Equivariant Neural Inertial Odometry for Microgravity Space Robotics

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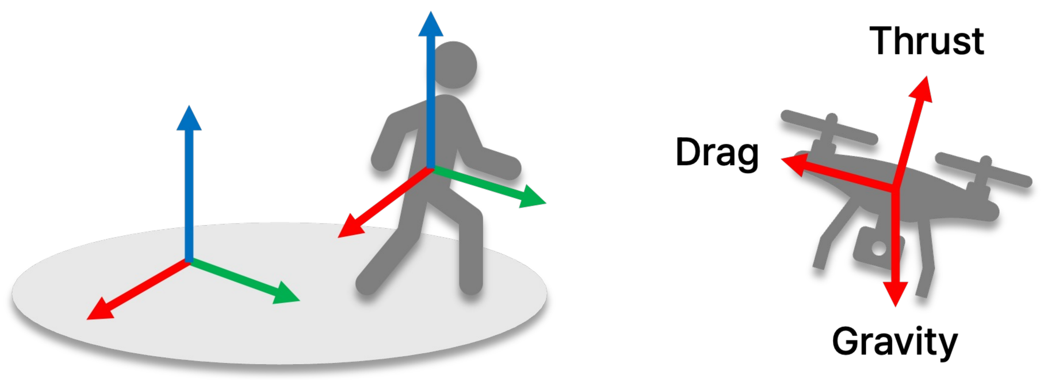
Background & Motivation

Neural Inertial Odometry (NIO) learns and predicts the translational motions from IMU-only, but existing methods rely on gravity-dependent priors inherited from terrestrial settings.



On Earth: Gravity as a strong motion prior

Pedestrian – gravity as a **coordinate reference**

- Horizontal dominant motion: walk on the ground
- Align to gravity: Gravity-Aligned Coordinate Frame

$$ {}^{G}\mathbf{a} = \mathbf{R}\,{}^{B}\mathbf{a},\ {}^{G}\boldsymbol{\omega} = \mathbf{R}\,{}^{B}\boldsymbol{\omega} $$

→ Reduces learning hypothesis space from SO(3) to SO(2)

Drone·UAV – gravity as a **feature observability** source

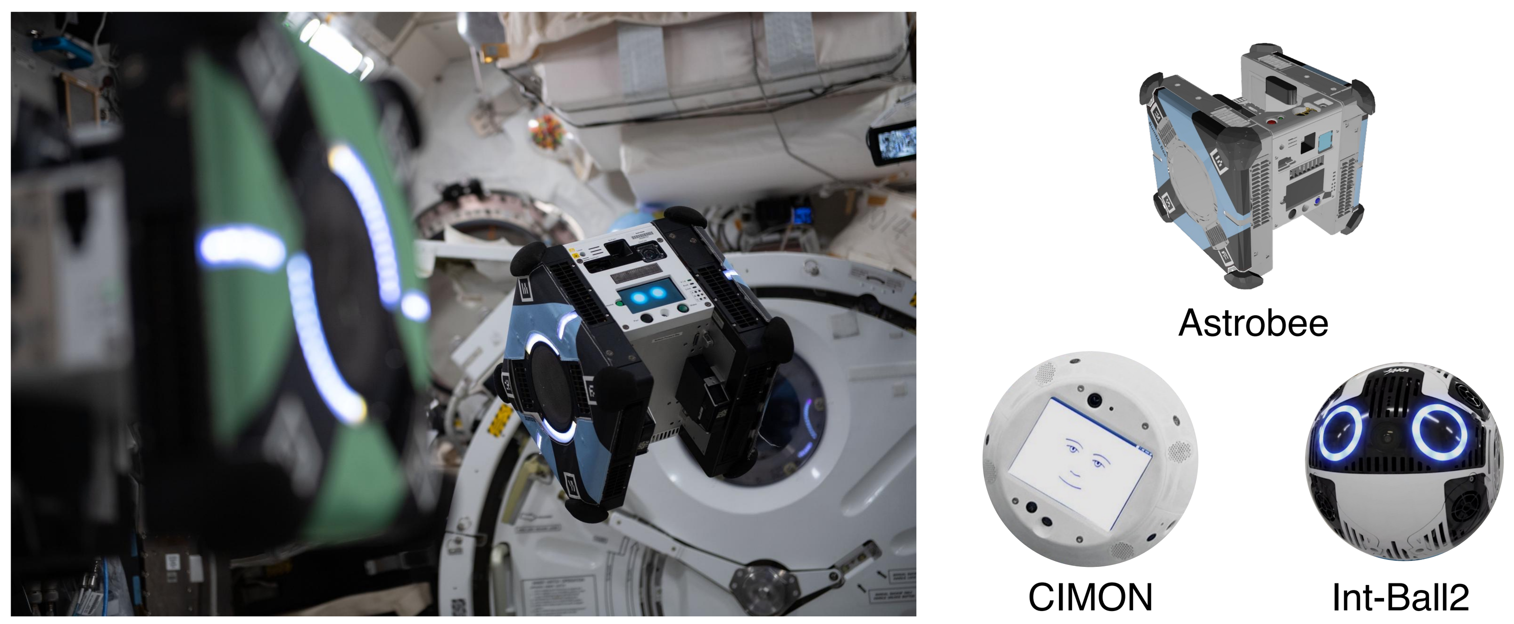
- Attitude coupled motion: increase tilt for thrust
- Embed attitude via gravity in body frame representation

$$ {}^{B}\mathbf{a} = \frac{{}^{B}\mathbf{F}_{net}}{m} + \mathbf{R}^{\top}\,{}^{G}\mathbf{g} $$

→ Enhances feature observability of the network

In Space: Gravity-dependent priors no longer hold

ISS free-flyers operate **in microgravity**, with fully arbitrary attitude, holonomic dynamics, and unconstrained 3D motion



- **Gravity-induced priors are inapplicable to ISS free-flyers**
- **No prior NIO has been tailored to microgravity settings**

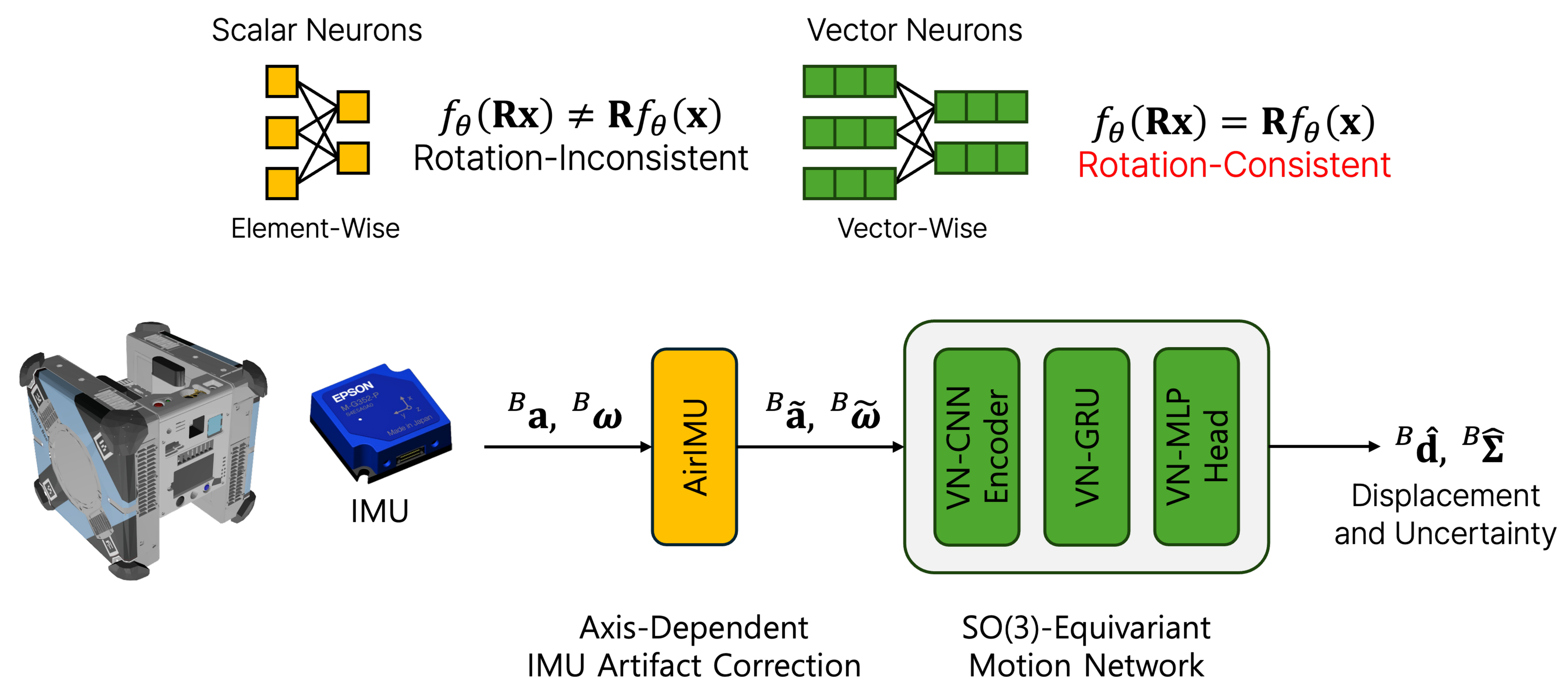
Contribution

- Proposes a **microgravity-tailored NIO** framework for unconstrained 3D free-flyer motion.
- Encodes **SO(3)-equivariance** as an architectural inductive bias for rotation-consistent motion prediction.
- Demonstrates **improved accuracy and generalization** on unseen Astrobee simulation trajectories.

Methodology

SO(3)-Equivariance as a Principled Inductive Bias

- Encodes rotational symmetry using Vector Neurons [1], rotation-consistent predictions under arbitrary 3D rotations.



❶ Axis-Dependent IMU Artifact Correction

- Learns and corrects asymmetric IMU bias/noise.
- Produces corrected IMU measurements for equivariant motion learning.

$$ {}^{B}\tilde{\mathbf{a}} = {}^{B}\mathbf{a} + {}^{B}\hat{\sigma}_{acc},\ {}^{B}\tilde{\boldsymbol{\omega}} = {}^{B}\boldsymbol{\omega} + {}^{B}\hat{\sigma}_{gyro} $$

❷ SO(3)-Equivariant Motion Learning

- Uses Vector Neuron-based 1D-CNN/GRU/MLP layers.
- Predicts **displacement** and corresponding **uncertainty** in an SO(3)-equivariant manner.

$$ \hat{\mathbf{d}}(\mathbf{R}\mathcal{X}) = \mathbf{R}\hat{\mathbf{d}}(\mathcal{X}),\ \hat{\boldsymbol{\Sigma}}(\mathbf{R}\mathcal{X}) = \mathbf{R}\hat{\boldsymbol{\Sigma}}(\mathcal{X})\mathbf{R}^{\top} $$

Experimental Result

Dataset

- Astrobee Robot Software Simulation Dataset
- 41 sequences with a total duration of 315 minutes

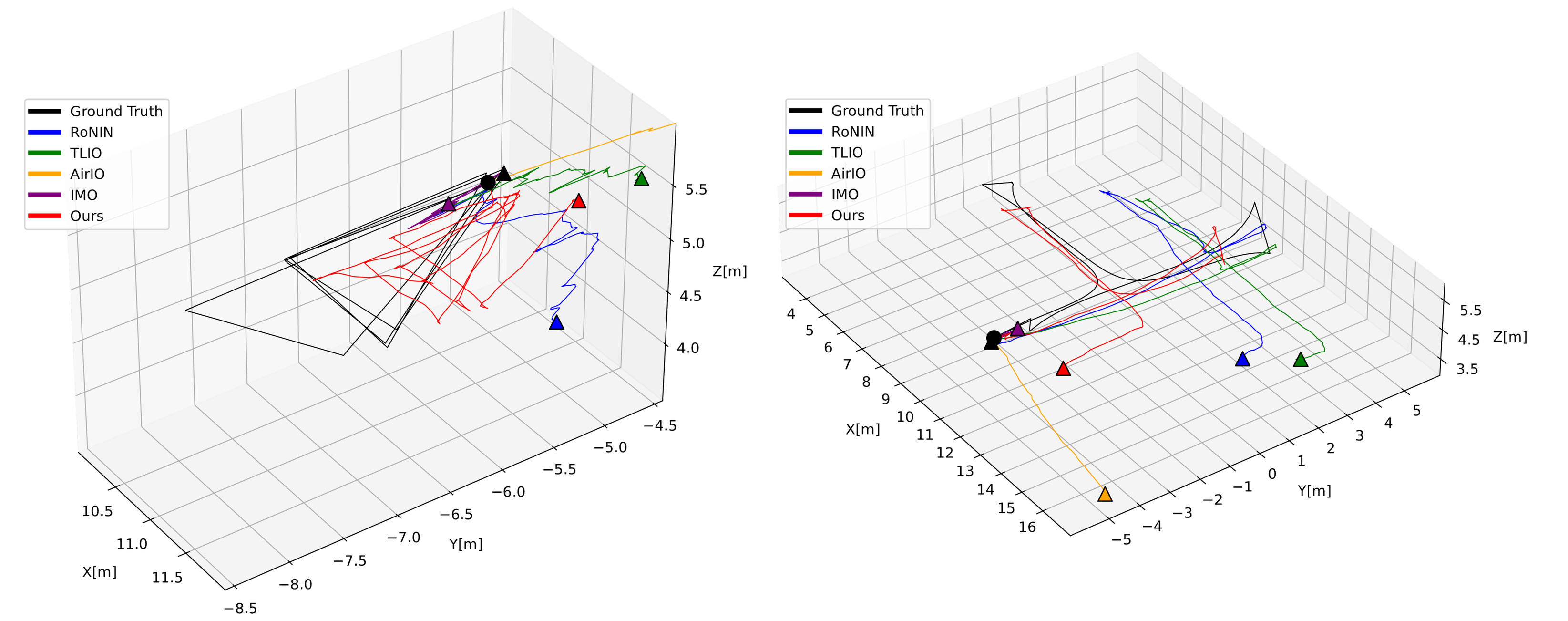
Metric

- RMSE ATE (Absolute Translation Error) [m]
- RMSE RTE (Relative Translation Error) @ 5s [m]

*Leverage ground-truth orientations for all methods

Sequence	Metric	RoNIN	TLIO	AirIO	IMO	Ours
Seen	ATE	2.3639	<u>2.2911</u>	3.0095	2.7928	**0.8335**
	RTE	0.2560	<u>0.2424</u>	0.2756	0.3012	**0.0876**
Unseen	ATE	<u>2.3859</u>	2.5291	3.2572	2.9146	**1.1413**
	RTE	0.2177	<u>0.2139</u>	0.2590	0.2687	**0.1204**

Qualitative Results on Unseen Sequences



xz-planar translation dominant sequence
xy-planar translation dominant sequence

Conclusion & Future Work

- Microgravity breaks gravity-induced priors of terrestrial NIO.
- SO(3)-equivariance serves as a principled inductive bias for microgravity NIO, improving accuracy and generalization.

Future Work

- Evaluation on real-world Astrobee ISS dataset [3]
- IMU Sim-to-Real Domain Transfer
- Attitude estimation using IMU-only under microgravity

[1] Deng, Congyue, et al. "Vector neurons: A general framework for so (3)-equivariant networks." *Proceedings of the IEEE/CVF international conference on computer vision.* 2021.
[2] Qiu, Yuheng, et al. "Airimu: Learning uncertainty propagation for inertial odometry." *arXiv preprint arXiv:2310.04874* (2023).
[3] Kang, Suyoung, et al. "Astrobee iss free-flyer datasets for space intra-vehicular robot navigation research." *IEEE Robotics and Automation Letters* 9.4 (2024): 3307-3314.

GIST MPIL Machine Perception and Intelligence Lab Carnegie Mellon University AIR LAB NASA irg