

Unsupervised Change Detection for Space Habitats Using 3D Point Clouds

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Paper: <https://arxiv.org/abs/2312.02396>

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Astrobee test unit docked in the Granite Lab at NASA
Ames Research Center



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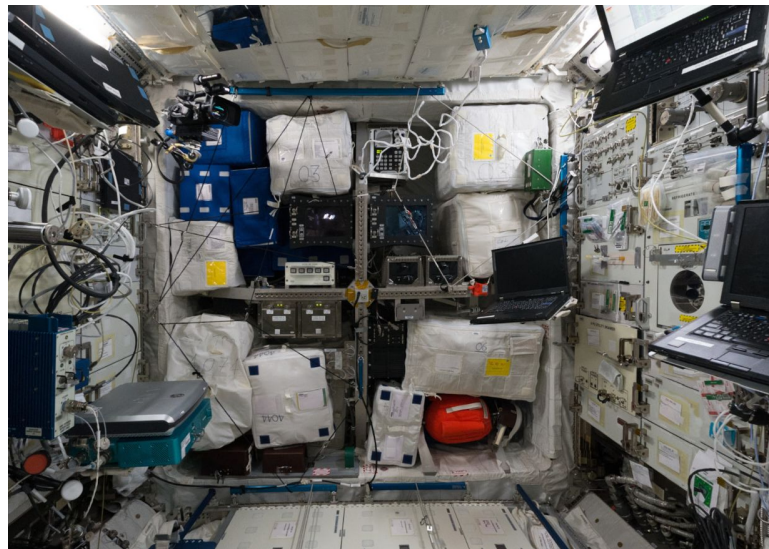
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Anomaly Detection

In space habitats, anomaly detection using space robots can:

- Alert operators to hazards (blocked vents, free-floating cargo)
- Improve the internal map of the environment



Stowed cargo on the ISS

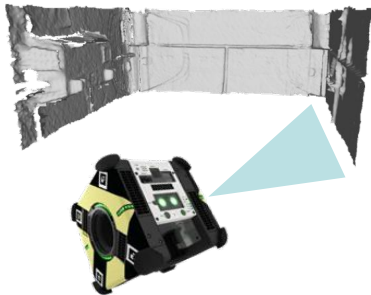
NASA, "Astrobee," Available: <https://github.com/nasa/astrobee>
ESA Virtual Tour, <https://esamultimedia.esa.int/multimedia/virtual-tour-iss/>

Anomaly Detection

Important for robots to perform tasks such as:

- **Mapping:** updating map only where changes occurred
- **Surveillance:** reporting possible environmental dangers
- **Inspection:** ID out-of-spec components in a factory line

Mapping



NASA

Surveillance



Boston Dynamics

Inspection



ABB



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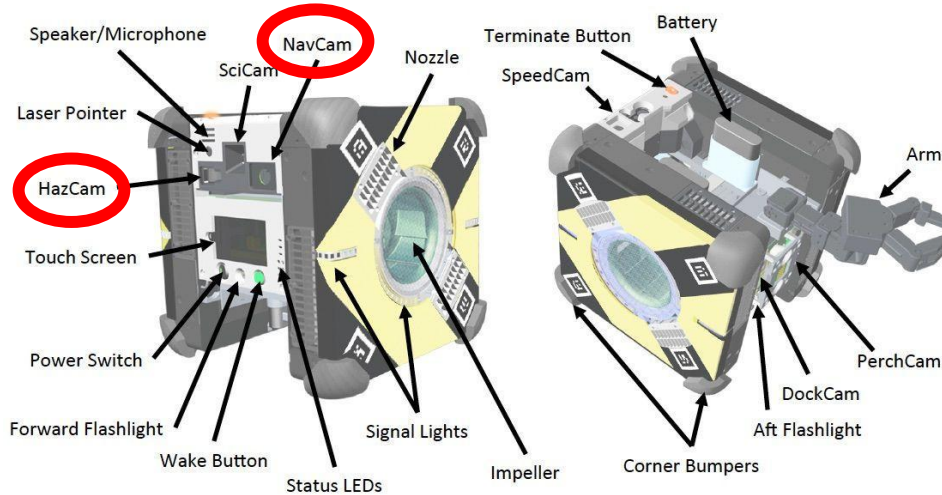


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Autonomy



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>

Image: NASA. Available: <https://www.nasa.gov/astrobee/>



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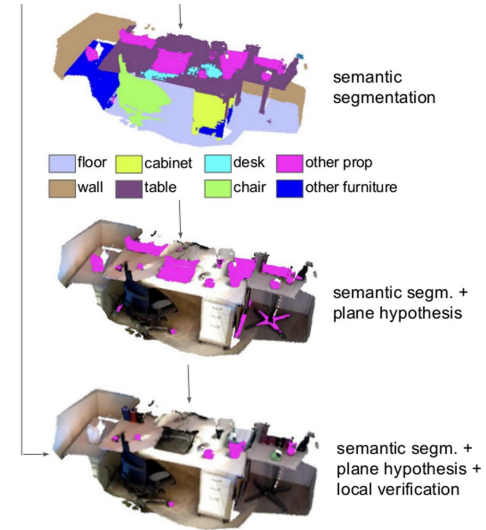
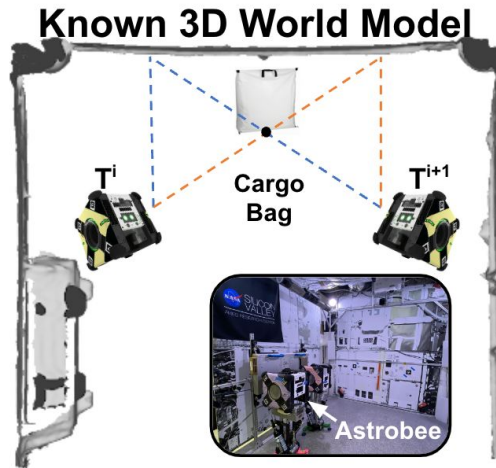
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Image-Based Change Detection (CD)

Geometric CD w/ camera pose, Global semantic/local geometric RGB images, and 3D map

CD w/ pose and two 3D maps



H. Dinkel, J. Di, J. Santos, K. Albee, P. Borges, M. Moreira, O. Alexandrov, B. Coltin, and T. Smith. "Multi-Agent 3D Map Reconstruction and Change Detection in Microgravity with Free-Flying Robots" *IAF Int. Astro. Cong. (IAC) 2023*, pp. 1-15.

E. Langer, T. Patten, and M. Vincze, "Robust and Efficient Object Change Detection by Combining Global Semantic Information and Local Geometric Verification," *IEEE/RSJ Int. Conf. Intell. Robot. Sys. (IROS) 2020*, pp. 8453-8460.



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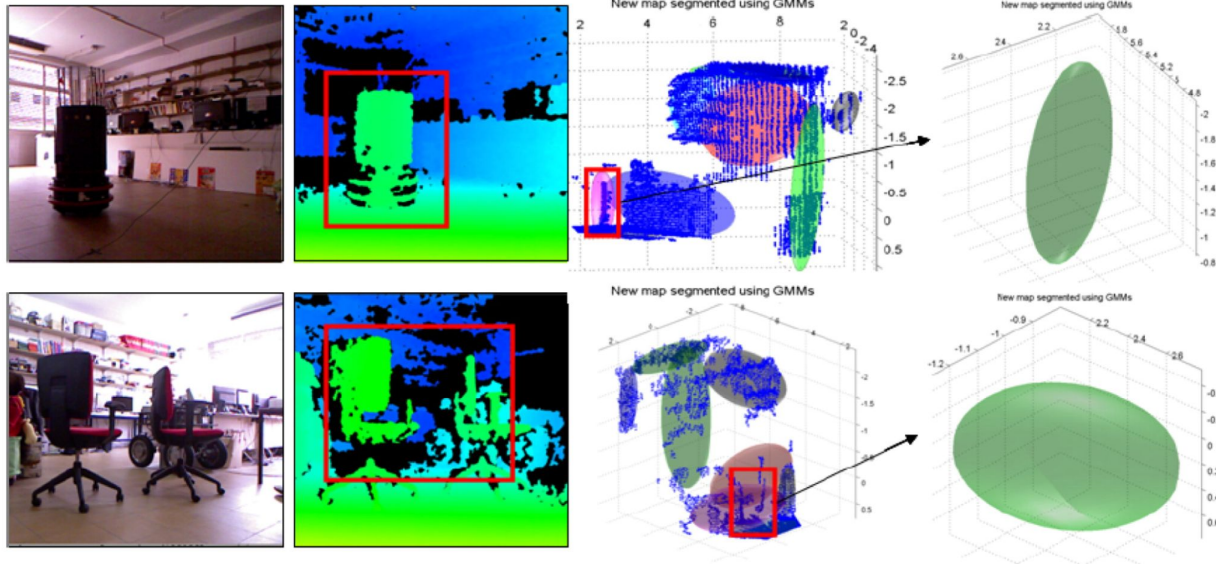


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3D Change Detection (CD) with GMM Clustering

GMM Clustering CD with 3D point clouds



L.J. Manso, P. Núñez, S. da Silva, S., and P. Drews-Jr. "A Novel Robust Scene Change Detection Algorithm for Autonomous Robots Using Mixtures of Gaussians," *Int. J. Adv. Robot. Syst.*, Vol. 11, 2014, p. 1–18



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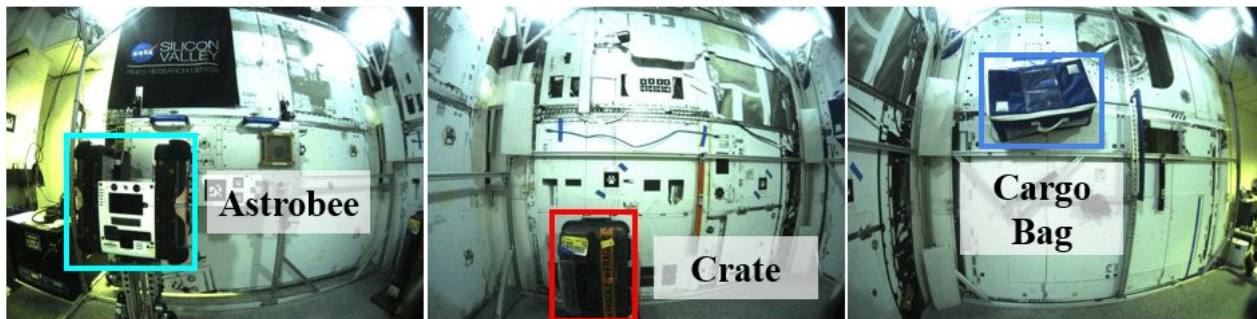
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Contributions

1. Unsupervised detection of added/*removed* objects
2. Detection of *multiple changes* at once
3. Evaluated on data collected in a *space-like environment*
4. Code released publicly



Algorithm Overview



Cargo bag **not** in scene



Cargo bag in scene



Cargo Bag



Detected Change

A.P. Dempster, N.M. Laird, and D. B. Rubin. "Maximum Likelihood from Incomplete Data Via the EM Algorithm," *J. R. Stat. Soc., Ser. B, Methodol.*, Vol. 39, 1977, pp. 1–22.

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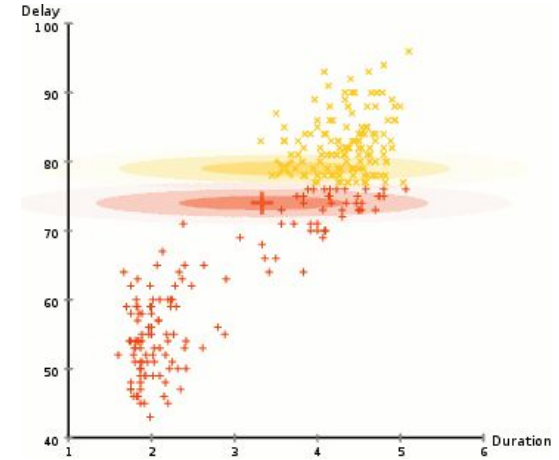
GMM Clustering with EM

Repeat until convergence:

- **E:** prob. that points belong to clusters
- **M:** update parameters and weights

Modification:

- Overestimate initial clusters, K
- Penalize high number of clusters and drive weights of weak clusters to 0



EM algorithm run on Old Faithful eruption data

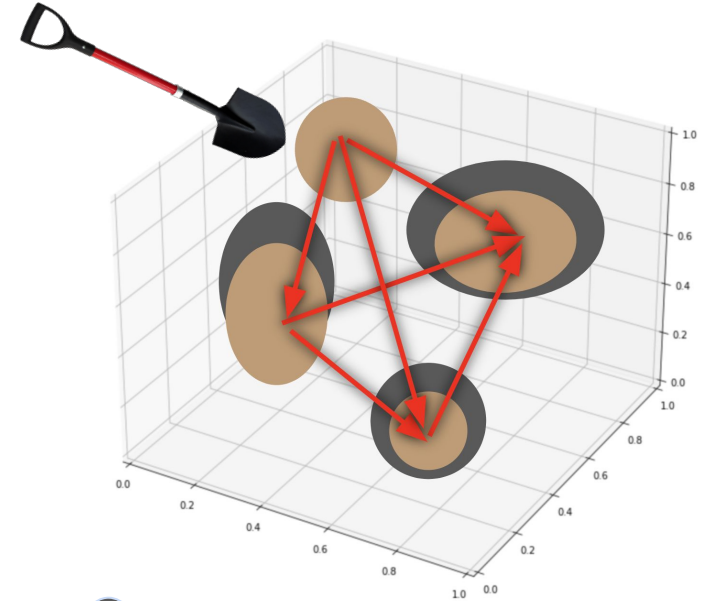
Dempster, A. P., Laird, N. M., and Rubin, D. B., "Maximum Likelihood from Incomplete Data Via the EM Algorithm," J. R. Stat. Soc., Ser. B, Methodol., Vol. 39, 1977, pp. 1–22

Figueiredo, M., and Jain, A., "Unsupervised Learning of Finite Mixture Models," *IEEE Trans. Pattern Anal. Mach. Intell.*, Vol. 24, No. 3, 2002, pp. 381–396

Earth Mover's Distance

Optimize **work** ($F \cdot D$) to transform one distribution to another

- **“Earth” (F):** weights
- **Distances (D):** matrix of distances between every means
- Move earth so each distribution of dirt piles look the same



- Distribution 1 (“holes”)
- Distribution 2 (“piles of dirt”)

Y. Rubner, C. Tomasi, and L.J. Guibas, “The Earth Mover’s Distance as a Metric for Image Retrieval,” *Int. J. Comput. Vis.*, Vol. 40, No. 2, 2000, p. 99.



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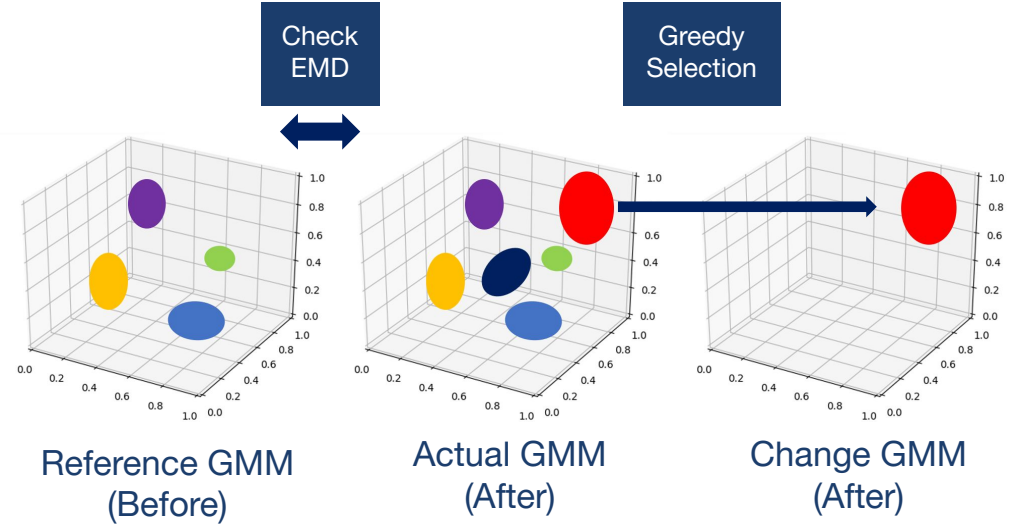
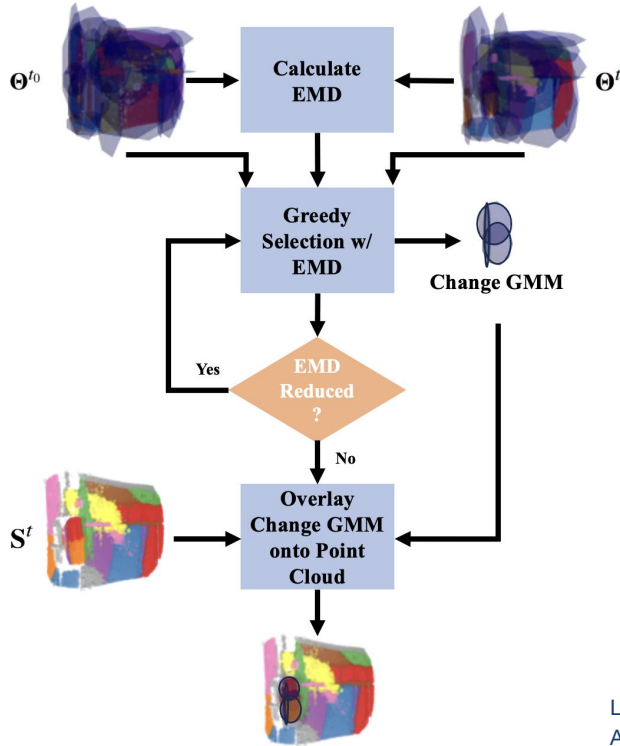
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Change Detection



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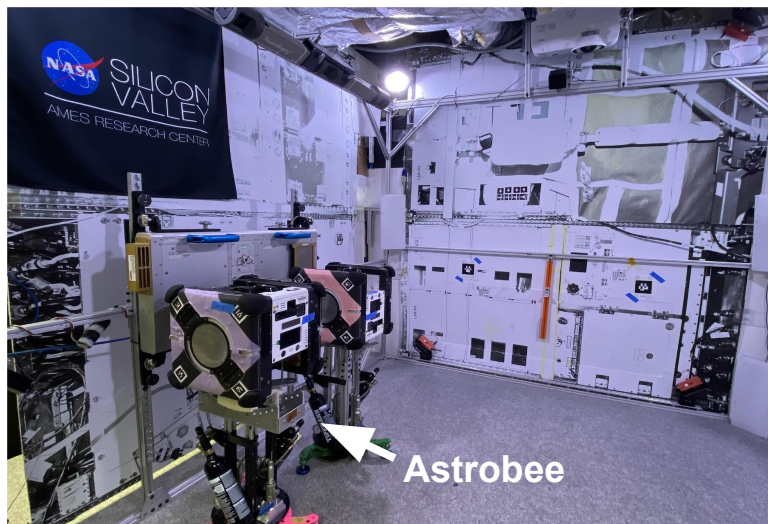
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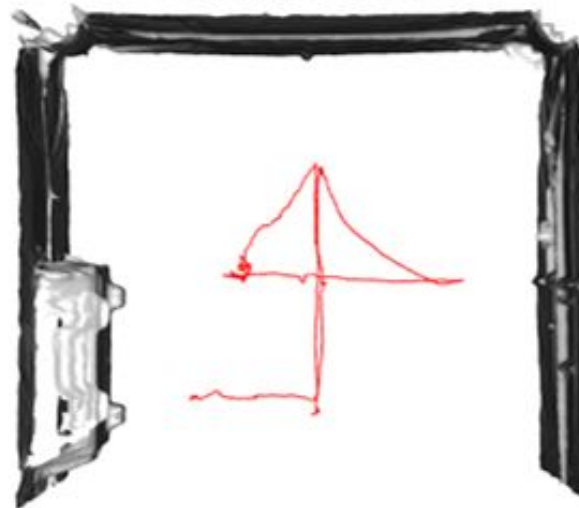
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Data Collection



Granite Lab



Astrobee Path in Granite Lab

H. Dinkel, J. Di, J. Santos, K. Albee, P. Borges, M. Moreira, O. Alexandrov, B. Coltin, and T. Smith. "Multi-Agent 3D Map Reconstruction and Change Detection in Microgravity with Free-Flying Robots" *IAF Proc. Int. Astro. Cong. (IAC)*, 2023.



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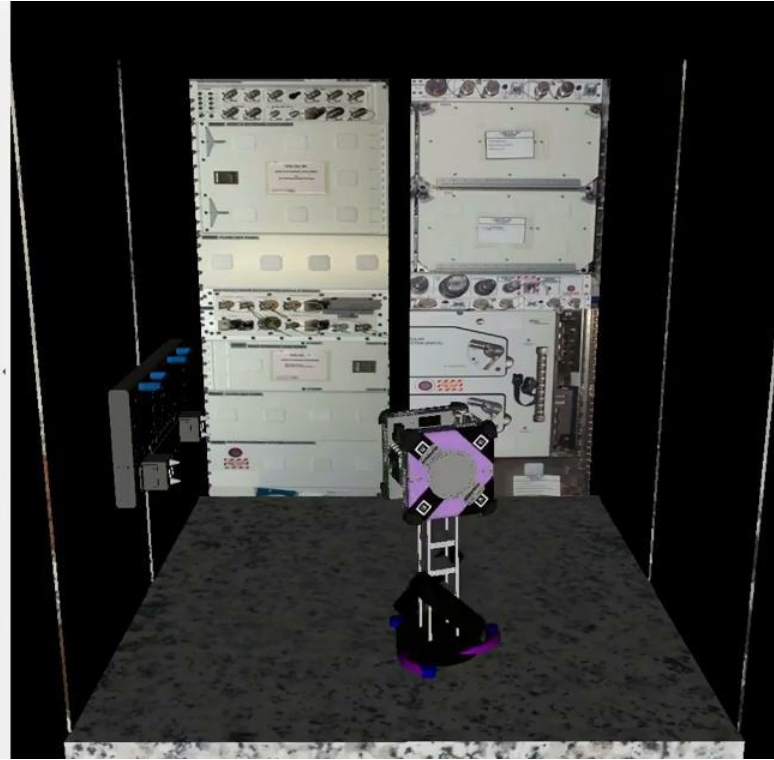
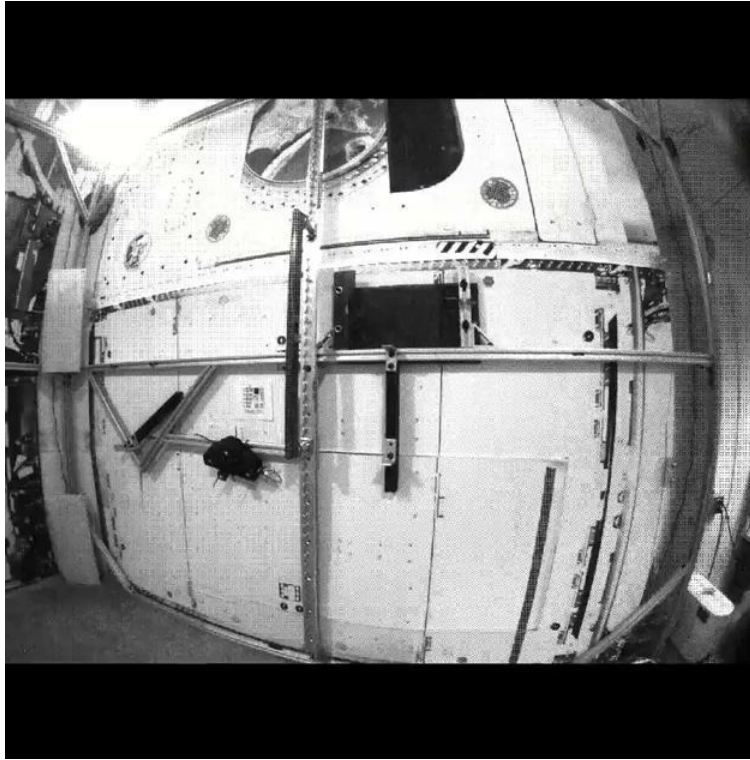
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Data Collection



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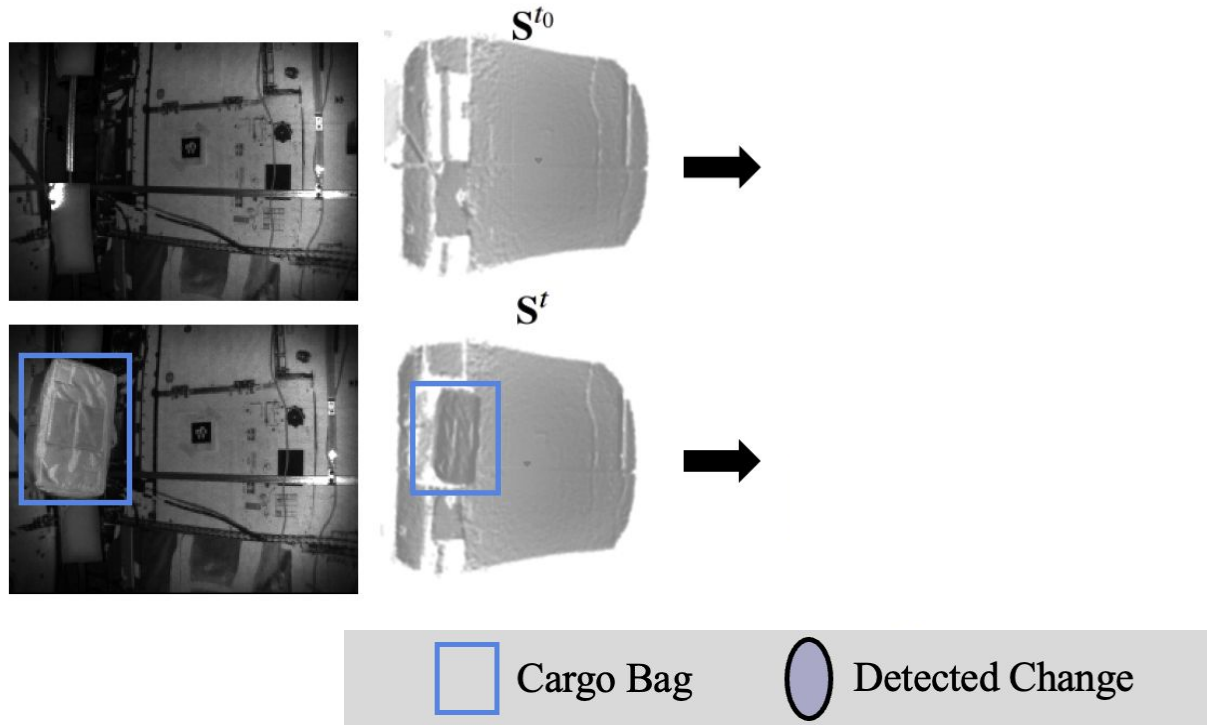
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CD in Single-Frame Point Clouds



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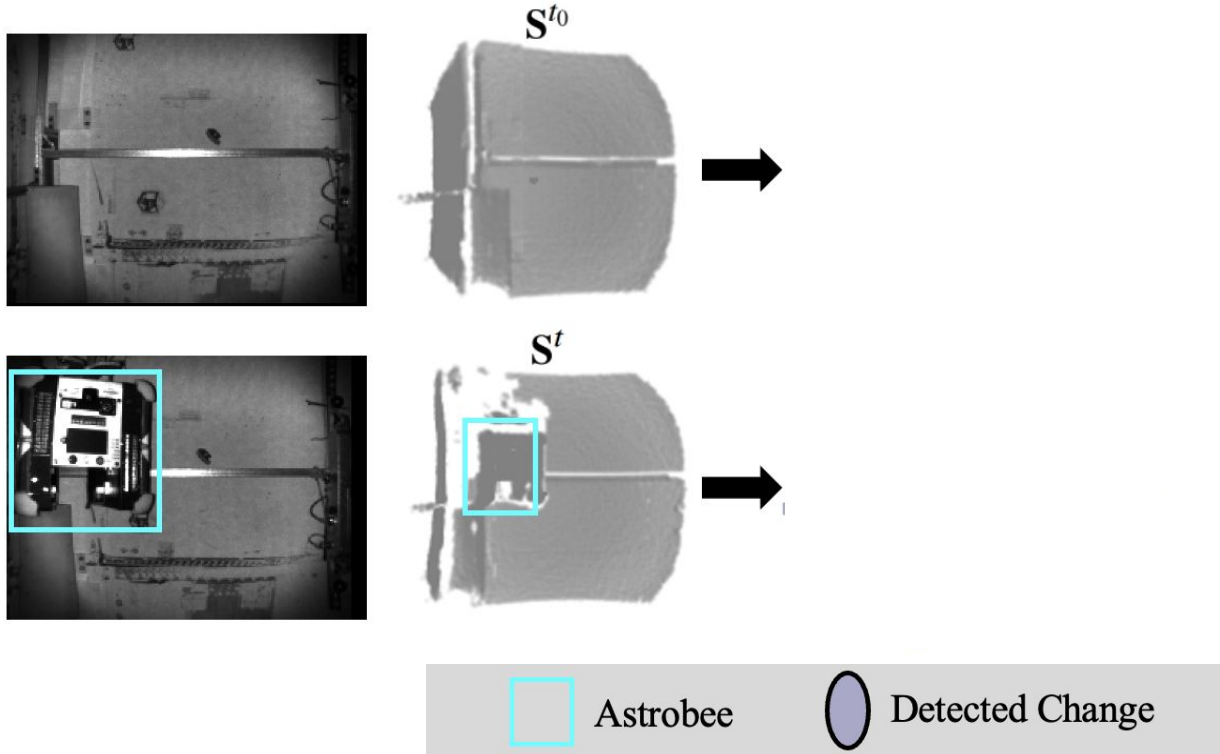


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CD in Single-Frame Point Clouds



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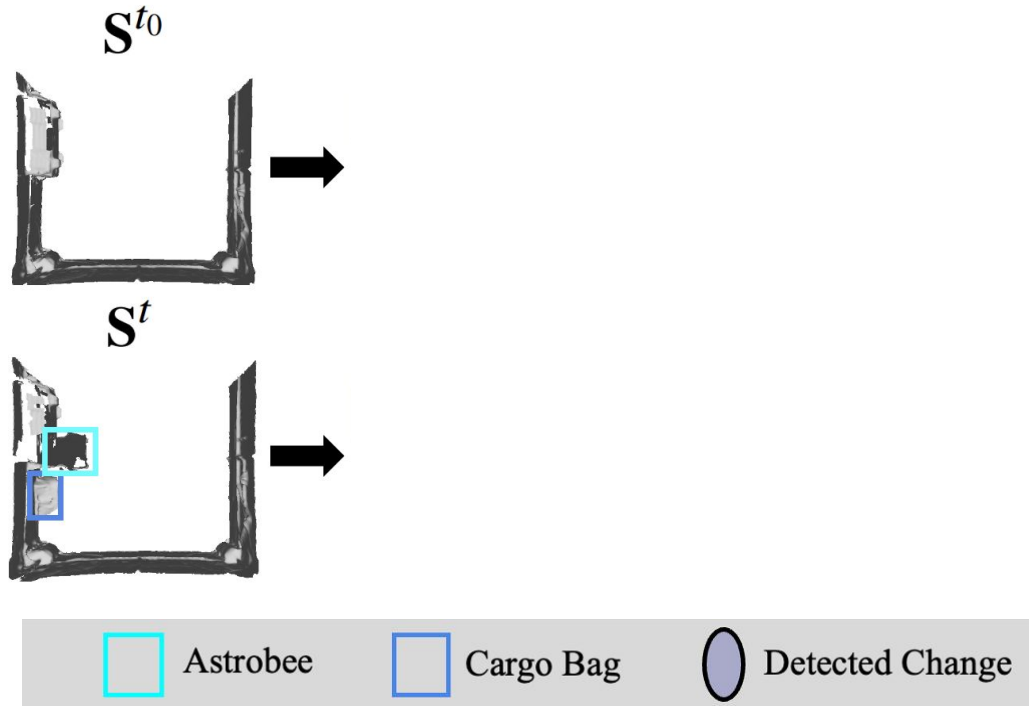


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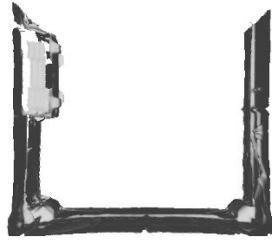


CD on Reconstructed Maps

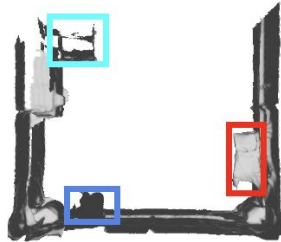


CD on Reconstructed Maps

S^{t_0}



S^t



Astrobee



Cargo Bag



Crate



Detected Change



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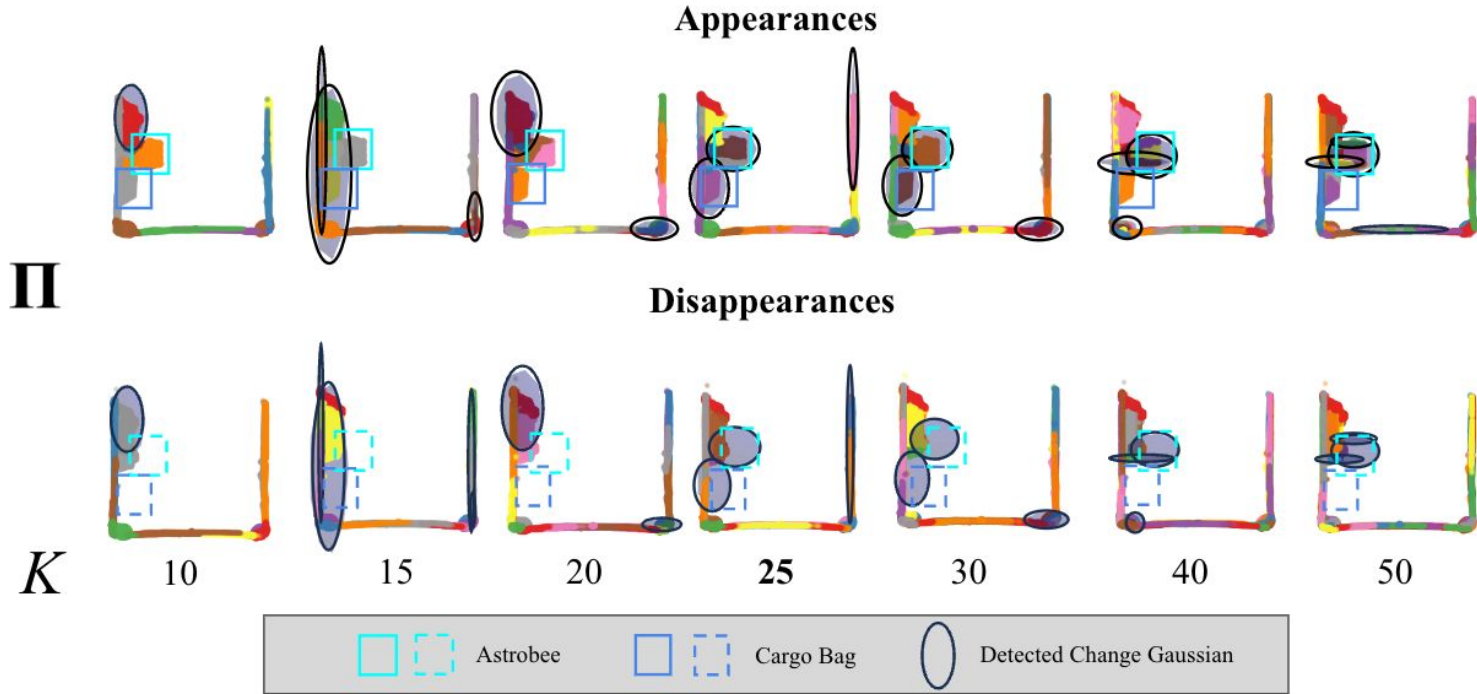


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Performance Metrics

Metric	One Object	Two Objects	Three Objects	
Accuracy	0.953	0.929	0.952	$(TP+TN)/(TP+TN+TN+FP)$
Precision	0.600	0.617	0.933	$TP/(TP+FP)$
Recall	1.000	0.667	0.750	$TP/(TP+FN)$
F1 Score	0.727	0.650	0.829	$2TP/(2TP+FP+FN)$

Varying the Maximum Initial GMM Clusters



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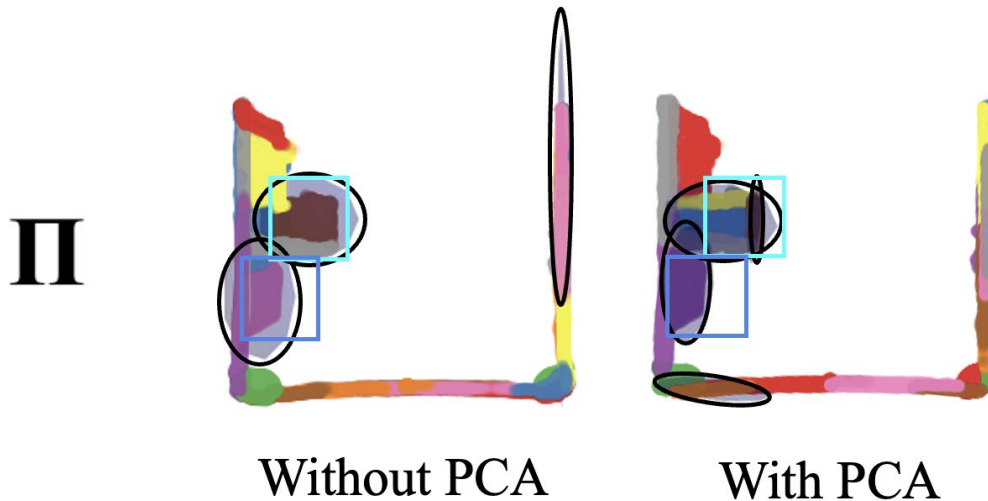


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Pre-Processing Data with PCA

PCA pre-processing: improved runtime ~10%



Astrobees



Cargo Bag



Detected Change



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Computation Time [s]*

K	Load Data	PCA	Clustering	CD (EMD)	Total
15	0.044	3.727	2043.113	0.677	2047.561
20	0.037	2.580	2804.327	1.491	2802.535
25	0.037	1.979	4496.449	3.070	4501.535
30	0.043	2.920	3307.551	2.708	3313.222
40	0.023	1.981	5209.999	5.254	5217.257
50	0.026	2.169	7714.528	9.415	7726.138

*Performed on Apple M1 processor



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Future Work

- Simultaneous appearances/disappearances
- Optimize for online processing
- Optimize K initialization and filtering
- Test on ISS (increased scene complexity)

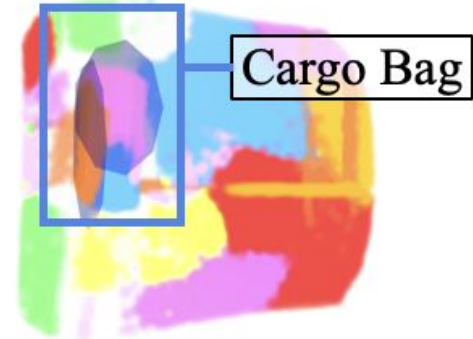


Image Credit: NASA. Available: <https://blogs.nasa.gov/spacestation/2023/07/20/a-third-round-of-eye-exams-for-the-week-maintenance-and-clean-up-activities-underway/>

Conclusions

Detects new or missing objects
without labeling data

- Multiple object detection also possible
- Released as open source on NASA's ISAAC codebase
- Pipeline shows potential with Granite Lab data



Acknowledgements

Funding

NASA, CSIRO Data61, the P.E.O. Sisterhood, Zonta International, and the Winston Churchill Fellowship funded this work. We also thank Ryan Soussan and the Astrobees Operations Team for their support. This work was conducted at the NASA Ames Research Center.



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Team



Jamie Santos



Holly Dinkel



Julia Di



Paulo Borges



Marina Moreira



Oleg Alexandrov



Brian Coltin



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Astrobee test unit docked in the Granite Lab at NASA Ames Research Center



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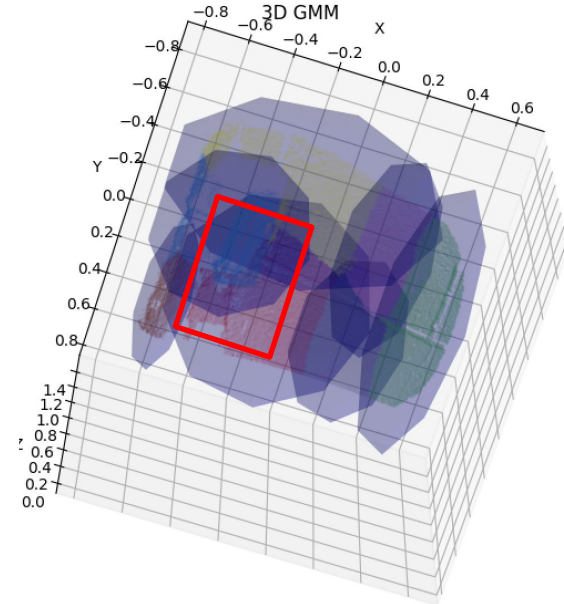
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- Can your slides be easily read from 15 meters away?

Methodology: Point Cloud → GMM

- **Goal:** summarize point cloud as a Gaussian Mixture Model (GMM) and compute changes as differences between Gaussian distributions
 - GMM clustering with Expectation-Maximization (EM)
 - Change detection with the Earth Mover's Distance (EMD)
 - Extract change Gaussians



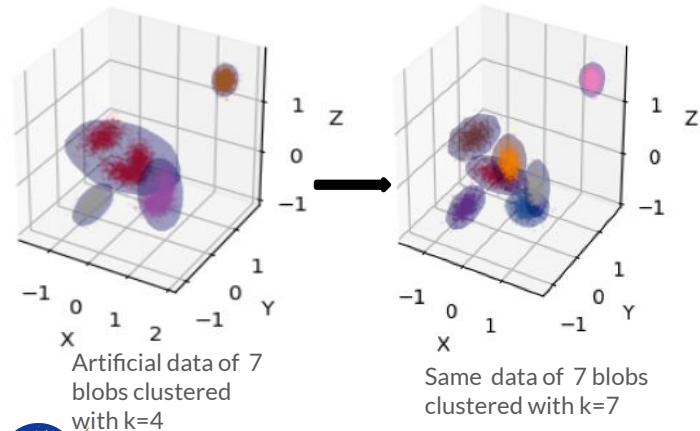
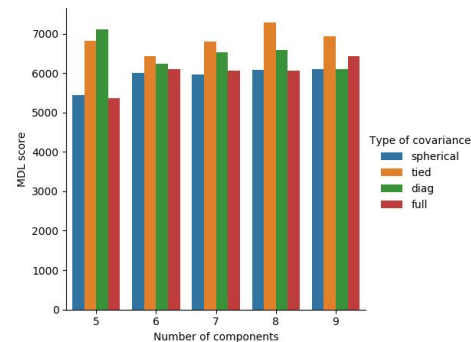
A.P. Dempster, N.M. Laird, and D. B. Rubin. "Maximum Likelihood from Incomplete Data Via the EM Algorithm," *J. R. Stat. Soc., Ser. B, Methodol.*, Vol. 39, 1977, pp. 1–22.

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Methodology

Determining “K”: An Initialization Problem

- Number of clusters (K) that best fit the data not given
- **Strategy 1: Scanning**
 - Perform EM with an array of probable K's
 - Average over several runs and select the best scoring model
- **Strategy 2: Modified EM**
 - Start with max K Gaussians
 - Iteratively delete Gaussians until log-likelihood of fit (minus penalty term) converges



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