Multi-Agent 3D Map Reconstruction and Change Detection in Microgravity with Free-Flying Robots

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*Equal contribution, Co-Presenters

NASA astronaut Shane Kimbrough poses aboard the International Space Station with three Astrobee robotic free-flyers.
Credit: NASA

Team

Paper→

https://hollydinkel.github.io/assets/pdf/IAC2023.pdf


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Introduction

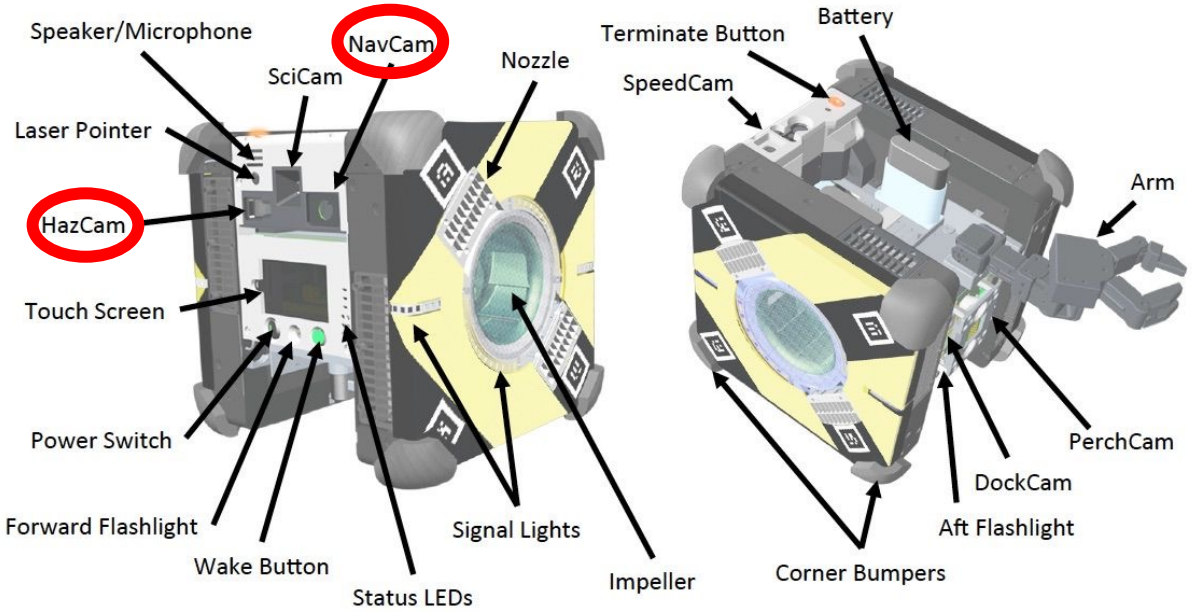
Motivation

- Astronaut time is limited
- Future orbital outposts potentially uncrewed
- Astrobee robotic free-flyer as astronaut assistant
  - Automate visual surveying

Astronaut Anne McClain with an Astrobee unit.
Credit: NASA

Motivation

- Astrobee developed by NASA Ames for ISS operation
  - 32cm cube-shaped mobile sensor platform
- Two sensors in this work:
  - NavCam: fixed-focus color camera, wide field of view (1 Hz)
  - HazCam: depth sensor, to generate environment point clouds

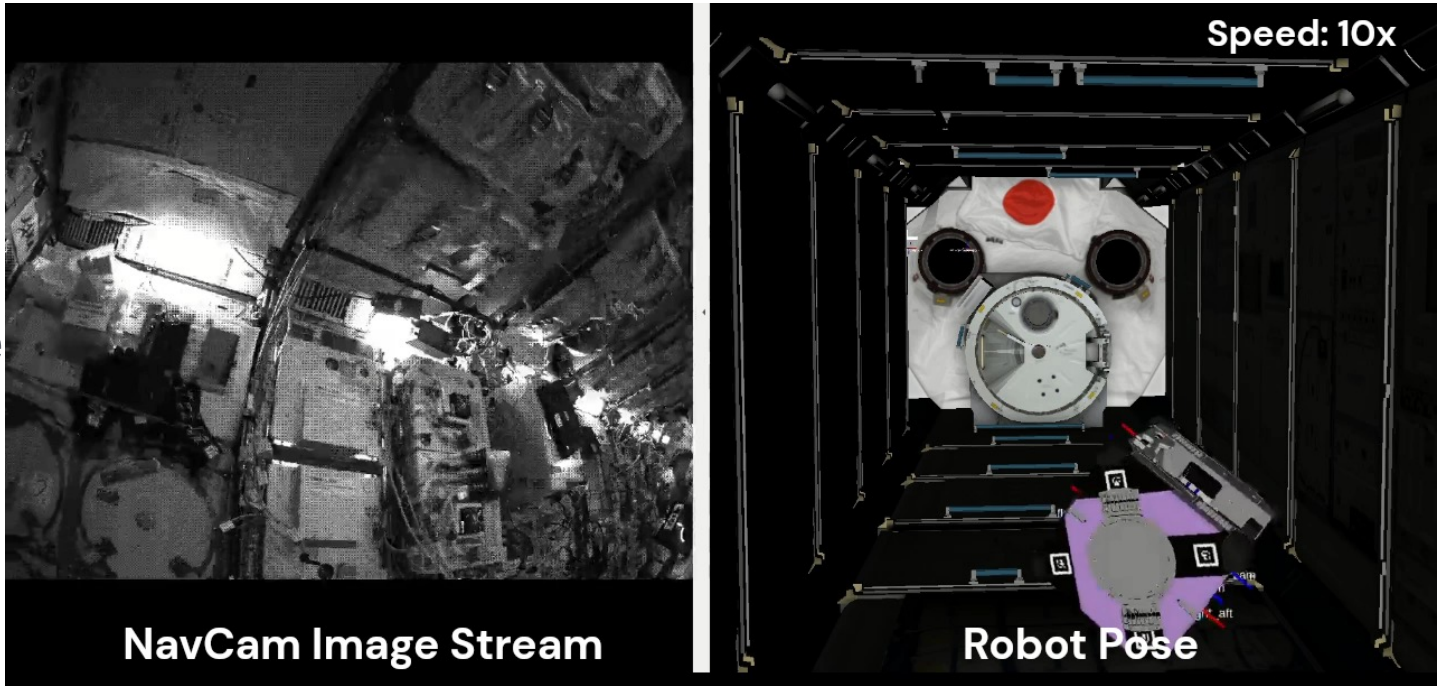


Astrobees are equipped with many sensors such as the HazCam and NavCam.

T. Smith, J. Barlow, M. Bualat, T. Fong, C. Provencher, H. Sanchez, and E. Smith. “Astrobee: A New Platform for Free-Flying Robotics on the International Space Station.” *In Int. Sympos. Artif. Intell. Robot. Autom. in Space (i-SAIRAS),* 2016.
NASA, “Astrobee,” Available: https://github.com/nasa/astrobee

Motivation

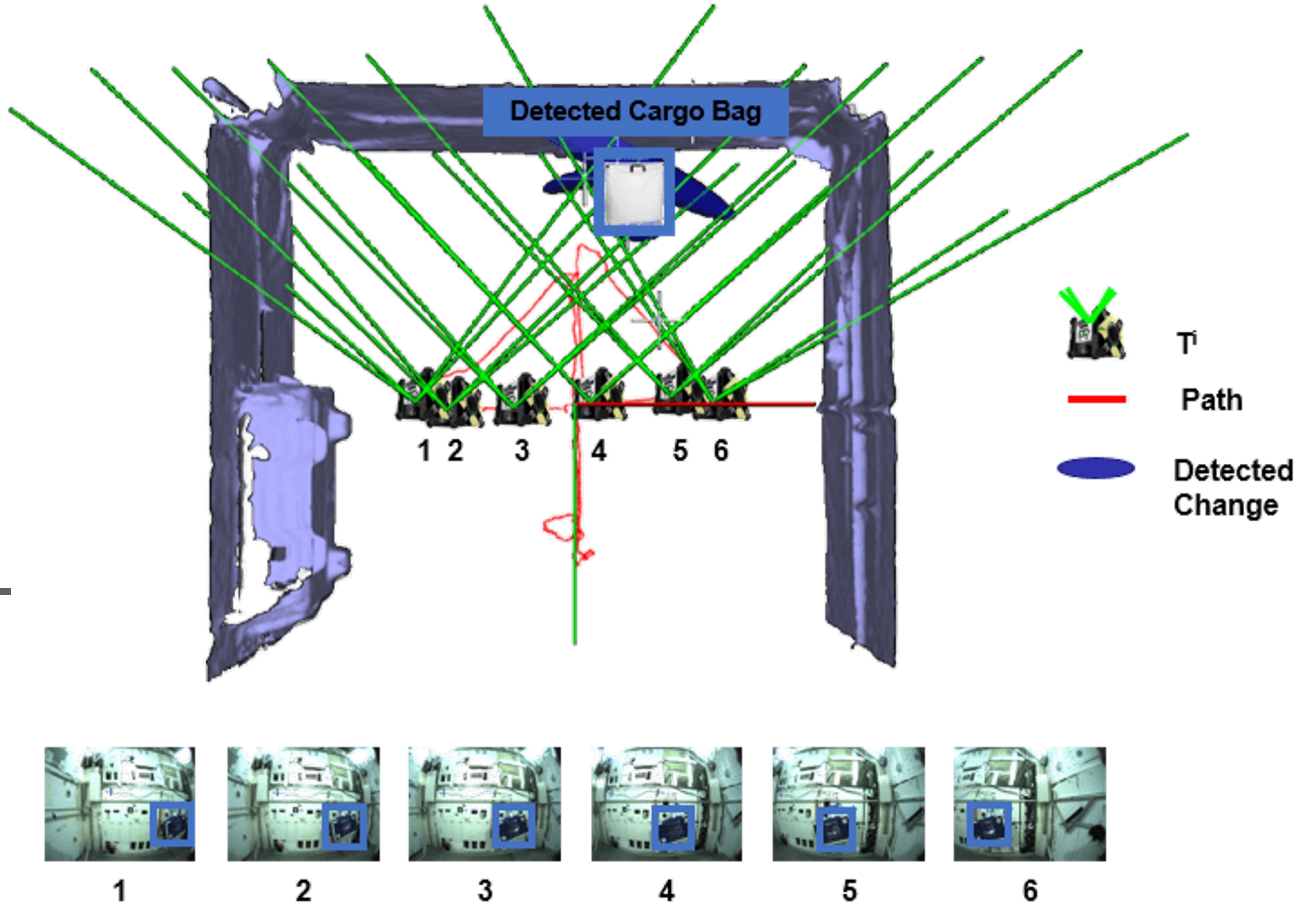
- Robots need updated maps but updating robot map is expensive
  - Astrobee on ISS Japanese Experiment Module (JEM)
- More efficient to only recompute local changes



NASA, “Astrobee,” Available: https://github.com/nasa/astrobee

Fast Change Detection

- Fast Image-Based Geometric Change Detection (FastCD)
- Fast geometric projection on small batches (<10) consecutive images
- Can be deployed in near-real-time on resource-constrained mobile robots



E. Palazzolo, C. Stachniss, "Fast Image-Based Geometric Change Detection Given a 3D Model" in *IEEE Int. Conf. Robot. Autom. (ICRA),* May 2018, pp. 6308—6315.

Contributions

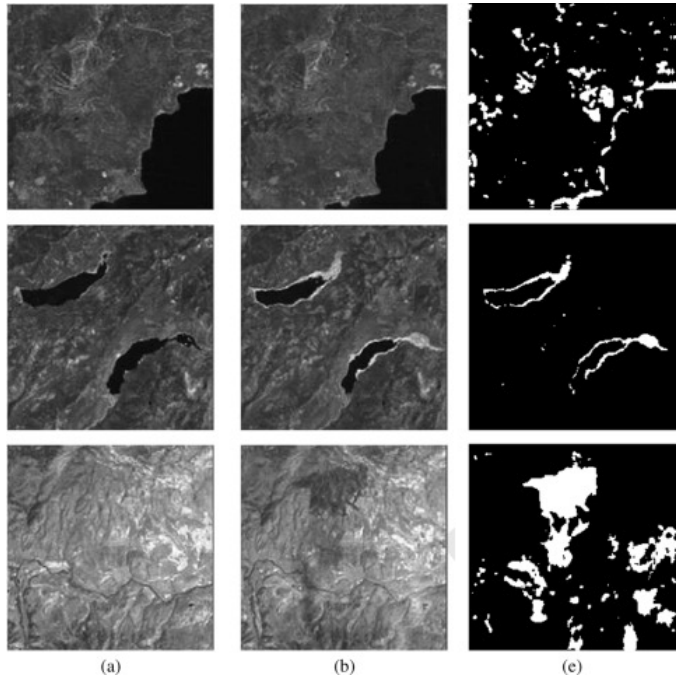
- Discussion of scene change detection framework on free-flyers
- Discussion of scene change detection considerations for resource-constrained robots in a space environment
- Demonstration and evaluation of method on Granite Lab and ISS data
- Open release of Granite Lab and ISS dataset

Astronaut Megan McArthur poses with an Astrobee robotic free-flyer.
Credit: NASA

Related Work

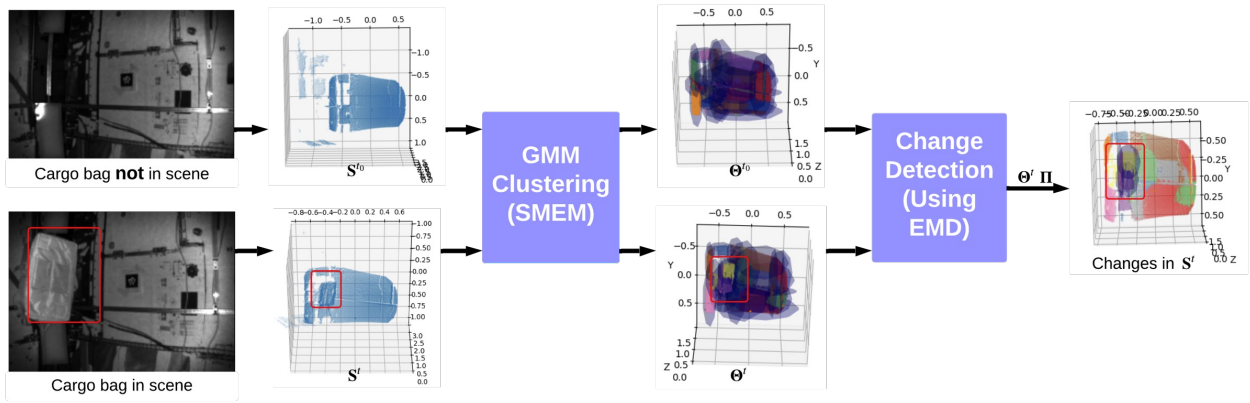
Related Work

2D Change Detection



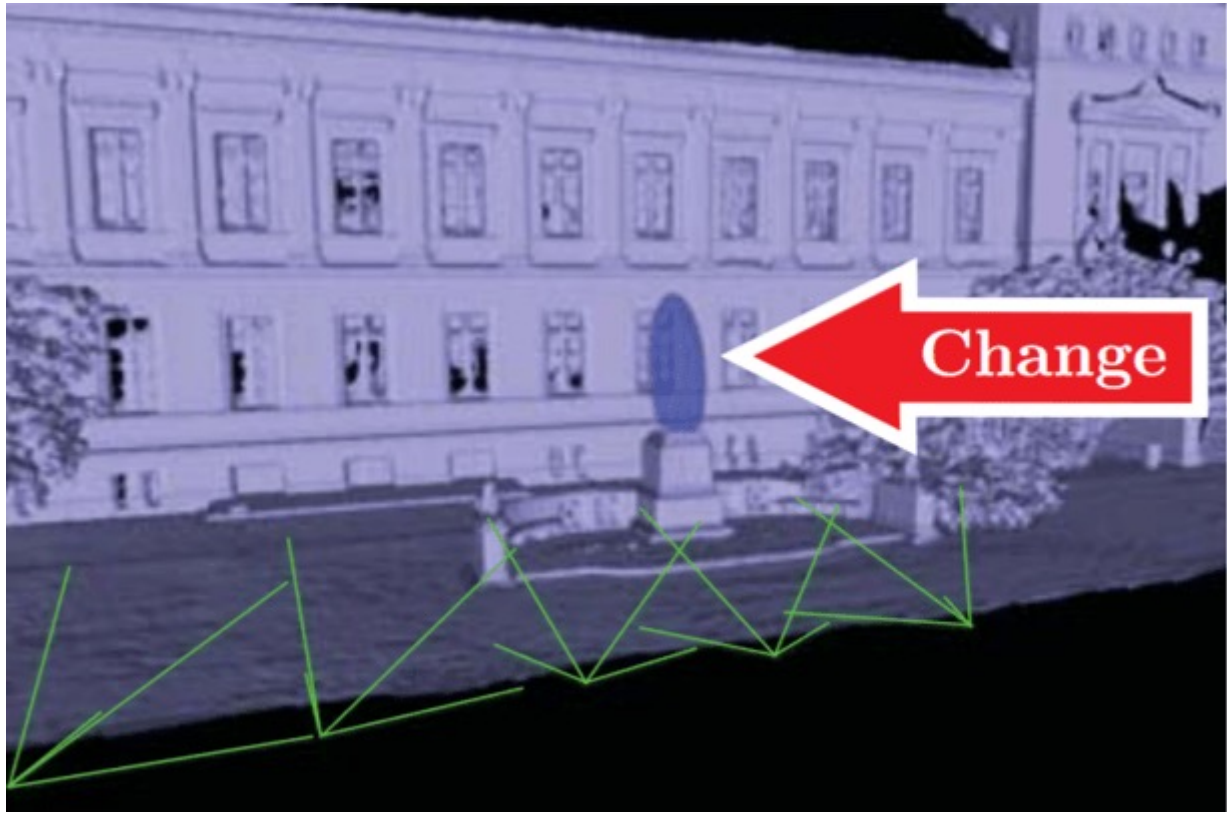
T. Celik. “Unsupervised Change Detection in Satellite Images Using Principal Component Analysis and K-Means Clustering.” *IEEE Geosci. Remote Sens. Lett.*, 6(4):772–776, 2009.

3D Change Detection



J. Santos, H. Dinkel, J. Di, P. V.K. Borges, M. Moreira, B. Coltin, and T. Smith. “Unsupervised Change Detection for Space Habitats Using 3D Point Clouds.” In *AIAA SciTech F.,* 2024.

Related Work



3D Change Detection with Images

- 3D change detection method based on sequences of images against a 3D world model
- Fast enough for a mobile system

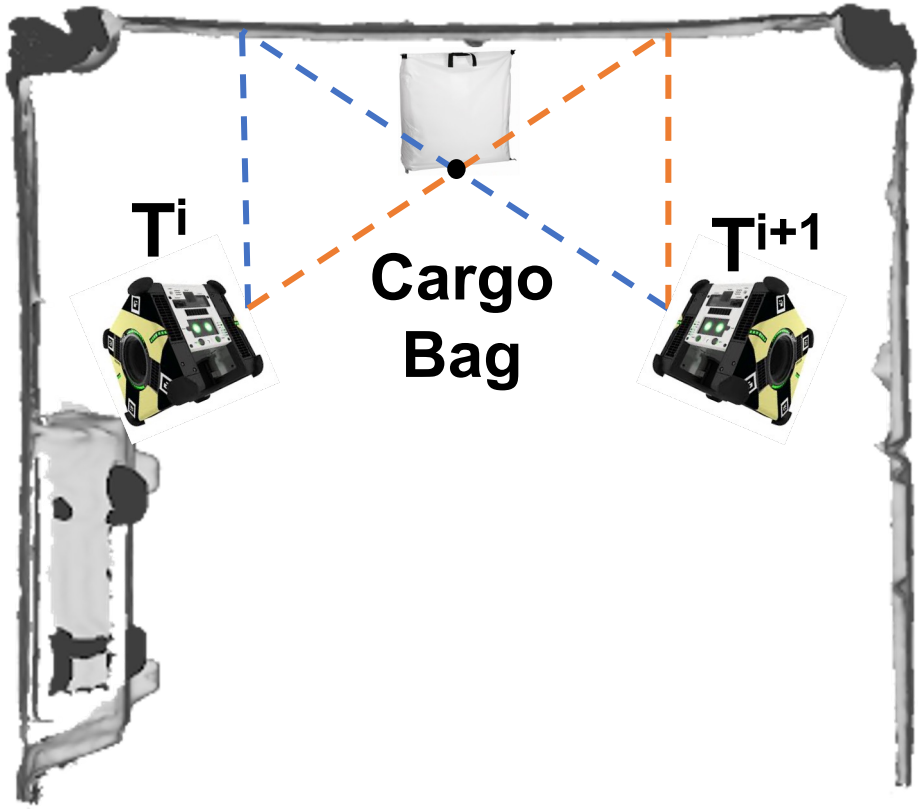
E. Palazzolo, C. Stachniss, “Fast Image-Based Geometric Change Detection Given a 3D Model” in *IEEE Int. Conf. Robot. Autom. (ICRA),* May 2018, pp. 6308—6315.

Methodology

Methodology

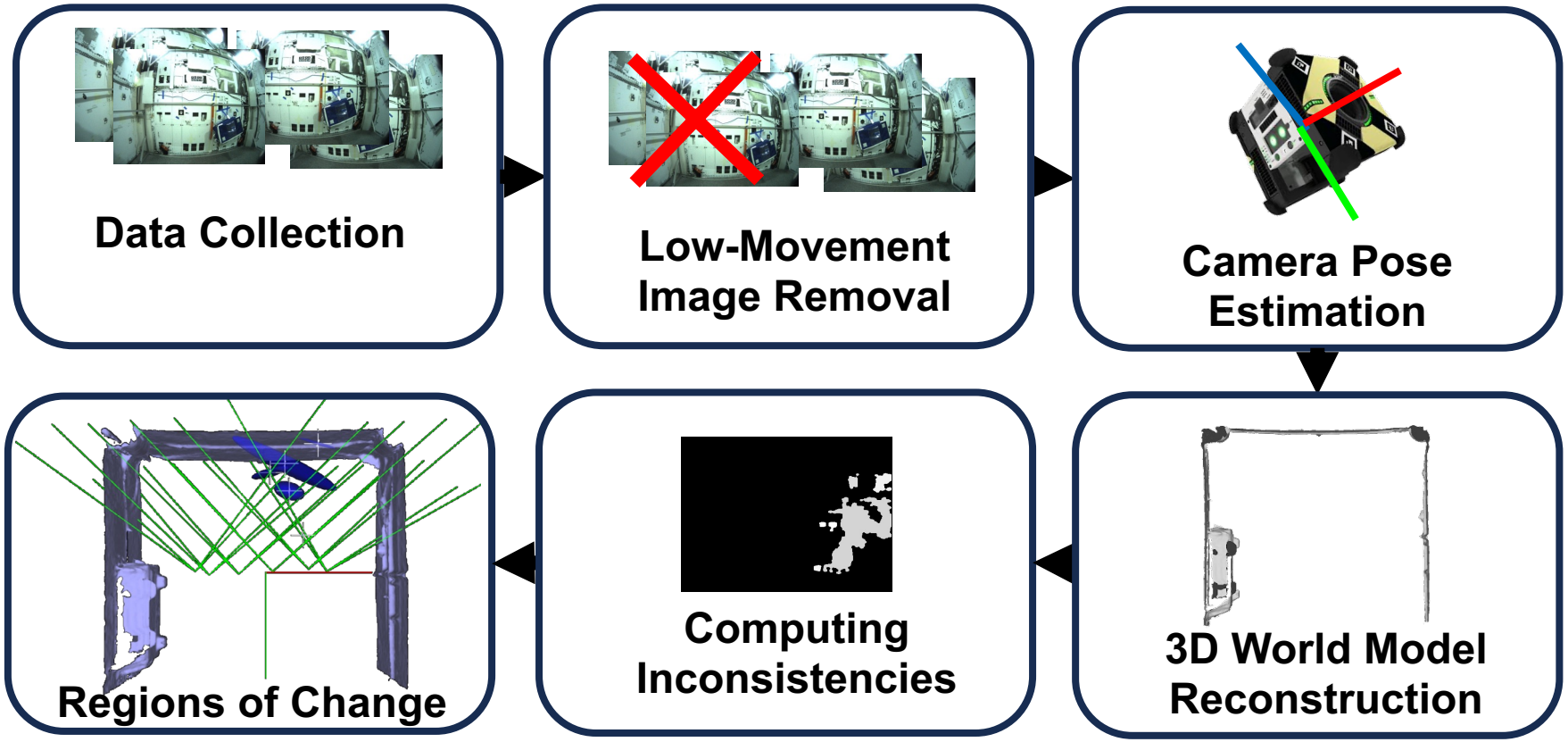
- Geometric intuition for FastCD
  - Back-project image I^i into 3D World model
  - Re-project I^i onto image plane I^{i+1}
  - Pixelwise differences are changes
- Multi-agent:
  - One robot survey is used to construct the world model
  - One robot survey is used to detect local changes

Known 3D World Model



Methodology

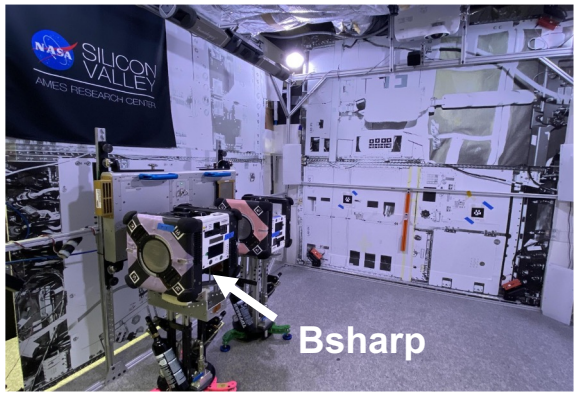
FastCD computes regions of change in 3D using sequences of RGB images and their camera pose



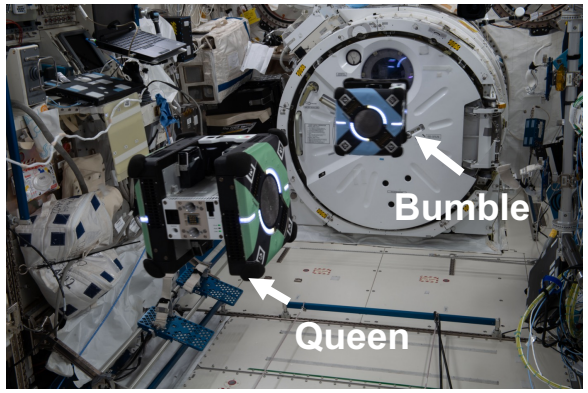
Data Collection

- Five surveys collected with an Astrobee unit in a ground test environment with “Bsharp” Astrobee
- Granite Lab
  - Paths incorporate more translation
  - 3DOF microgravity simulated with air bearings
  - Highly structured
- Six surveys collected with Astrobee units on ISS with “Bumble” and “Queen” Astrobees
- ISS
  - Paths incorporate more rotation
  - 6DOF microgravity is real
  - Highly cluttered

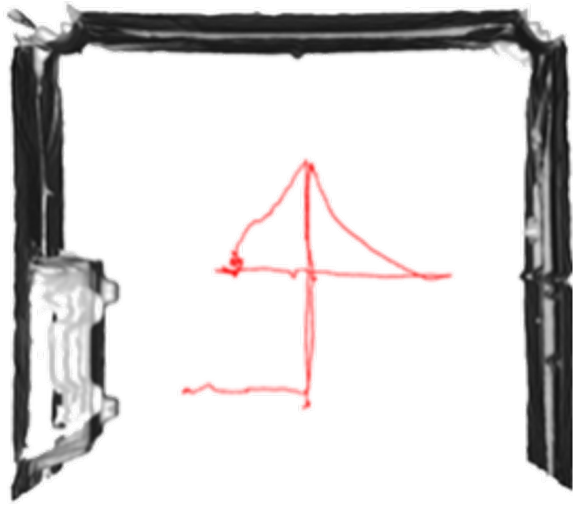
Granite Lab



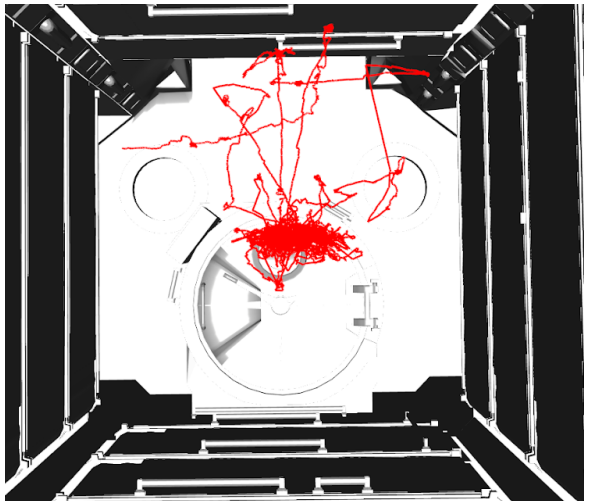
ISS*



Bsharp Path in Granite Lab



Bumble Path in ISS JEM

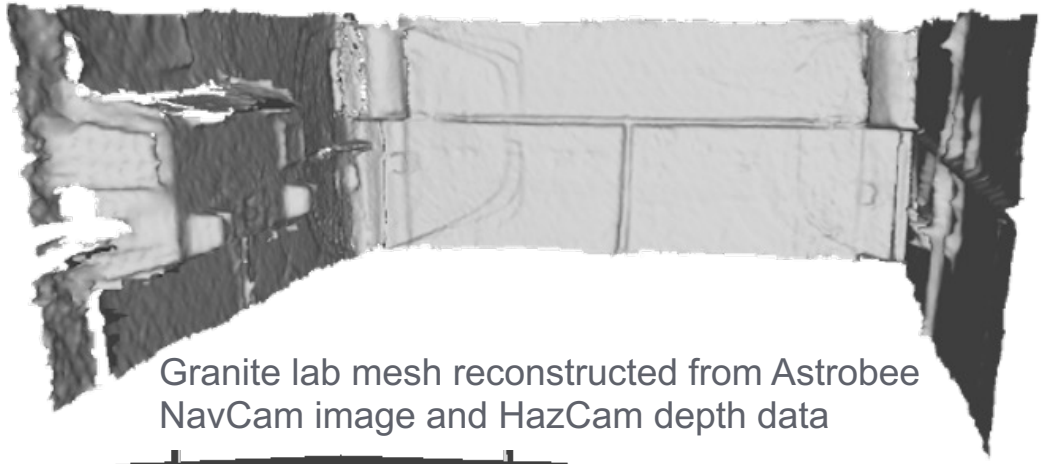


NASA, “Astrobee,” Available: https://github.com/nasa/astrobee

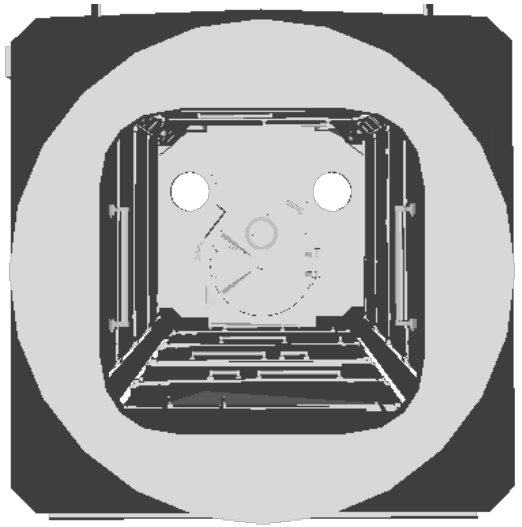
*Image Credit: NASA. Available: https://www.nasa.gov/collection-asset/isaacastrobee-team-successfully-completes-11th-joint-space-station-activity

3D World Reconstruction

- Image data from the NavCam are registered with depth information from the HazCam using structure-from-motion
- Depth point clouds are fused into a mesh using camera poses
- The Granite Lab 3D world model (top right) is included with the contributed dataset
- The simulated ISS JEM 3D World model (bottom right) is included with the contributed dataset



Granite lab mesh reconstructed from Astrobee NavCam image and HazCam depth data



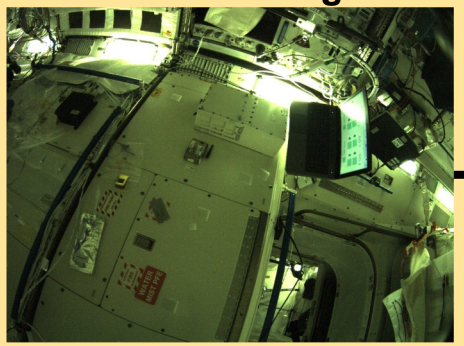
Simulated ISS JEM 3D model

R. A. Beyer, O. Alexandrov, and S. McMichael. “The Ames Stereo Pipeline: NASA’s Open Source Software for Deriving and Processing Terrain Data.” *Earth Space Sci.*, 5, 2018.
R. Soussan, V. Kumar, B. Coltin, and T. Smith. “AstroLoc: An Efficient and Robust Localizer for a Free-flying Robot.” *IEEE Int. Conf. Robot. Autom. (ICRA)*, pages 4106–4112, 2022.
C. Sweeney. “Theia Multiview Geometry Library: Tutorial & Reference.” [Online] Available: http://theia-sfm.org, 2023.

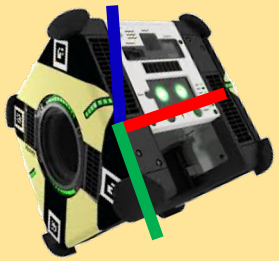
Computing Inconsistencies

Inputs

NavCam Image



Robot Pose

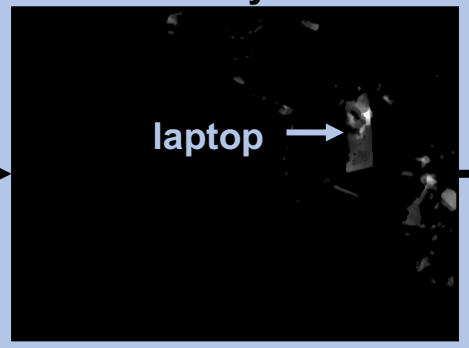


NavCam Extrinsics

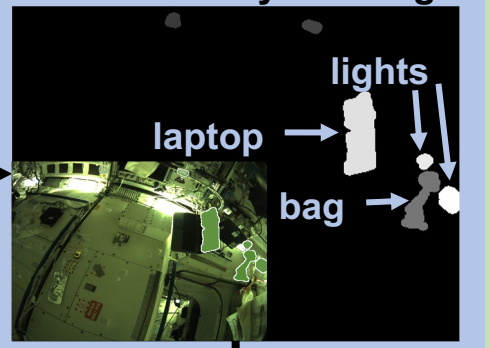
$^{Astrobee}X_{NavCam}$

Image Comparison

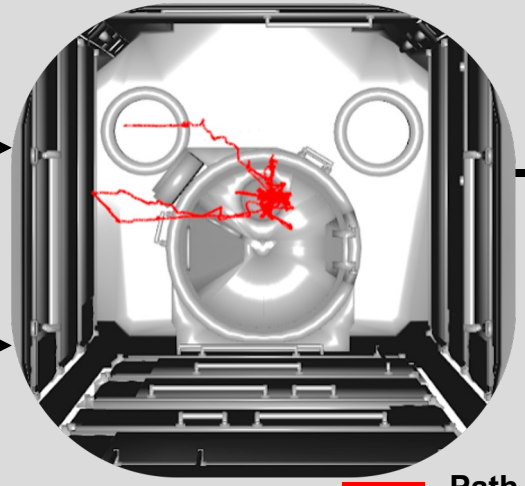
Inconsistency Detection



Inconsistency Filtering



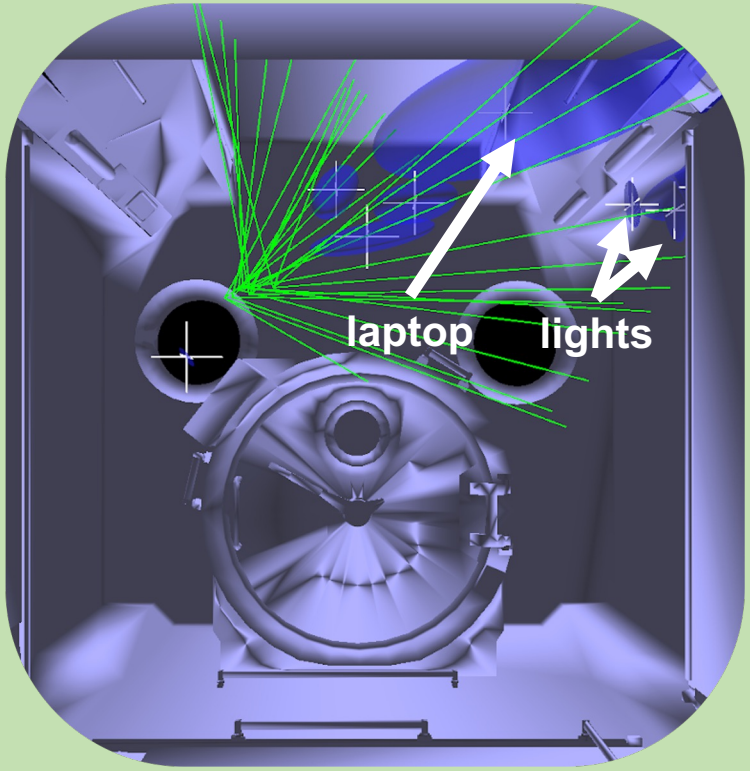
NavCam Path



Path

Estimating 3D Change Regions

Output

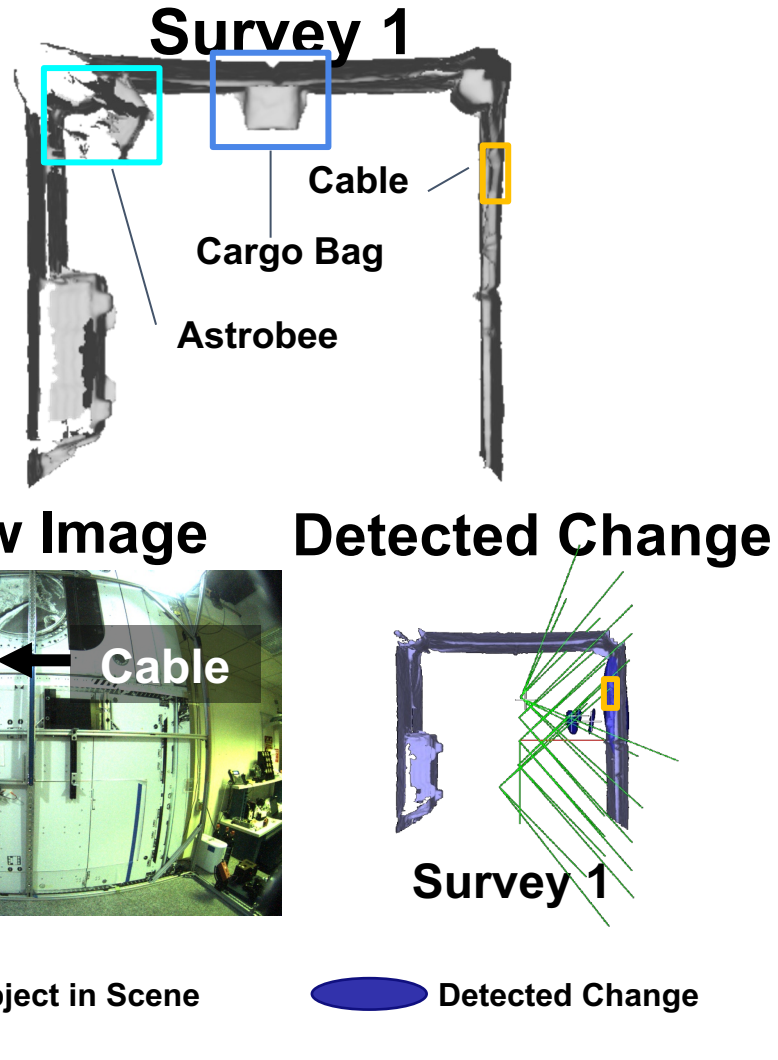


Detected Change

Results

Granite Lab Results

- Five surveys in Granite Lab
- One or more objects introduced in surveys 1-4:
  - Cable
  - Cargo Bag
  - Crate
  - Astrobee unit
- Change detection and object discovery in surveys 1-4
- Survey 5 used for 3D world model reconstruction



Compute Runtimes

- Runtimes on Granite Lab data

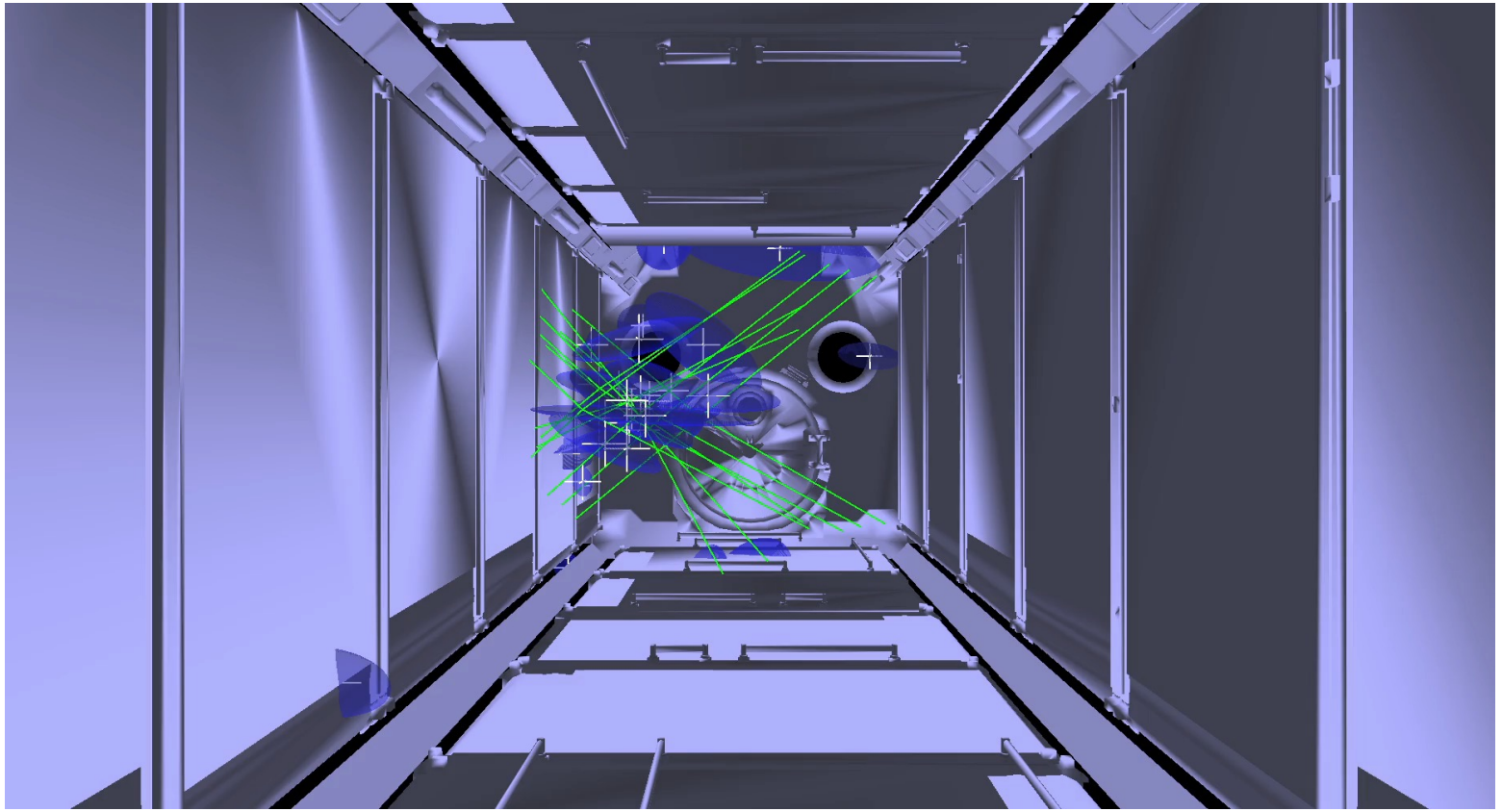
Runtime [s]

n	Data Loading	Inconsistencies	3D Change
2	0.844	0.311	0.054
3	0.800	0.606	0.076
4	0.843	1.156	0.134
5	0.835	1.891	0.161
6	0.842	2.280	0.266
Per Image	-	**≈ 0.281**	-

~5Hz

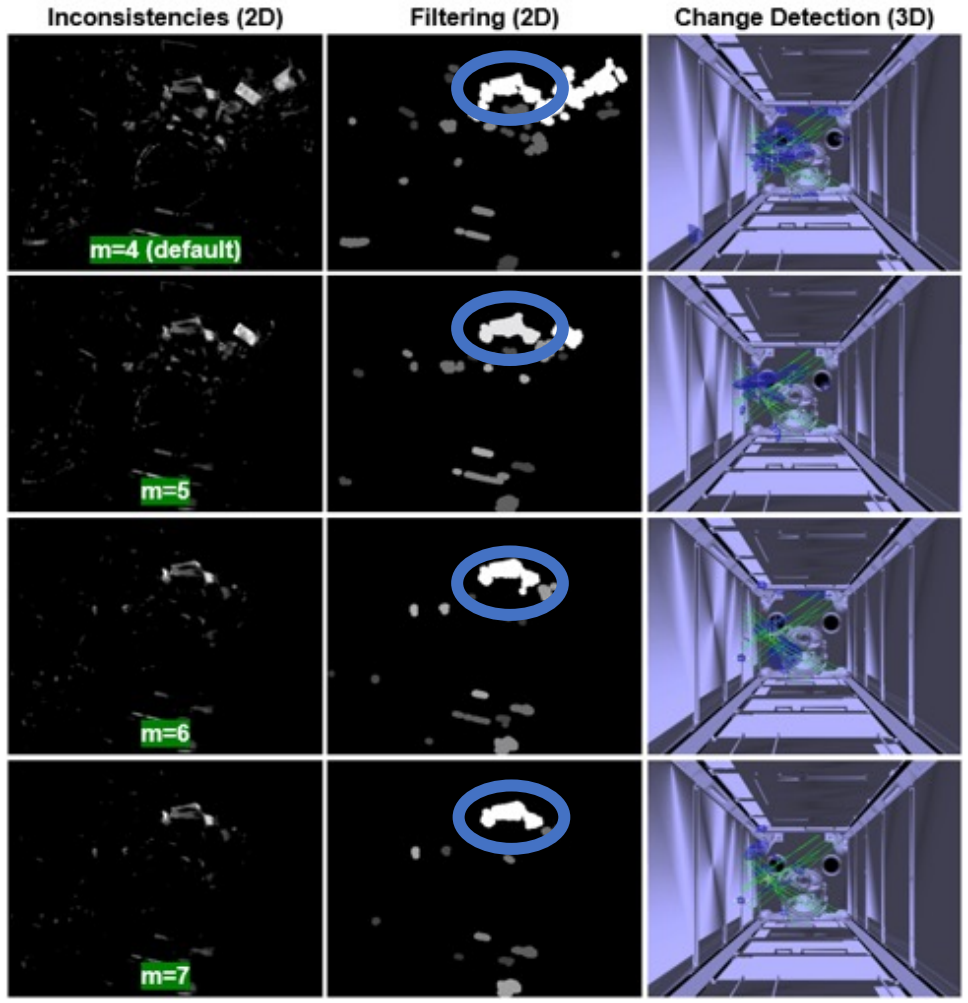
ISS Activity Results

- Two Astrobee units each perform three surveys of the JEM
- Environment was not modified



NASA, "*ISS Activity 9 Data Release*", June 8, 2022. Available: https://nasagov.app.box.com/s/4ign43svk39guhy9ev8t5xkzui6tqjm1?page=1
E. Palazzolo, C. Stachniss, "Fast Image-Based Geometric Change Detection Given a 3D Model" in *IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 6308—6315.

Inconsistency Filtering



NASA, "*ISS Activity 9 Data Release*", June 8, 2022. Available: https://nasagov.app.box.com/s/4ign43svk39guhy9ev8t5xkzui6tqjm1?page=1
E. Palazzolo, C. Stachniss, "Fast Image-Based Geometric Change Detection Given a 3D Model" in *IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 6308—6315.

Conclusions

Future Work

- Multiple camera and robot geometric scene change
- Improve robustness to illumination change
- Runtime analysis on embedded processors
- Compare performance of FastCD for rotation-only and translation-only images
- Compare accuracy and computation time for FastCD with other change detection methods

Conclusion

- FastCD estimates the location of changes in a world using a small number of images and corresponding camera poses
- FastCD can be implemented on a mobile platform for near real-time change detection to enable rapid response to anomalies in the environment
- FastCD is evaluated on Granite Lab and ISS data
- Granite Lab and ISS dataset is open-sourced
- Unlocks numerous benefits for assistive robotics
- Step towards robots in human environments

Acknowledgments

NASA, the Jet Propulsion Laboratory, CSIRO Data61, the Future Space Leaders Foundation, the P.E.O. Sisterhood, Zonta International, the Winston Churchill Fellowship, and the Soffen Memorial Fund funded this work. We also thank Ryan Soussan and the Astrobee Operations Team for their support.

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[6]NASA Ames Research Center, Moffett Field, CA, USA
*Equal contribution, Co-Presenters

Paper →

https://hollydinkel.github.io/assets/pdf/IAC2023.pdf

Thank You!

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