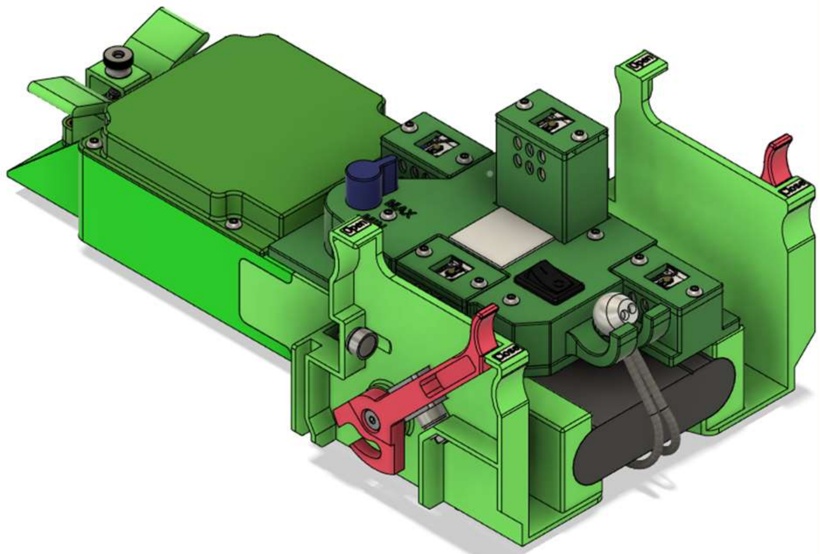
- **Capture image of 4-LED illuminated targets**
- **6-DOF state extracted from 2D image based on photogrammetry**

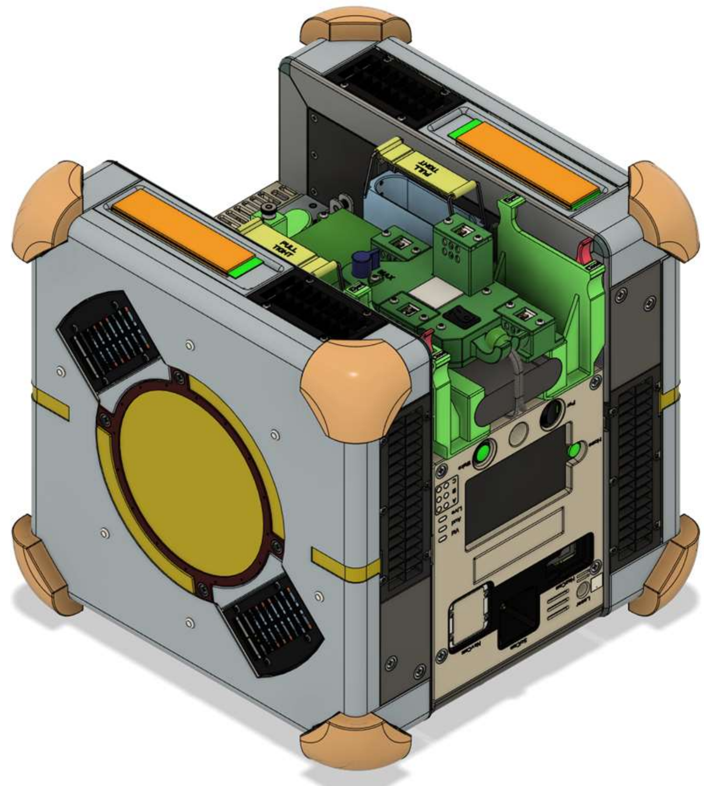
SVGS Mission on ISS

1. Demonstrate SVGS as position-attitude SOFTWARE sensor deployed using Astrobee's hardware resources
2. Assess SVGS performance in proximity maneuvers on ISS:
    - Stand-alone maneuvers: SVGS readings compared to Astrobee metrology
    - Formation flight maneuvers: SVGS is used to generate motion commands to Astrobee in leader-following formation flight
    - Demonstrate SVGS in Multi-target operation: multiple SVGS beacons of different color support range extension and formation flight

SVGS Payload- Rev 7

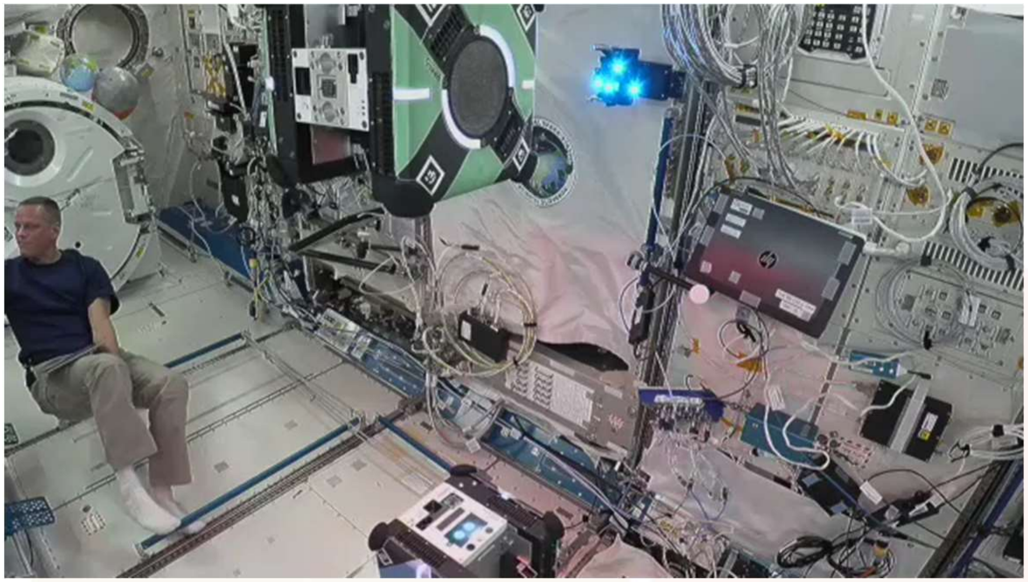
- SVGS payload uses M561payload interface
- Bungee cord retention for battery
- Battery over-discharge protection circuit
- EM shield changed to Mu-metal foil
- ULTEM 9085

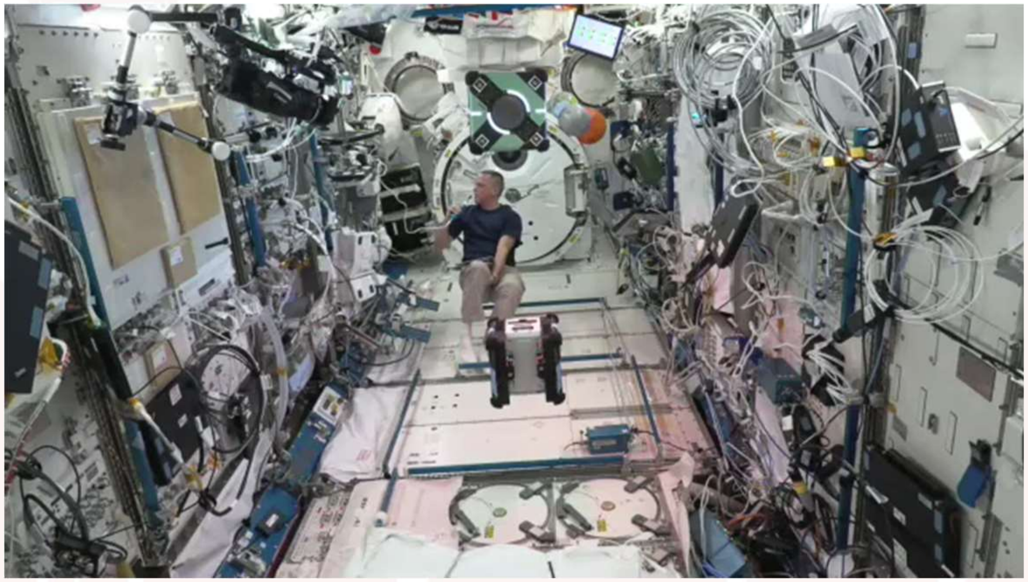




Maneuver 2A (Queen) + 2F (Bumble)

SVGS-2: 06 July 2022





space enabled

innovation learning center

ISS U.S. NATIONAL LABORATORY

NASA

Aurora FLIGHT SCIENCES

NAVAJO TECHNICAL UNIVERSITY

K.A.R.M.A.

CALIFORNIA STATE UNIVERSITY LONG BEACH 1949

STEM 365

Access to quality education is a human right

A competition

- *Middle School (5 weeks in summer)*
- *High School (3 months in fall)*

A programming challenge

- *Students program on space robots*
- *Software-based and game-specific*

Zero is for **Zero Cost**

- *No entry fees*

Zero is for **Zero Configuration**

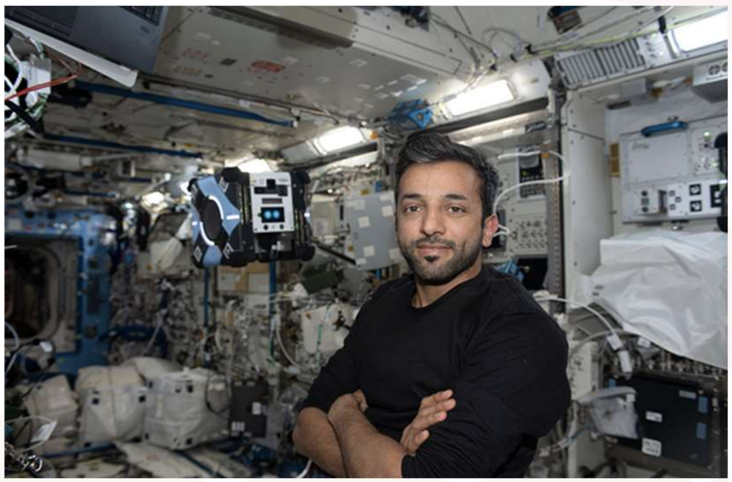
- *Everything is programmed online*

Zero is for **Zero Gravity**

- *Final competition occurs aboard the ISS*

Zero Robotics Programming Challenge, 2023

جامعــة خليفــة
Khalifa University



جــامعــة الشــارقــة
UNIVERSITY OF SHARJAH

The first UAE Zero Robotics Programming Challenge (ZRPC) was held with 7 UAE teams from 5 universities during May and June 2023. The final event was hosted by UAE Astronaut Sultan Al Nayedi on the ISS.

AUD
AMERICAN UNIVERSITY IN DUBAI

كليــات التقنيــة العليــا
Higher Colleges of Technology

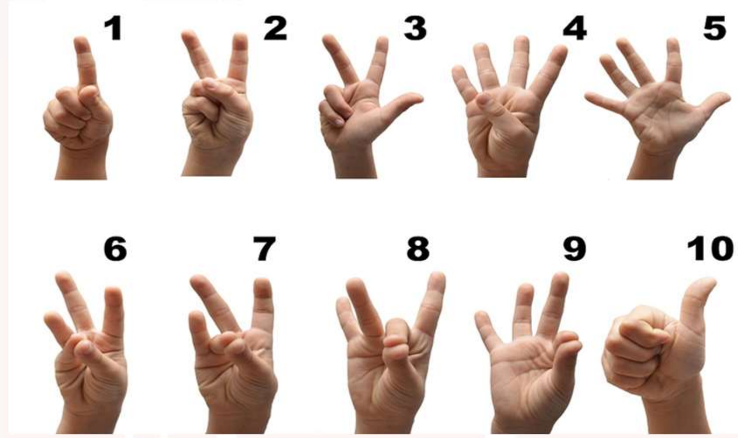
جامعة الإمارات العربية المتحدة
United Arab Emirates University
UAEU

Summer 2023 Zero Robotics Middle School Game: “LUNABEE” – a moon-based science adventure

Game Phase 1: Hand Signal Recognition

This 2023 Zero Robotics Middle School Competition will include the gesture recognition on Astrobee for the first time and expects to have about 700 student participants.

The Astronaut communicates with Astrobee using American Sign Language (ASL) to give instructions to the robot about a simulated lunar sample collection mission



NAVAL
POSTGRADUATE
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Spacecraft Robotics
LABORATORY

ASTROBATICS
An Advanced Free-Flyer Maneuver Experimental Campaign using Astrobee

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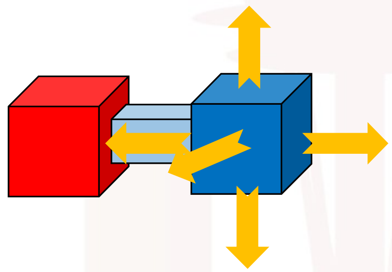
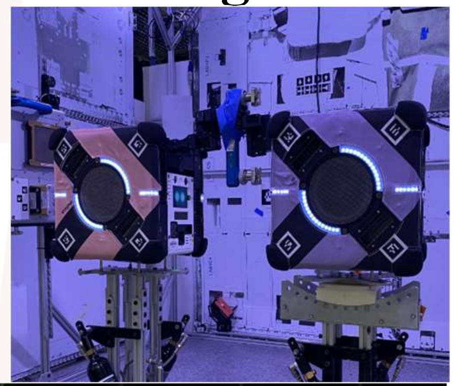
Current Graduate Students:
Isuru Basnayake, PhD Candidate, NMSU
John Martinez, NMSU
Maj. Jonathan Kohler, NPS

S4: TR-MPC vs. Standard MPC for Cargo Retrieval

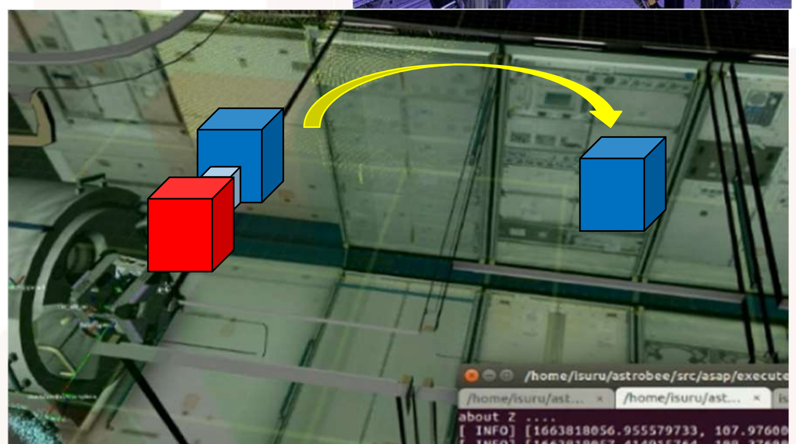
Comparison of Tube Based Robust MPC (TRMPC) and Standard MPC (SMPC) for cargo retrieval in cases where cargo mass estimates are inaccurate





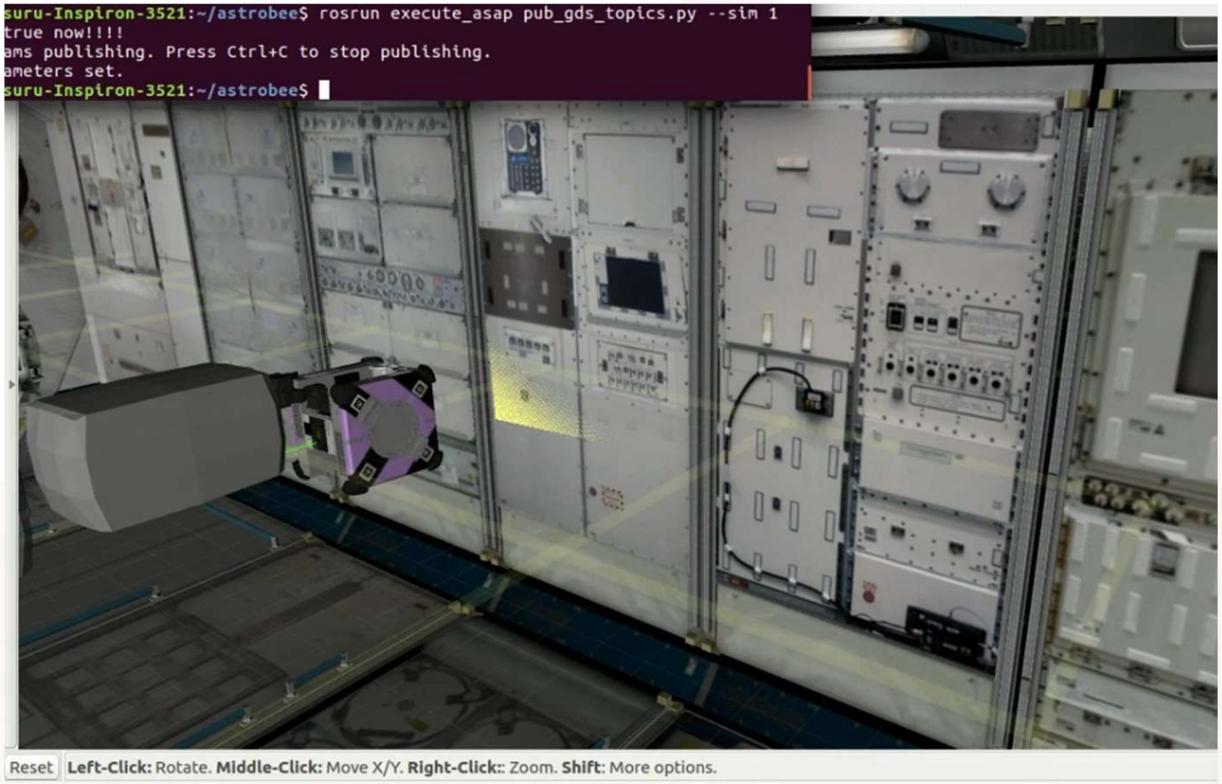
S4 Astrobatics Maneuver Plan:

- Initial Conditions
  - Two Astrobees gripping same free-floating handrail
  - One Astrobee is active, one is passive and acting as cargo
- Set at same configuration and starting location
- Use thrusters to move to a goal location
- Repeat for progressively worse mass estimates



Topic: S1 / S2a / S2b / S3/ S4 / S5

Gazebo Simulation: Tube-Based MPC for Cargo Retrieval

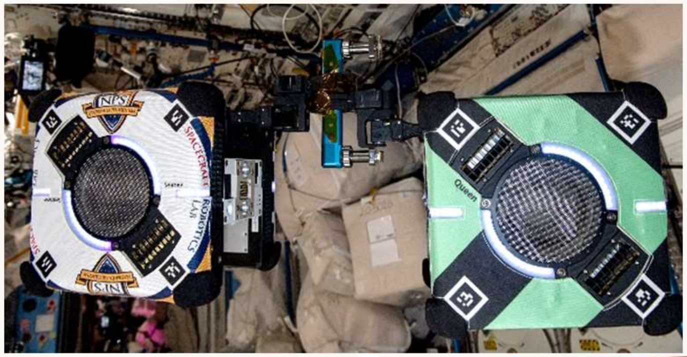


Tested with a 10kg cargo estimate

ISS Experiment: Tube-Based MPC for retrieval of cargo with inaccurate inertia estimates

Tested with a 10kg cargo estimate (inactive Astrobee)

- **Initial Condition:**
  2 Free-floating Astrobee vehicles grasping onto a common handrail
- Active Astrobee moves from initial position to goal position
- Goal position issue

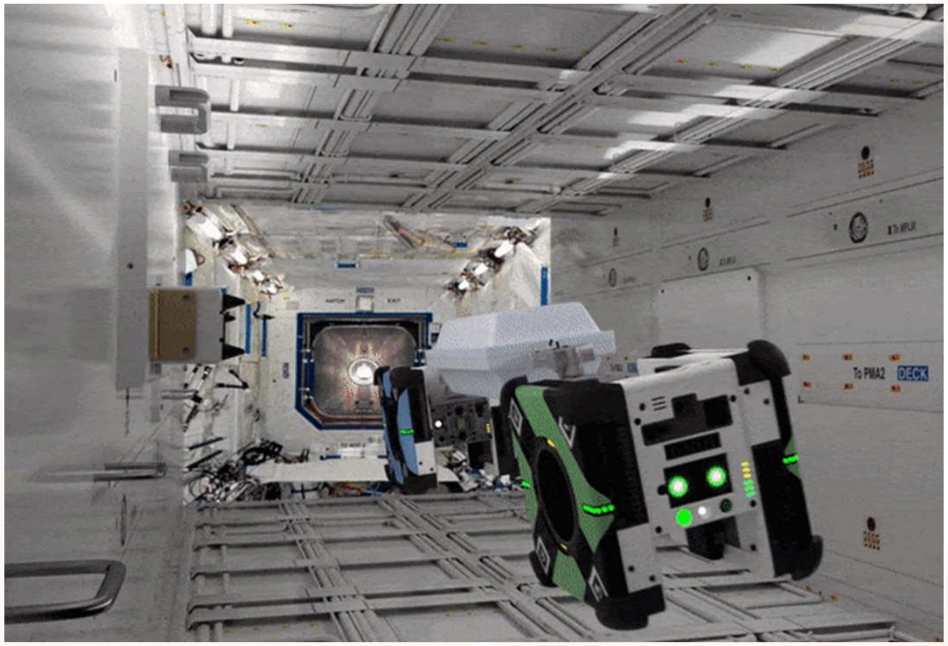


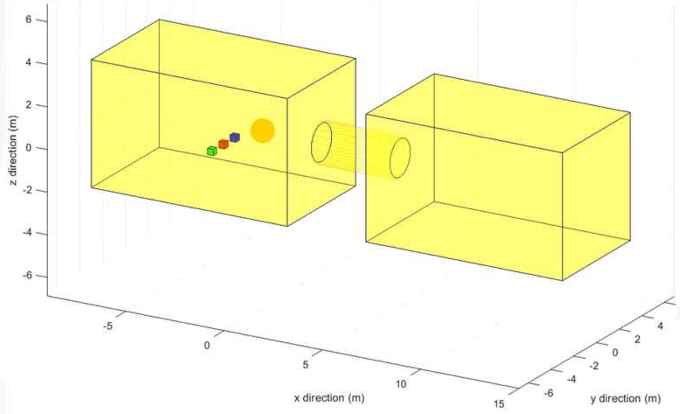
Topic: S1 / S2a / S2b / S3/ S4 / S5

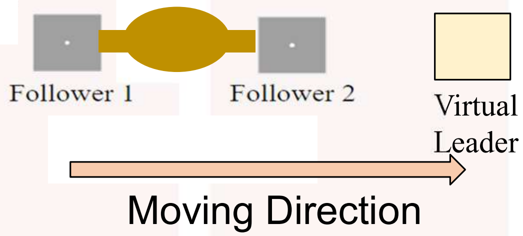
S5: Multi-Agent Cargo Transportation (late summer 2023)

Two Astrobees move one cargo bag using a Decentralized MPC framework

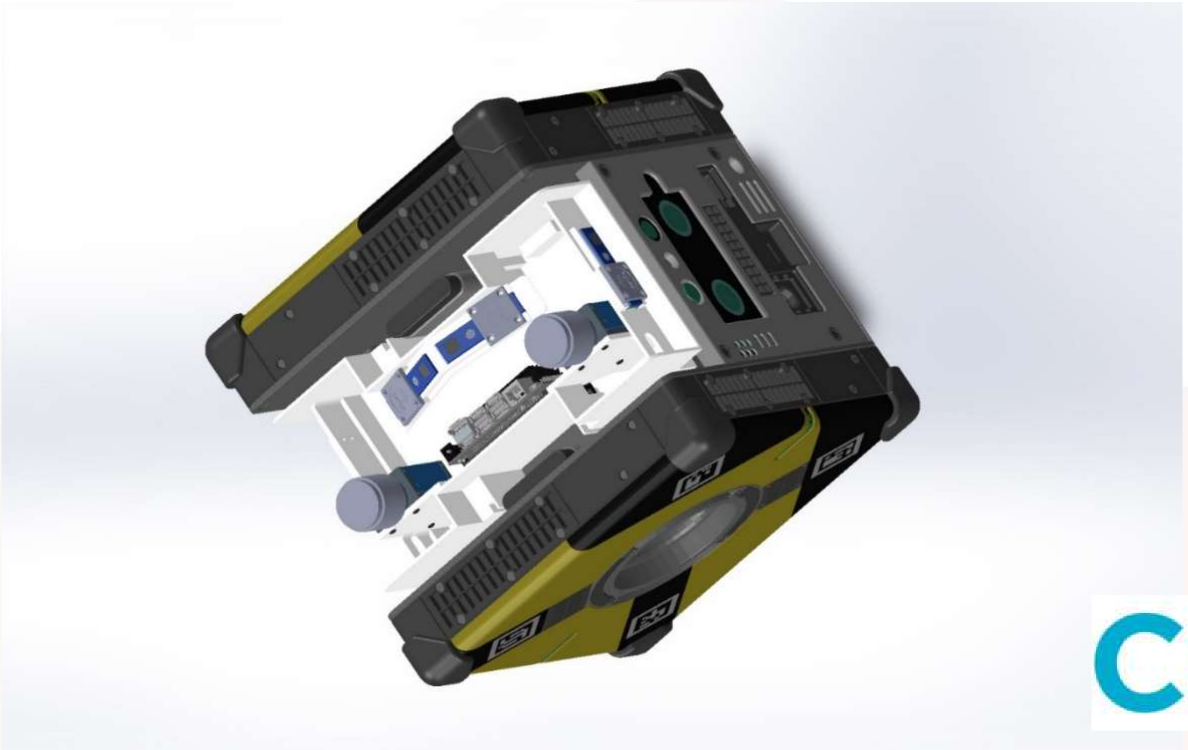
Prior work: Formation flying by DMPC framework







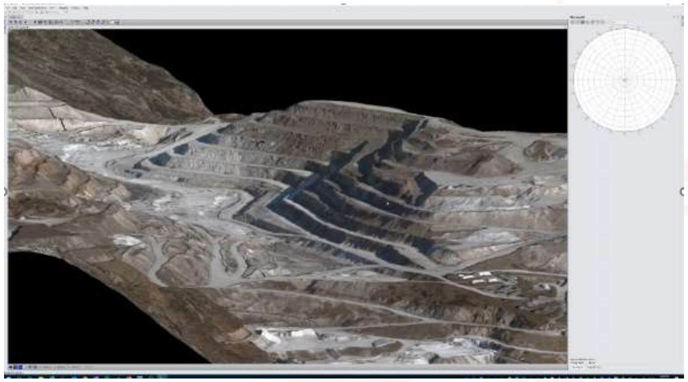
Multi-resolution scanning (MRS) payload for the International Space Station



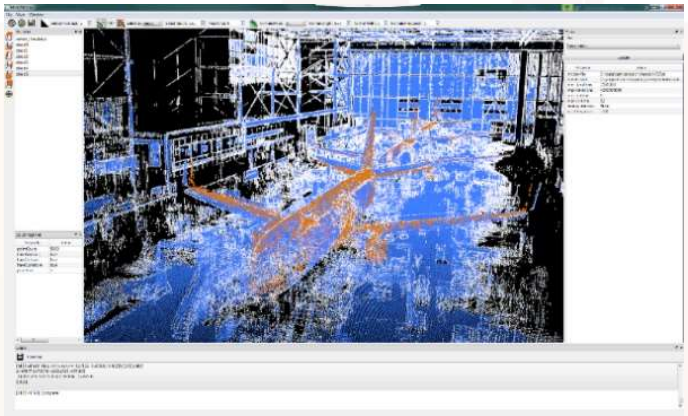
CSIRO

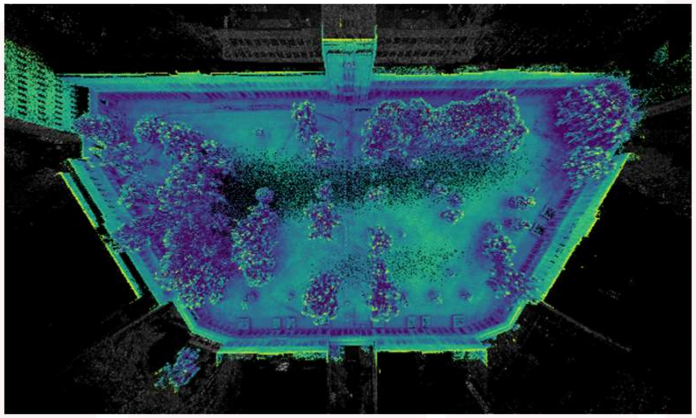
Multi resolution scanning – key technologies

CSIRO Stereo-Depth Fusion (SDF)
– Hi resolution stereo-depth fusion scanning



CSIRO WildCat SLAM
(Simultaneous Localisation and Mapping) – large area positioning and mapping

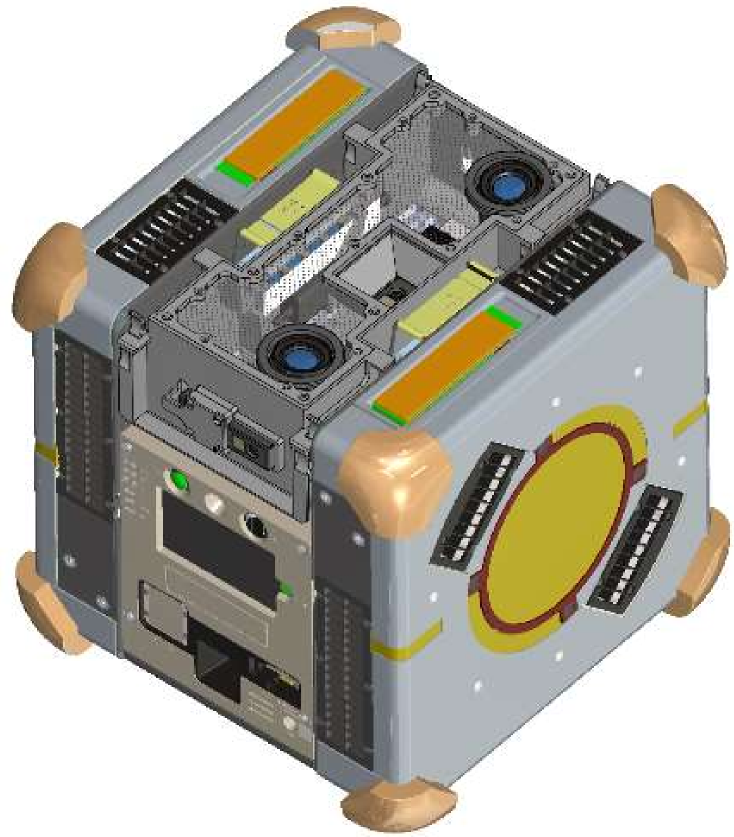




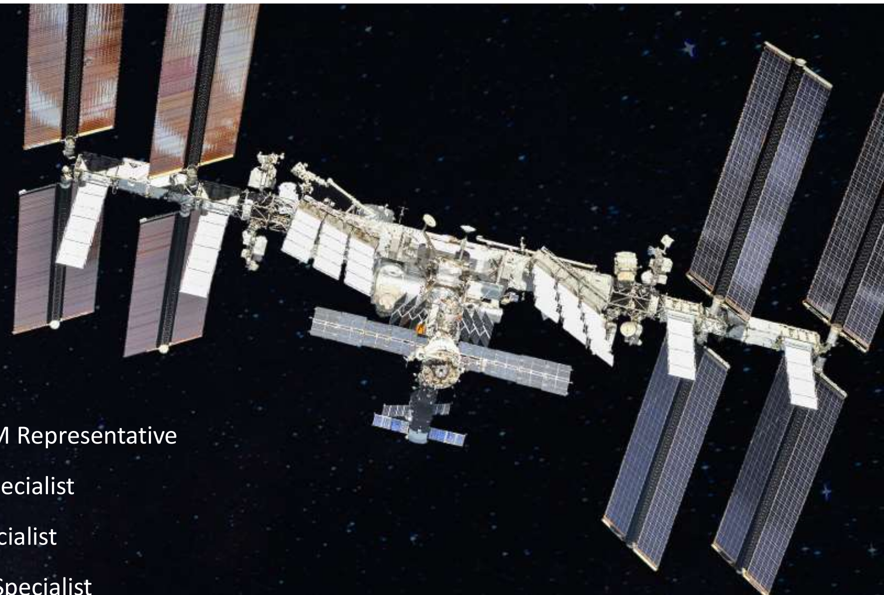
- CSIRO collaboration with Boeing to develop a fused sensor system for space based autonomous multi-resolution 3D scanning
- Interior ISS/Gateway using autonomous scanning, supported by NASA's Astrobee robot

Payload Specifications

- ULTEM Housing
- Compute - Xavier NX
- Stereo camera - Allied Vision
- Additional sensors - Picoflexx (x 3) & IMU
- Total mass: ~1500gms




QUESTIONS?



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Melissa Boyer - Payload Integration Manager Backup

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