

Drift-Free Visual Compass Leveraging Digital Twins for Cluttered Environments

Project Page

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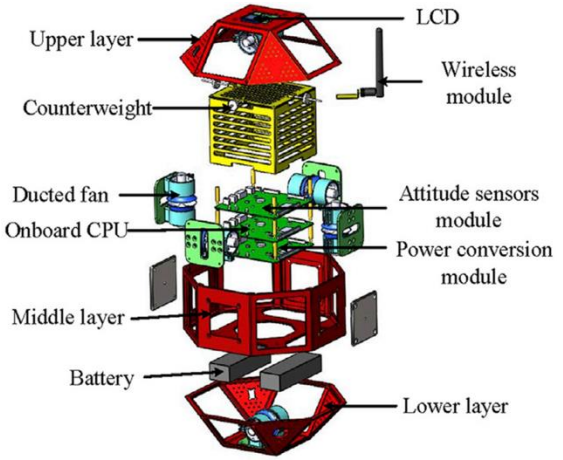
Development of Free-Flying Robots for Space Stations

- Astrobee (NASA, US)

- CIMON (DLR, ESA)

- Int-Ball 2 (JAXA, Japan)

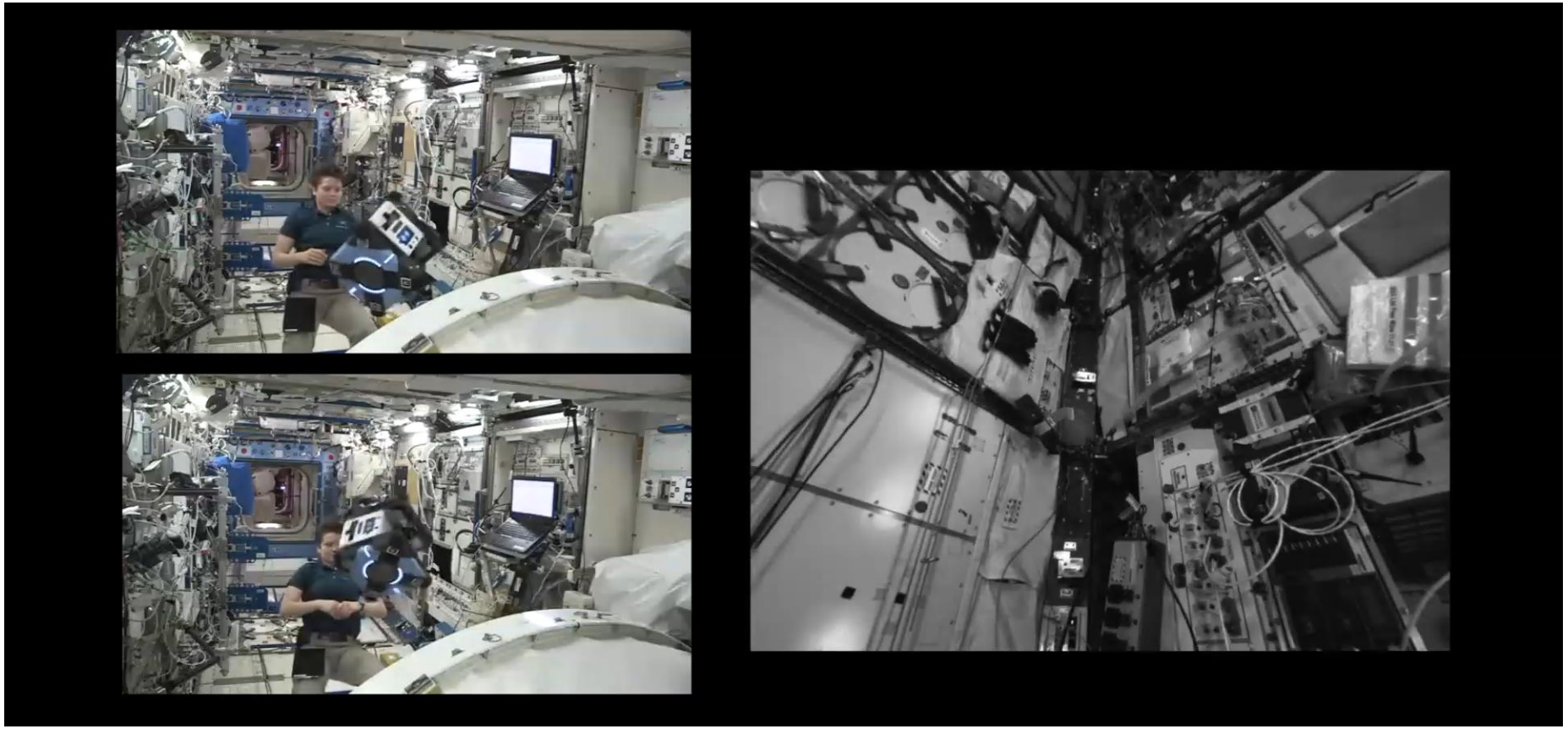
- AAR-2 (CASC, China)



360° Rotation: A Major Challenge for Visual Navigation in Space Robotics

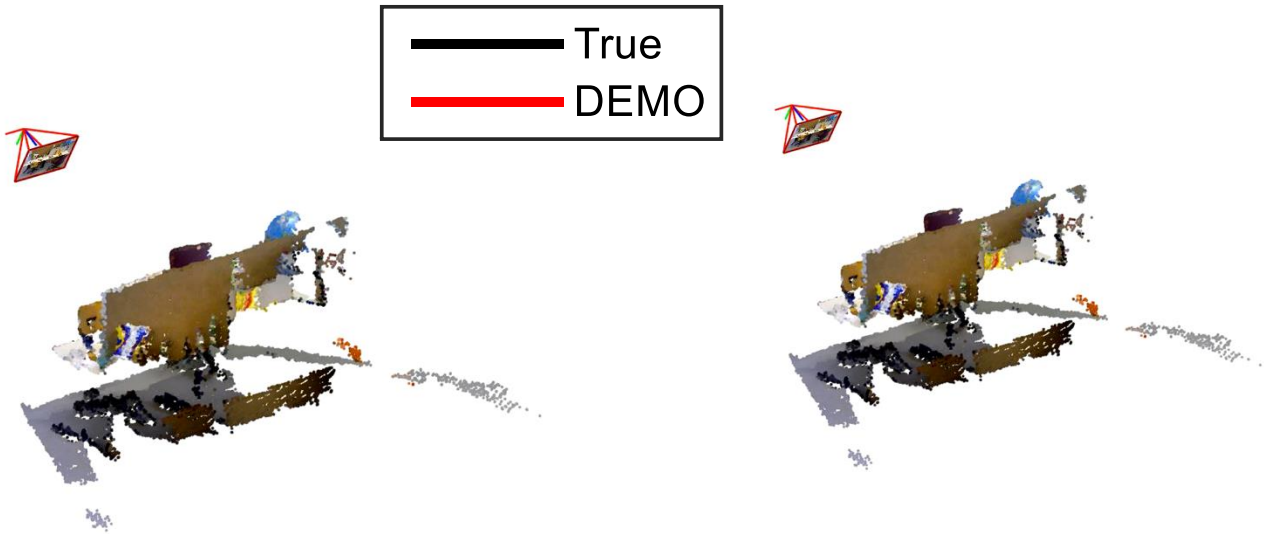
Robots on Earth

Space Robots



- In microgravity, the unrestricted 360° rotational motion of space robots is one of the primary causes of failure in visual navigation.

Rotational Drift: The Main Source of Positional Inaccuracy in VO & SLAM



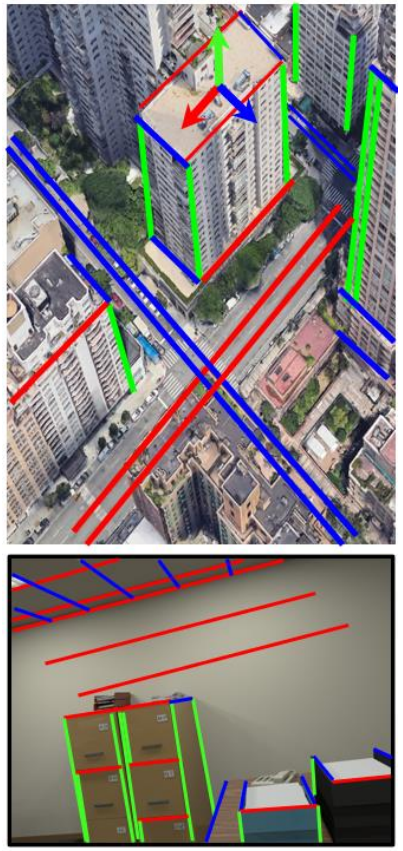
Inaccurate (left) and True (right) Camera Orientation

- Rotations cause nonlinearity in VO & SLAM

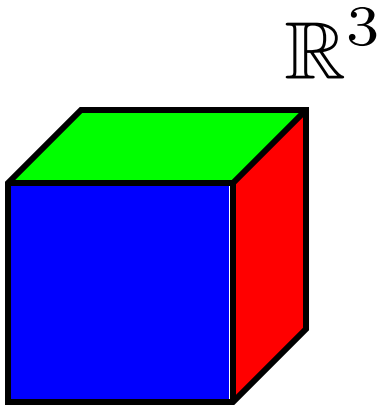
[Zhang, Ji, Michael Kaess, and Sanjiv Singh. "Real-time depth enhanced monocular odometry." IROS, 2014.]

Drift-Free Rotation Estimation Leveraging Structural Regularities

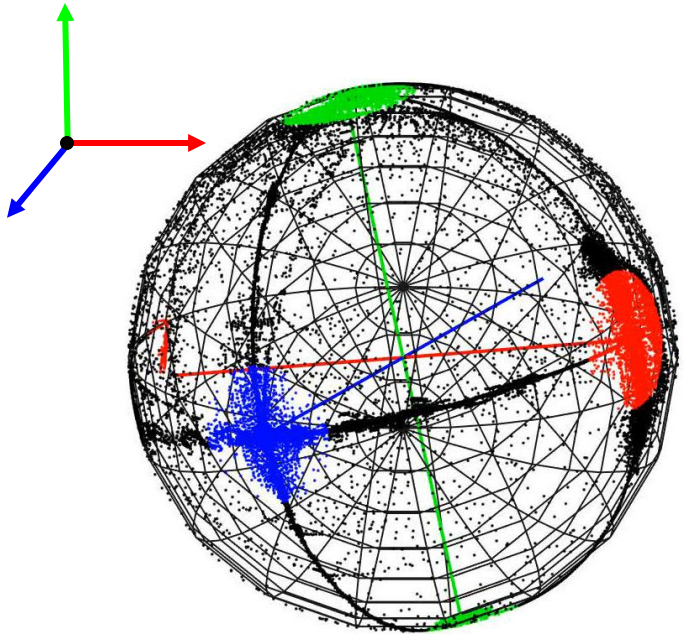
Manhattan World



Urban Environments



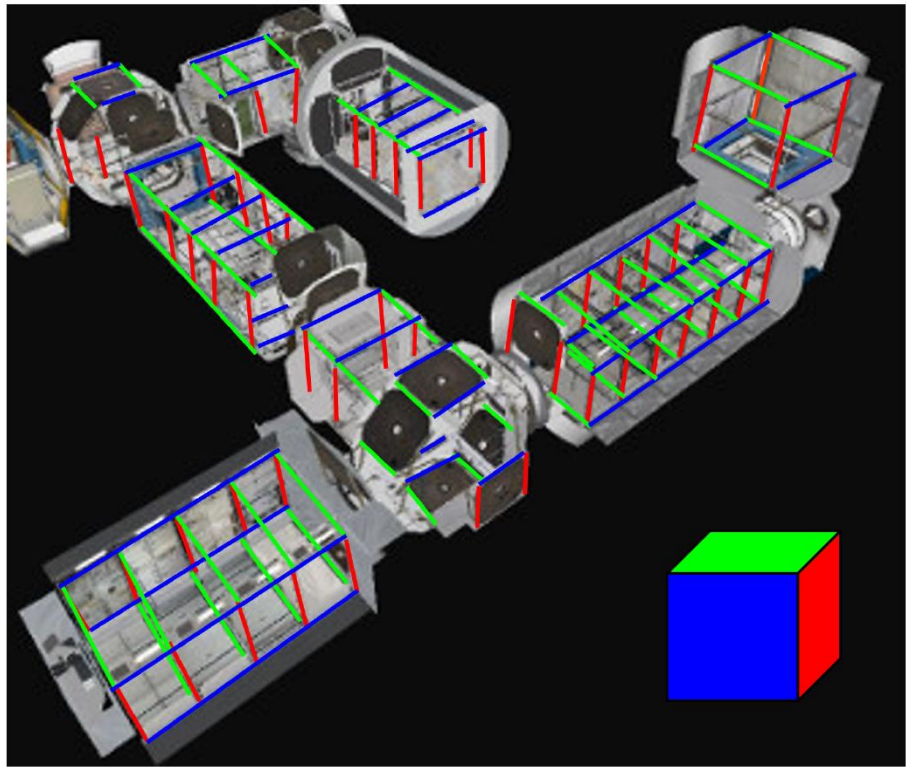
Manhattan World Tracking

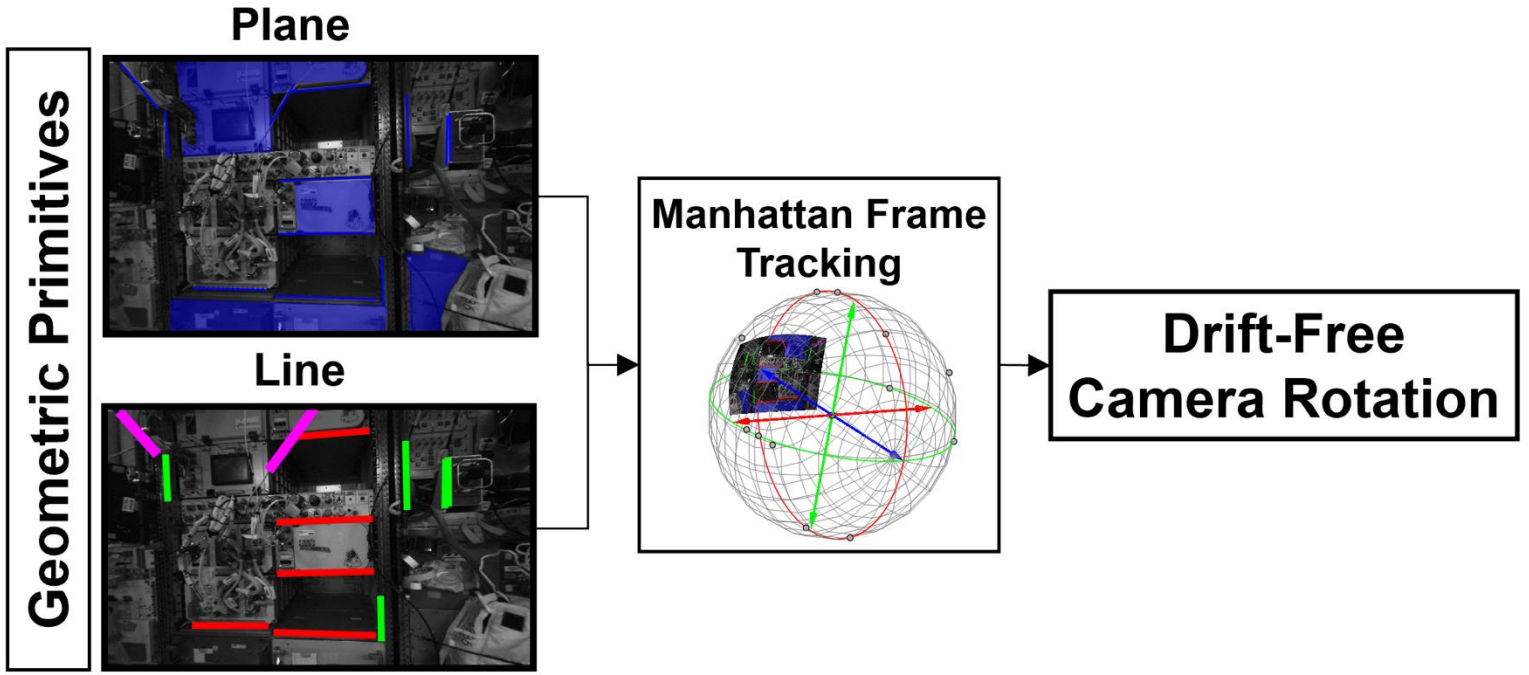


- Drift-free rotation estimation is possible through accurate structural model tracking.

[J. M. Coughlan and A. L. Yuille, “Manhattan world: Compass direction from a single image by Bayesian inference,” in ICCV, 1999.]

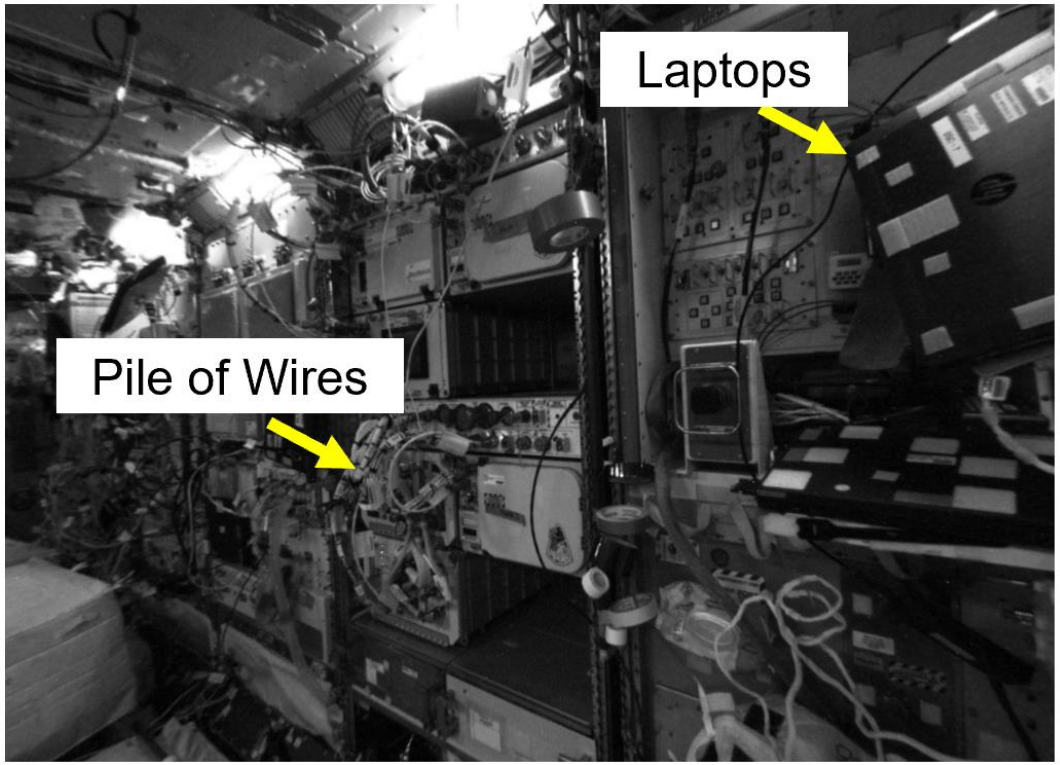
Drift-Free Rotation Estimation Leveraging Structural Regularities

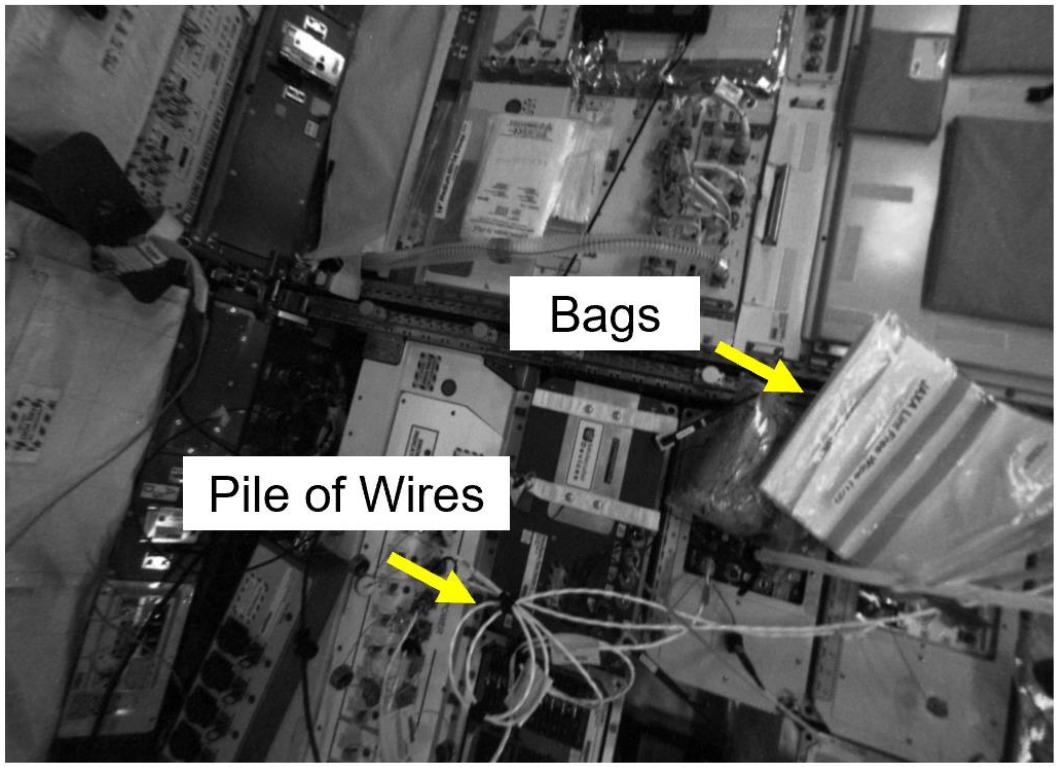




- The ISS is **a representative example** that satisfies **MW assumption**.

Challenge: Clutter and Dynamics in the ISS



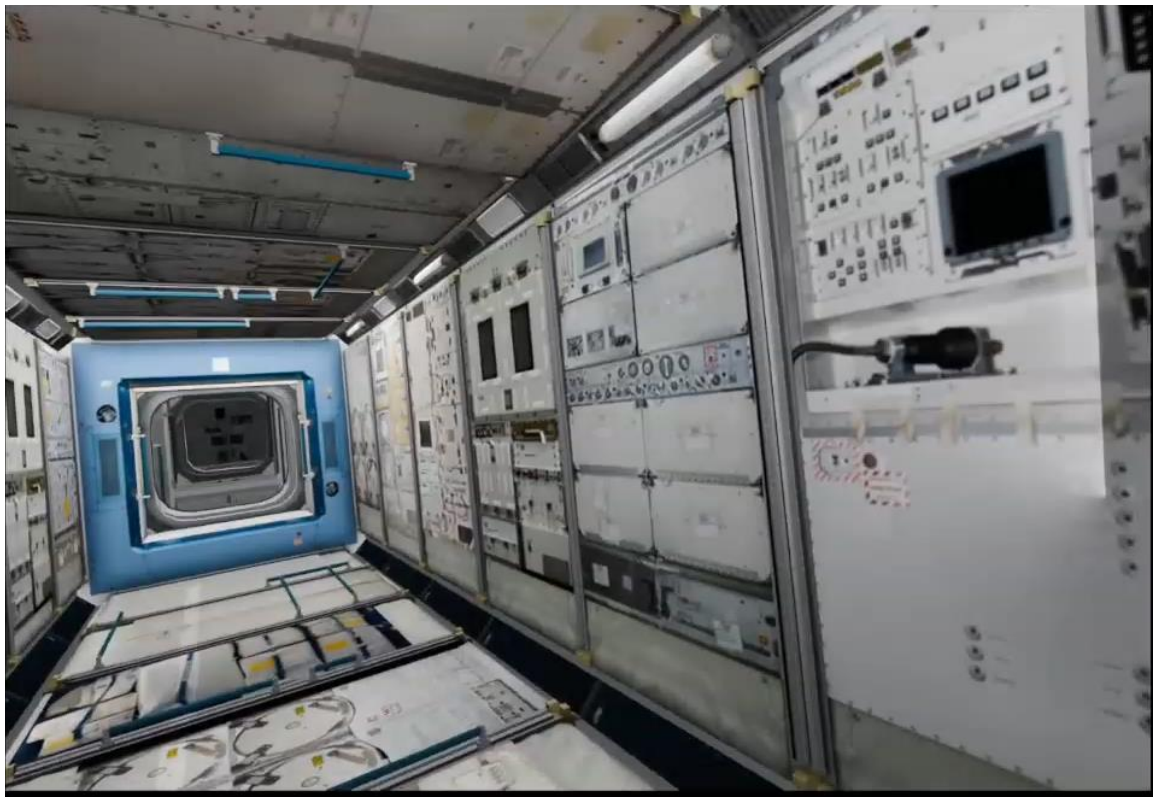


- Excessive outliers caused by dynamic and cluttered objects make existing MW tracking methods fail.

Clutter-Free Digital Twin (3D CAD Model)

Cluttered ISS Interior

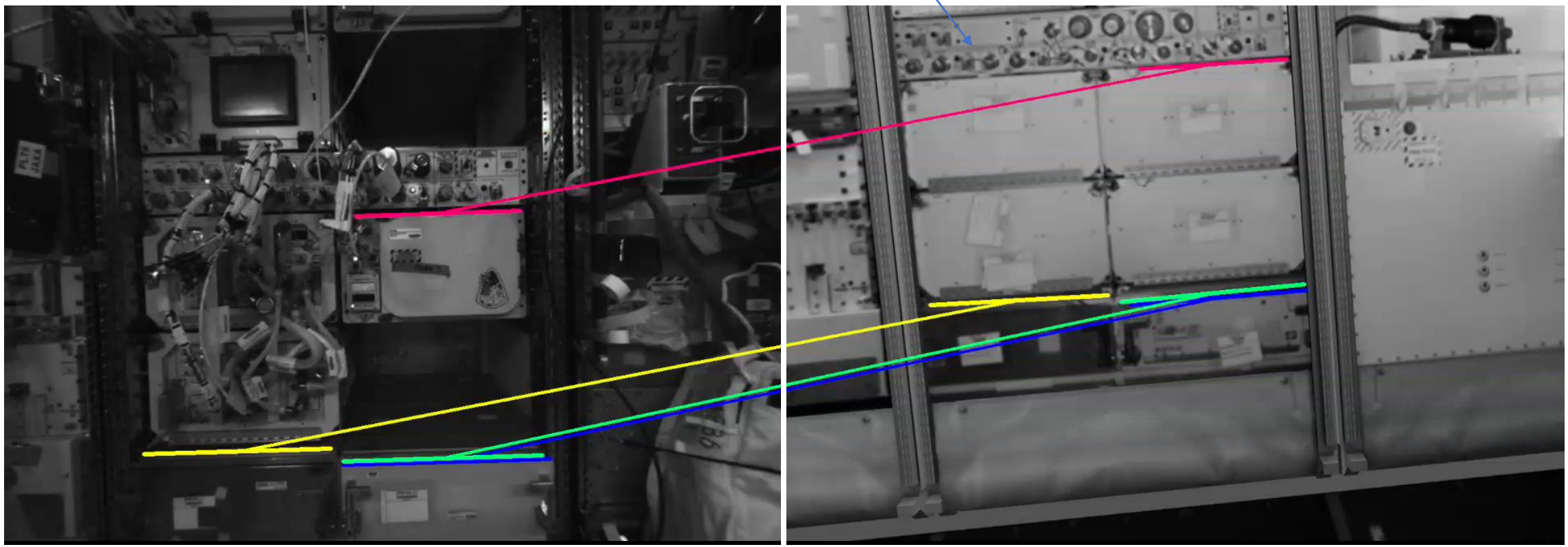
Clutter-Free Digital Twin



Digital Twin-Based Outlier Rejection (DTOR)

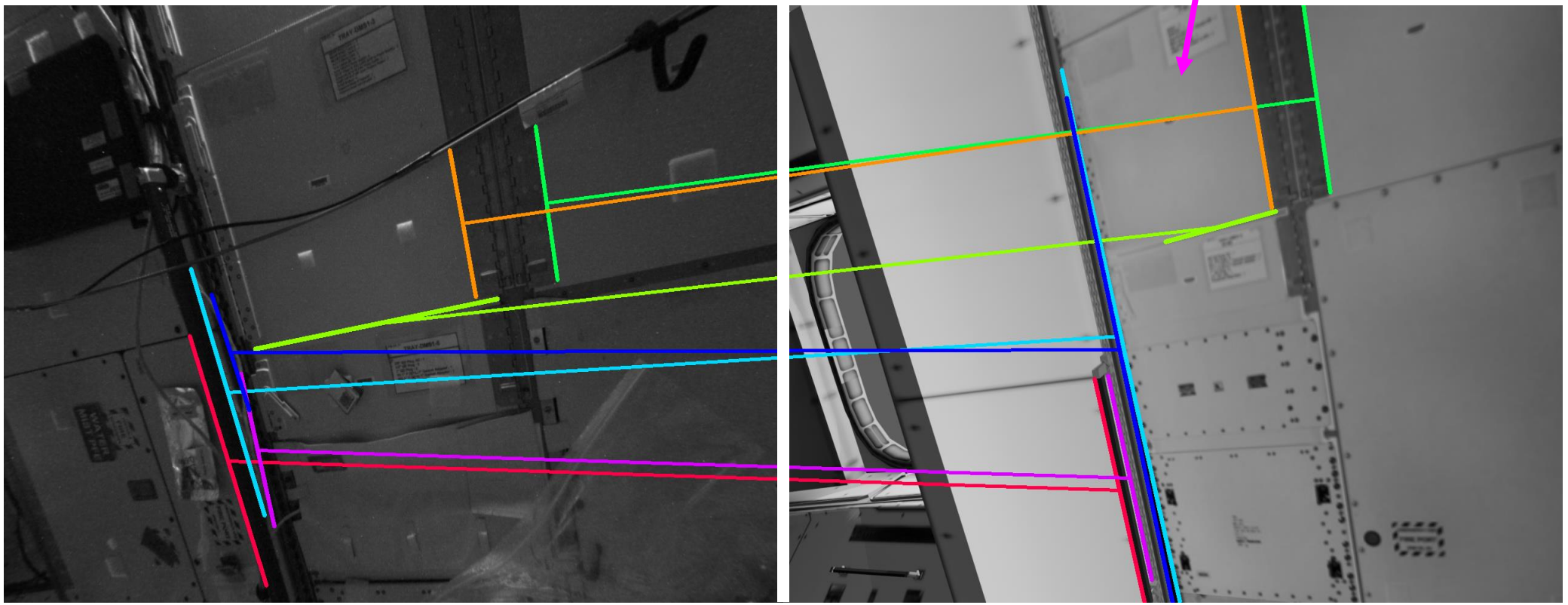
Cluttered ISS Interior

Clutter-Free Digital Twin



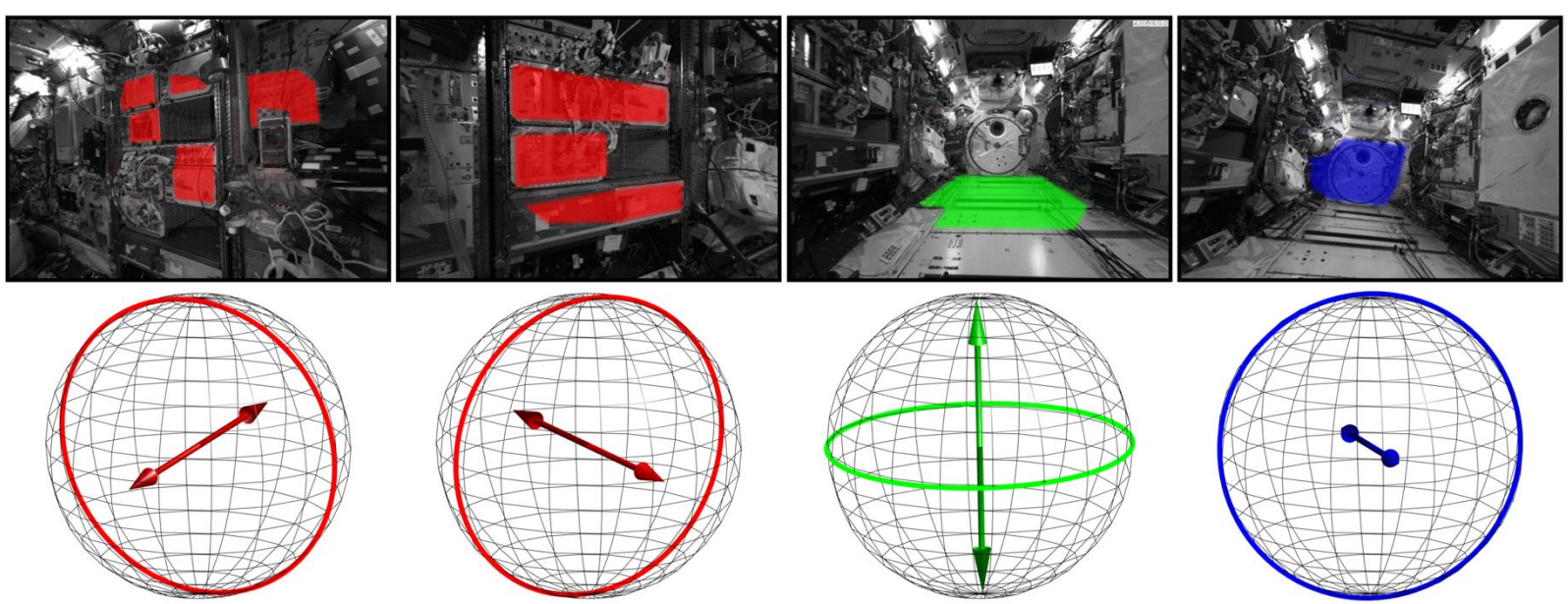
Line Matching (*GlueStick*) Between ISS Image and Rendered Digital Twin

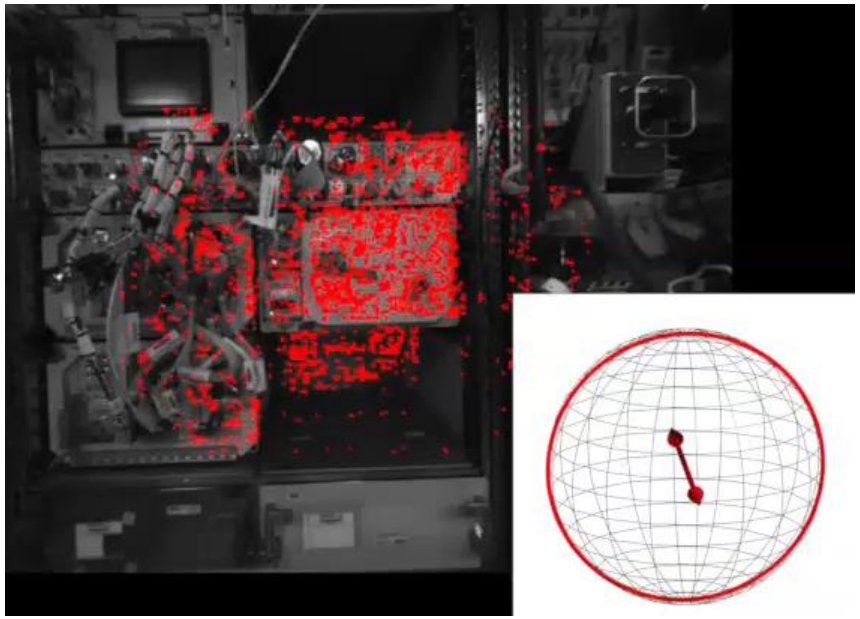
We use the estimated pose from the (k-1)th frame for rendering the digital twin at the kth frame.



[Pautrat, Rémi, et al. "Gluestick: Robust image matching by sticking points and lines together," in CVPR 2023.]

Dominant Plane Detection and Tracking

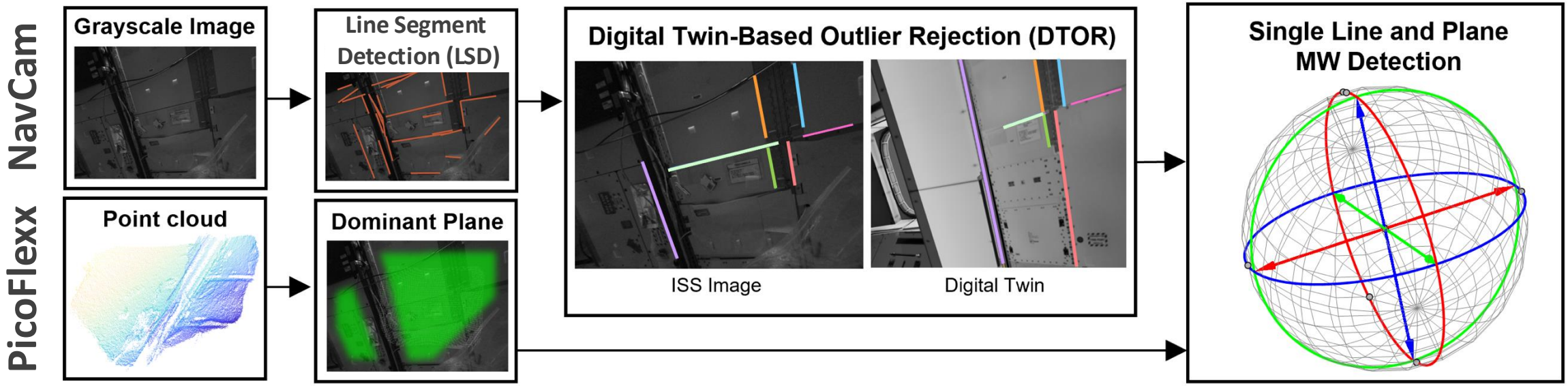


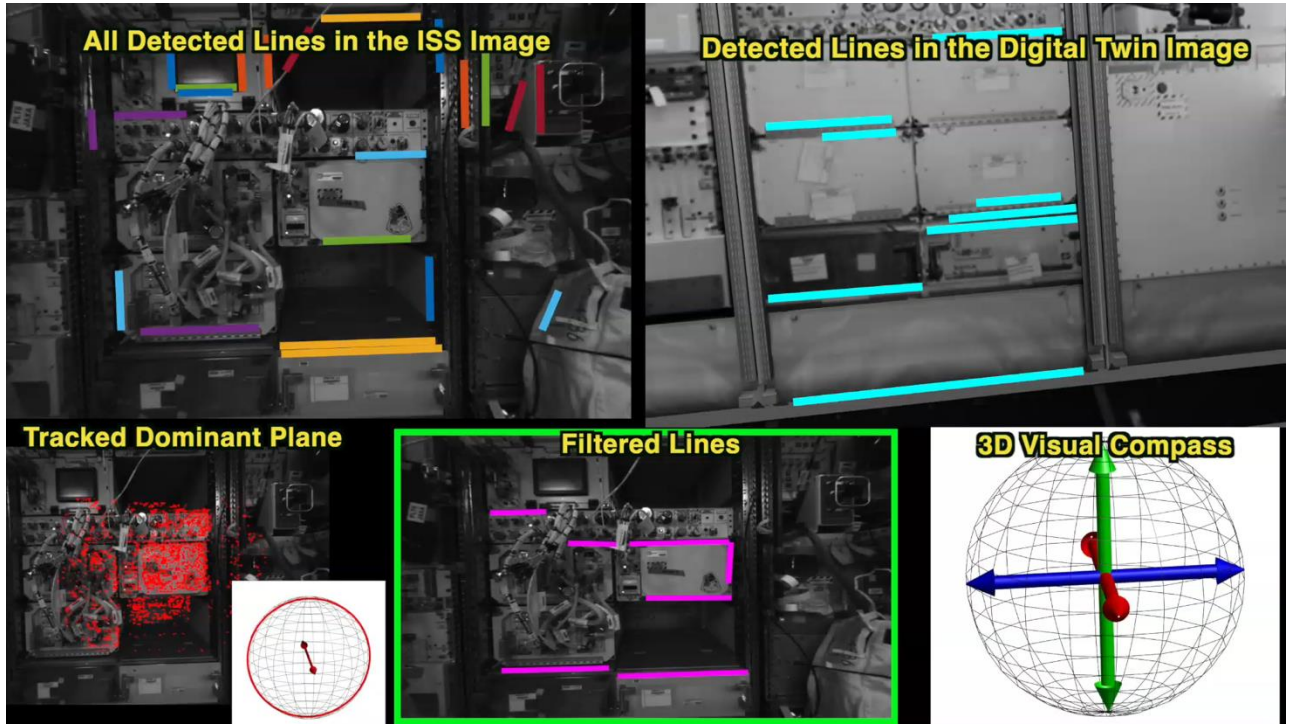


- We track the dominant plane by checking normal density and detect a new one when it becomes unreliable.

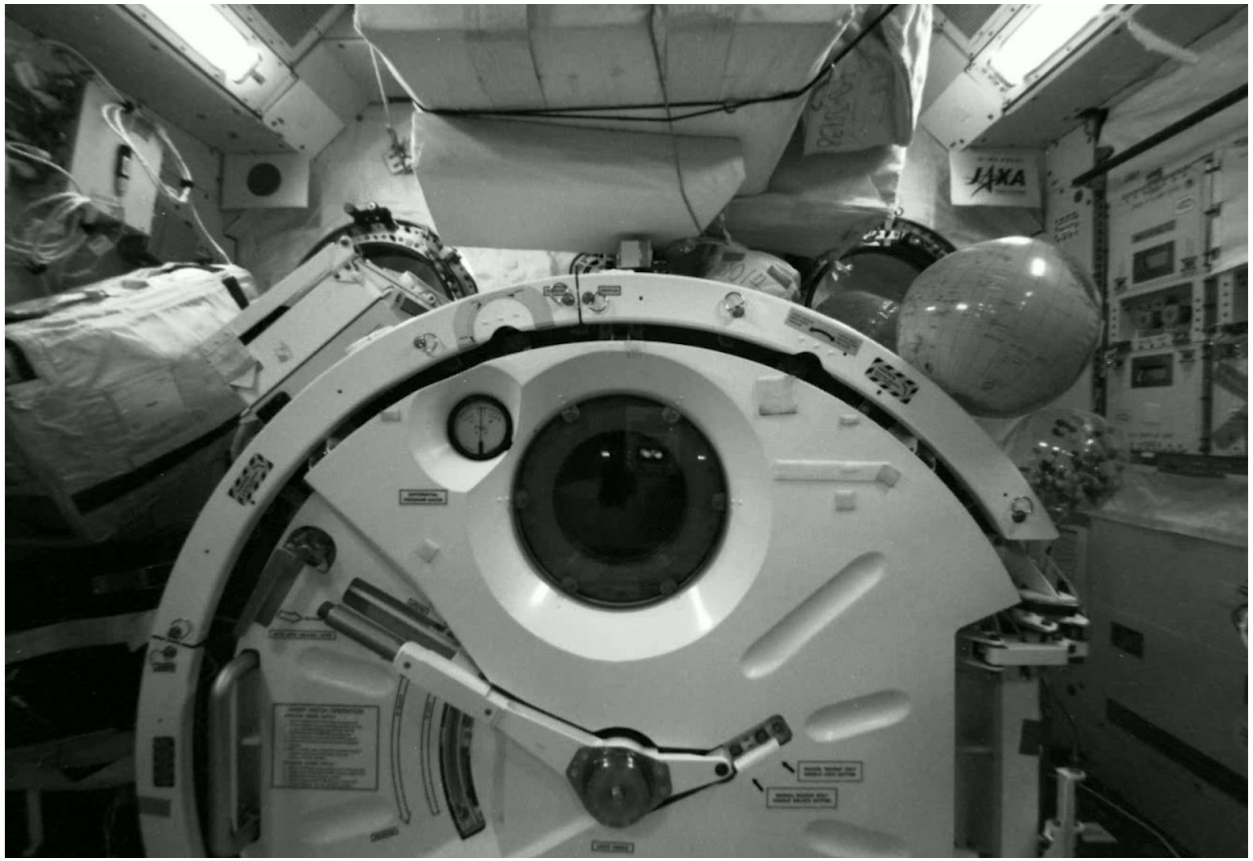
[Pautrat, Rémi, et al. "Gluestick: Robust image matching by sticking points and lines together," in CVPR 2023.]

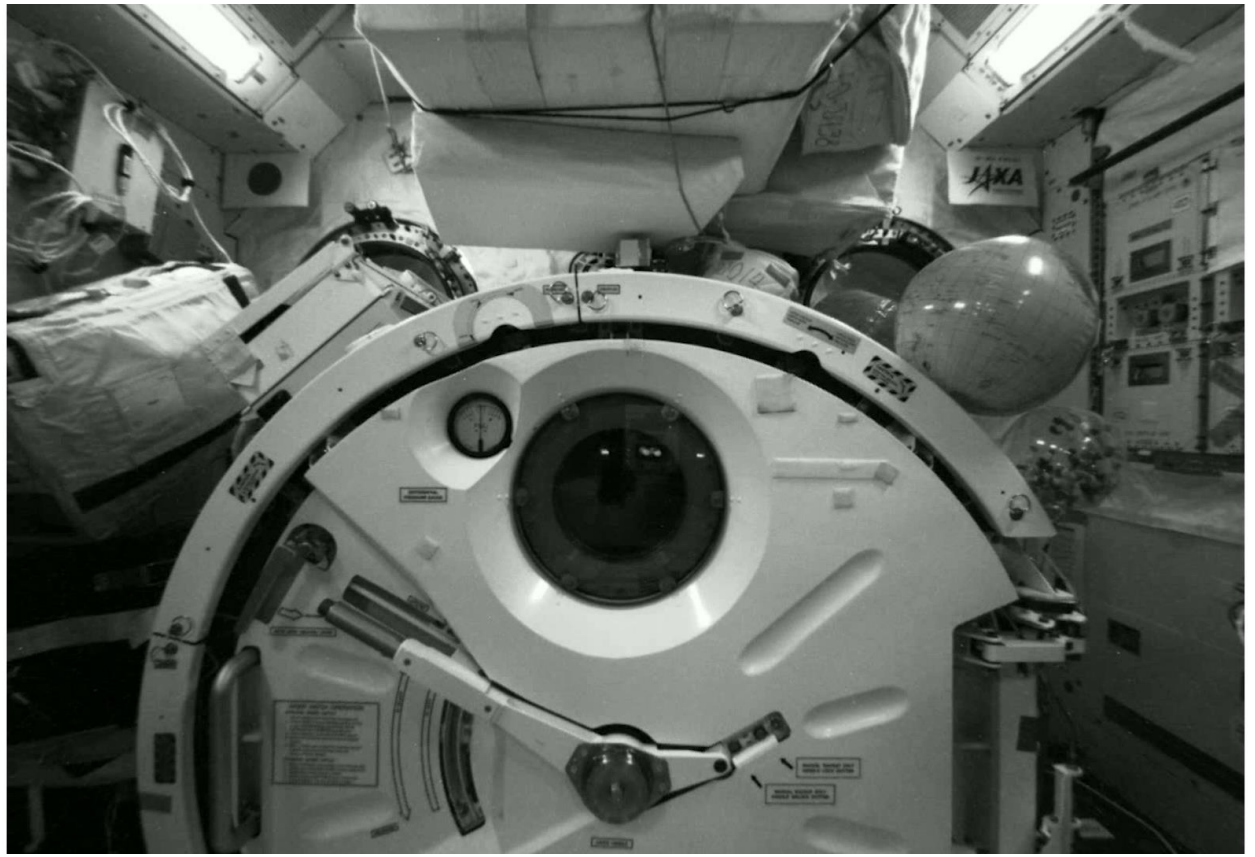
Drift-Free Rotation Tracking Pipeline





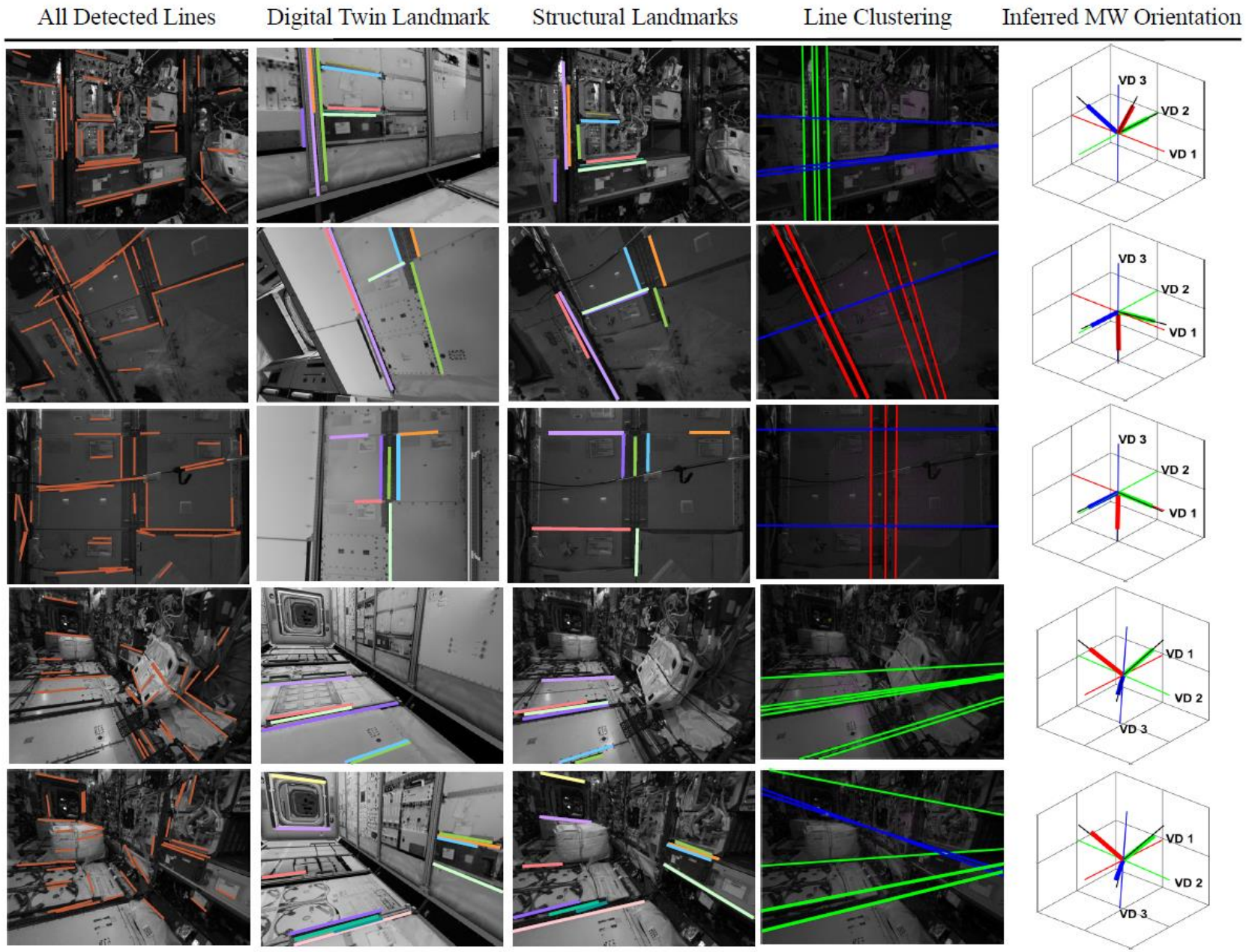
Astrobee ISS Free-Flyer Datasets





[Kang, Suyoung, et al. "Astrobee iss free-flyer datasets for space intra-vehicular robot navigation research." IEEE RA-L (2024).]

Qualitative Results on Astrobee ISS Dataset



Quantitative Results on Astrobee ISS Dataset

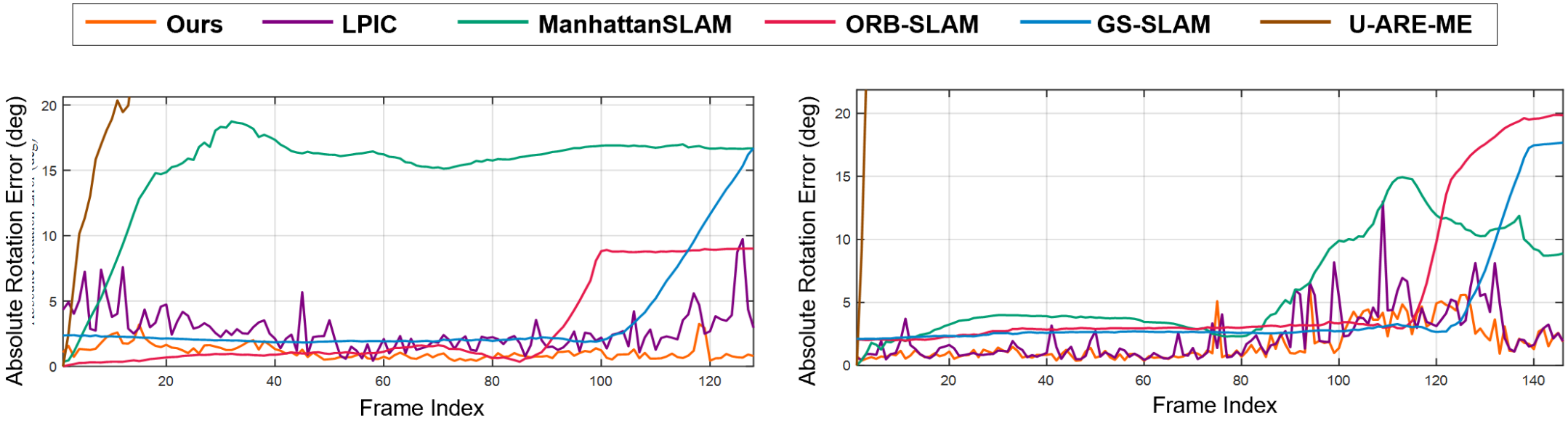
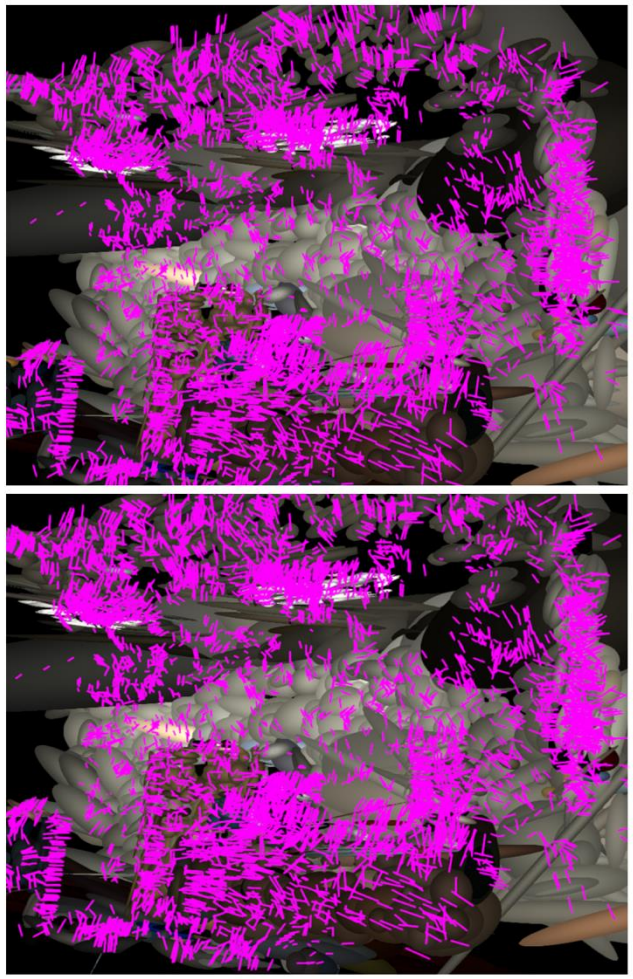


Table I. Absolute Rotation Error Comparison (unit: degree)

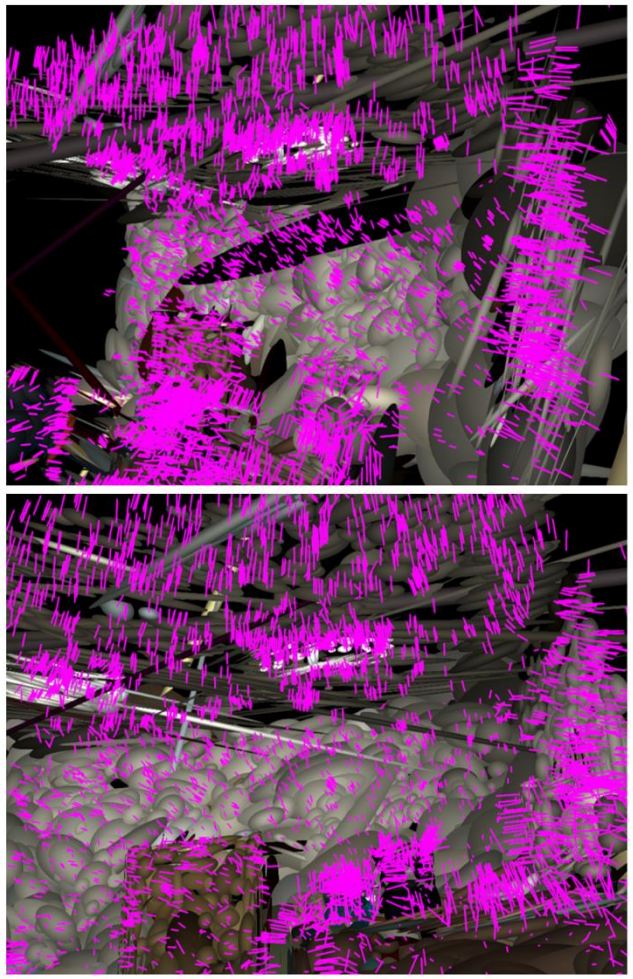
Dataset		Structural Model-based Methods				General-purpose Methods	
		Proposed	LPIC	ManhattanSLAM	U-ARE-ME	GS-SLAM	ORB-SLAM3
Astrobee Dataset	kibo_rot 1	**1.75**	2.32	4.26	63.67	7.17	4.09
	kibo_rot 2	**1.09**	2.74	2.94	49.56	14.53	3.42
	kibo_trans	1.44	3.56	1.66	32.03	**1.17**	1.47
	Average	**1.43**	2.87	2.95	48.42	7.62	2.99

Future Work: Manhattan-Aligned Gaussian Splatting SLAM

RGB, Depth Image Pair



3D Gaussian Splatting SLAM



Proposed

Takeaway Messages

- On the ISS, free rotation and clutter make visual navigation challenging.
- Remember our DTOR—it removes clutter to achieve drift-free rotation estimation in space.

Source Codes and Datasets:

Thank you for your time!