UNMANNED SYSTEMS LAB

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IEEE International Symposium on Safety, Security, and Rescue Robotics

TEXAS A&M UNIVERSITY
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Online Multi Camera-IMU Calibration

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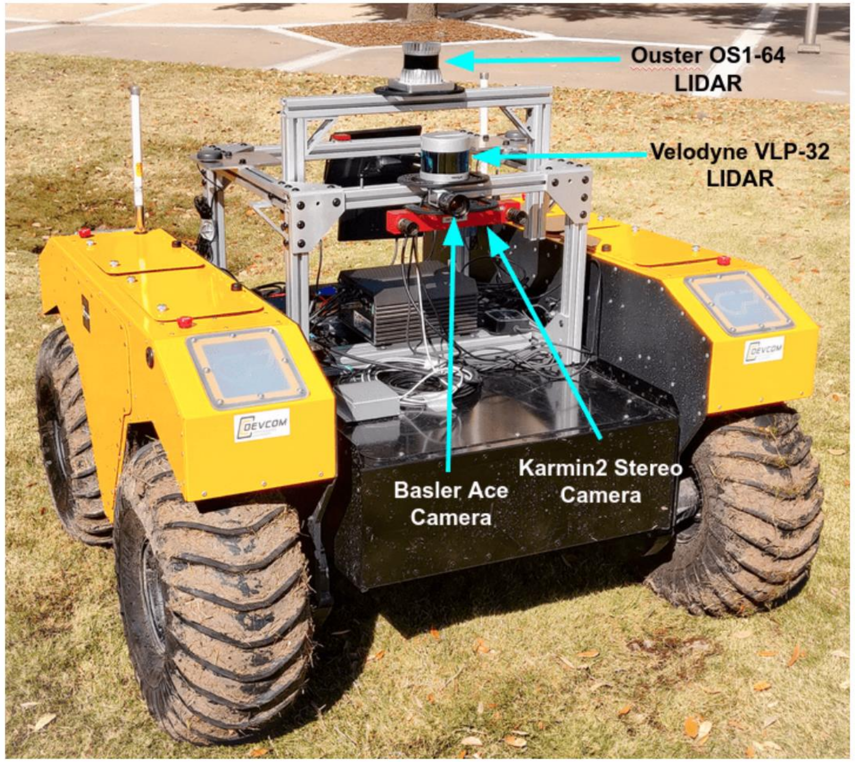
Presentation Outline

- Motivation
- Estimator Design
- Simulation Results
- Experimental Results
- Future Work / Conclusions

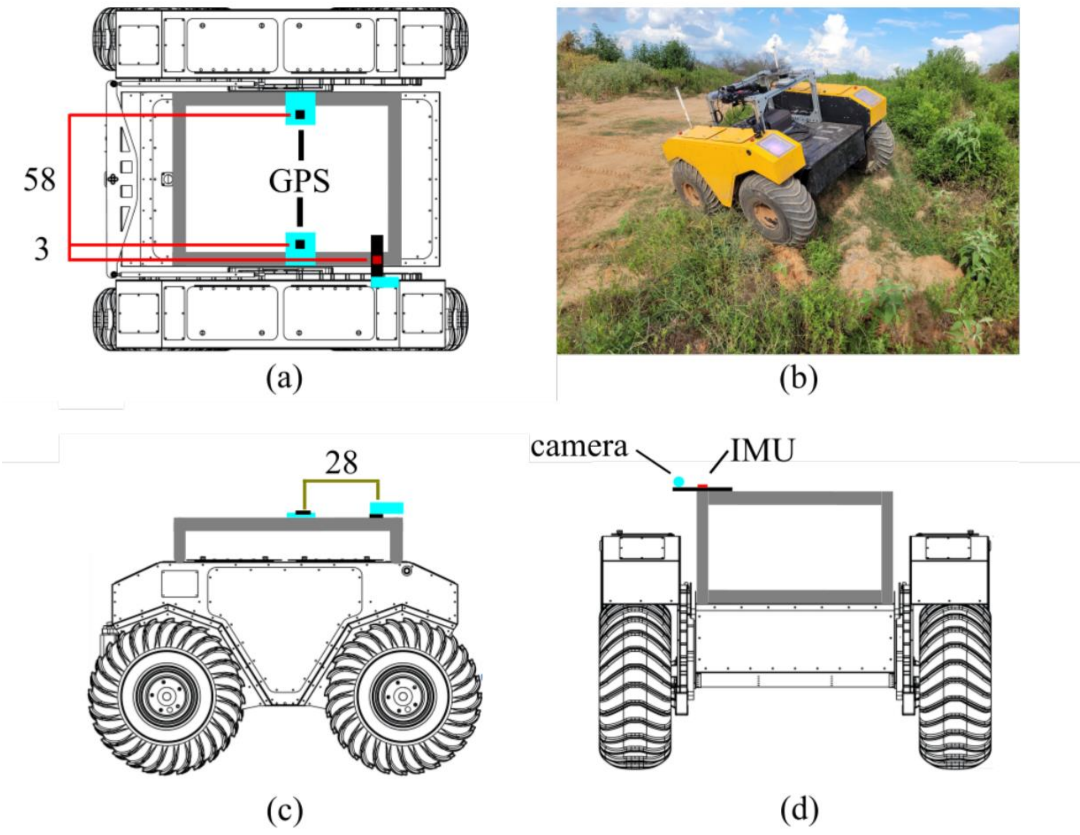
The Need for Calibration

- Mobile robotic systems rely on proprioceptive and exteroceptive sensors
- Accurate sensor integration requires good intrinsic and extrinsic calibration
- Poor calibrations often lead to visual-inertial odometry and SLAM divergences
- Therefore, it is necessary for mobile robotic systems to have highly accurate calibrations throughout the use lifecycle



The Challenges of Calibration

- It is difficult to achieve good, consistent sensor calibrations
- High-accuracy calibration devices are costly and time-consuming
- Batch processes are cheap, but cannot handle calibration changes
- Therefore, accurate, online processes for calibrating IMU-camera systems are desirable



Example Challenging Scenario

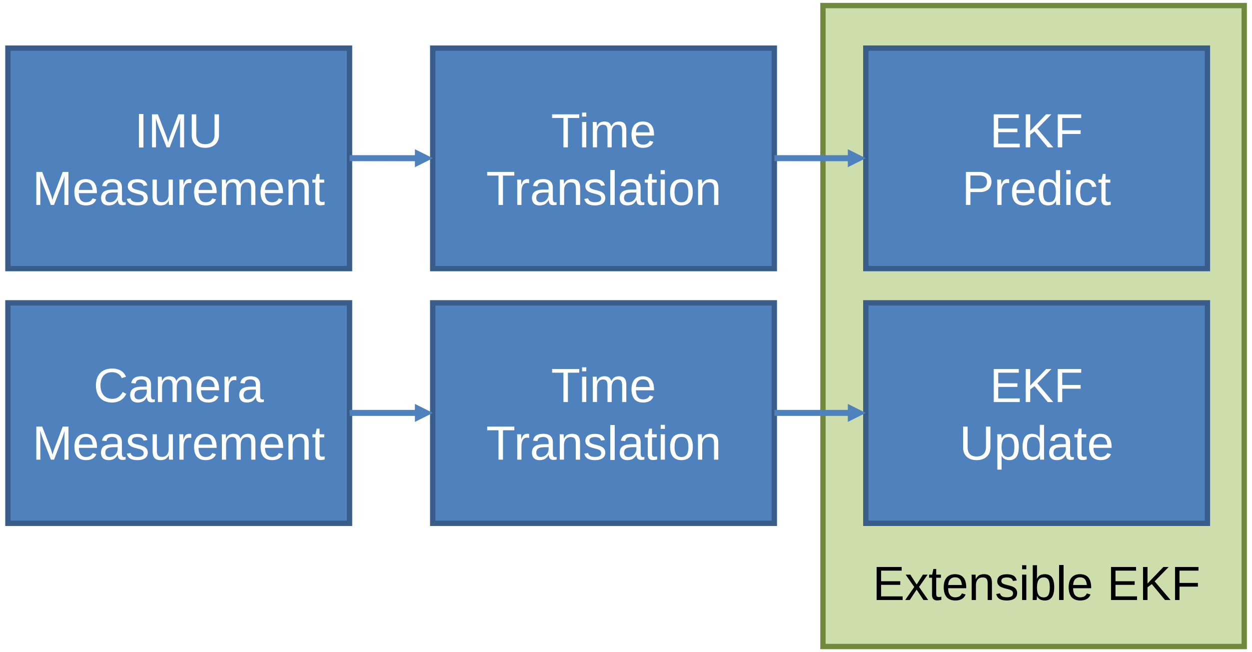
- Shocks and vibrations impact initial calibrations
- There are drastic lighting differences based on FOV
- Returning to calibration environment would be time consuming and costly

Problem Statement

- Create an online multi-camera IMU calibration filter
- Design camera count flexibility into the filter
- Utilize high-accuracy, generic fiducial markers for detection
  - Trades robustness for additional accuracy
- Handle time translation, where closed-loop corrections are not possible

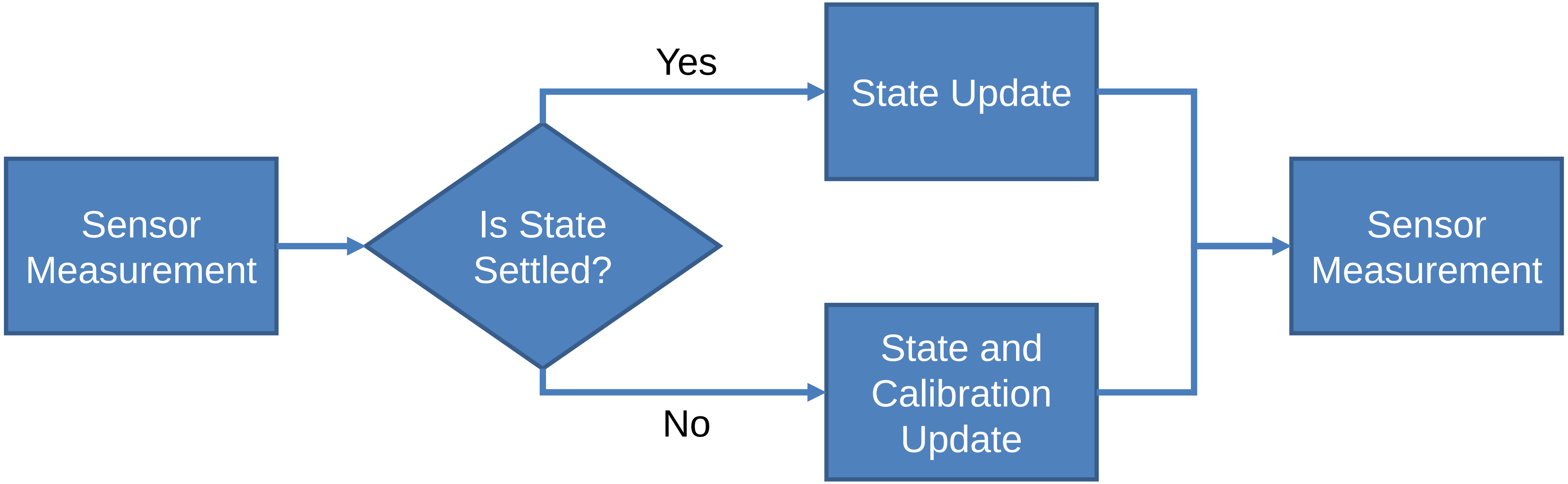
Filter Design

- Body States
  - Position, Velocity, Orientation …
- IMU States
  - Extrinsic Offsets, Intrinsic Biases
- Camera States
  - Extrinsic Offsets
- Time Translation
  - Time offset and skew parameters



Settle-Detection

- Monitoring EKF states for settle criteria
- Consider a state settled when uncertainty is sufficiently reduced
- Once settled, we modify the update equations to not adjust calibrations
  - With higher rates and number of sensors, this can improve performance

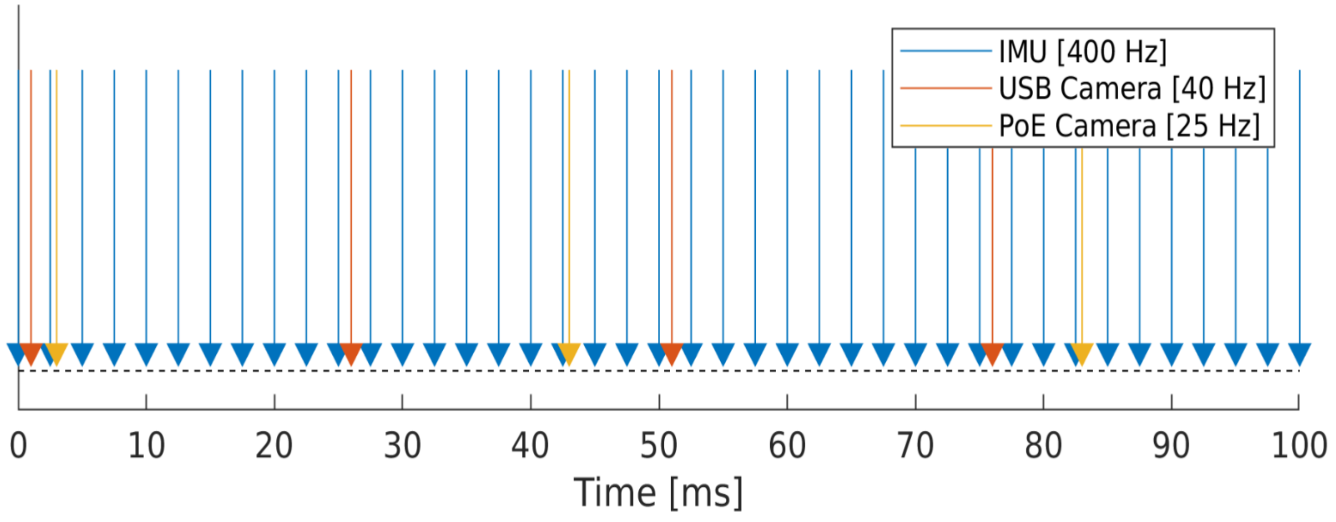


Shift-Detection

- Monitor EKF states for shift criteria using just residuals
- Using a sliding-window t-test, we test residuals for changes in calibrations
- When a shift in calibration is detected, reinstate the full update equation

Sensor Timing and Rates

- IMU
  - 400 Hz VectorNav VN 300
- Cameras
  - 40 Hz USB 3.0 Basler Ace
  - 25 Hz PoE Pointgrey Blackfly
- Resulting Measurement Stream
  - Non-synchronized measurements
  - Varying network delays (10-100 ms)



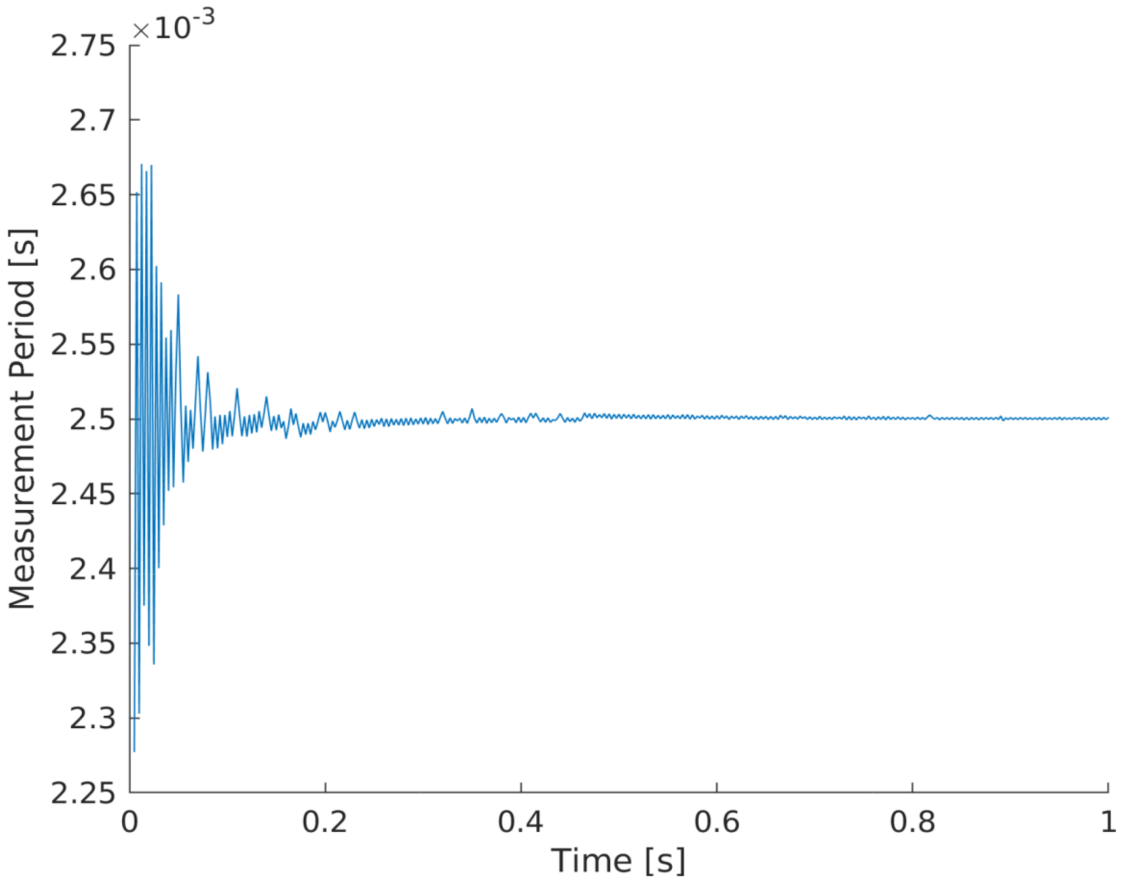
Time Translation Filter

- Many sensors are not PTP capable
- Local sensor clocks are consistent
- Network delays vary and are difficult to predict
- A one-way filter was used to pre-process measurement time
- Adjusted measurement time was then fed into filter
- Simple measurement model allows for linear filter updates

$$t_{fitler} = \alpha\, t_{sensor} + \beta$$

Time Translation Results

- Implemented for USB Sensors
- Converged quickly for high-rate sensors
- Reduced measurement jitter
- Corrects for simultaneous packets



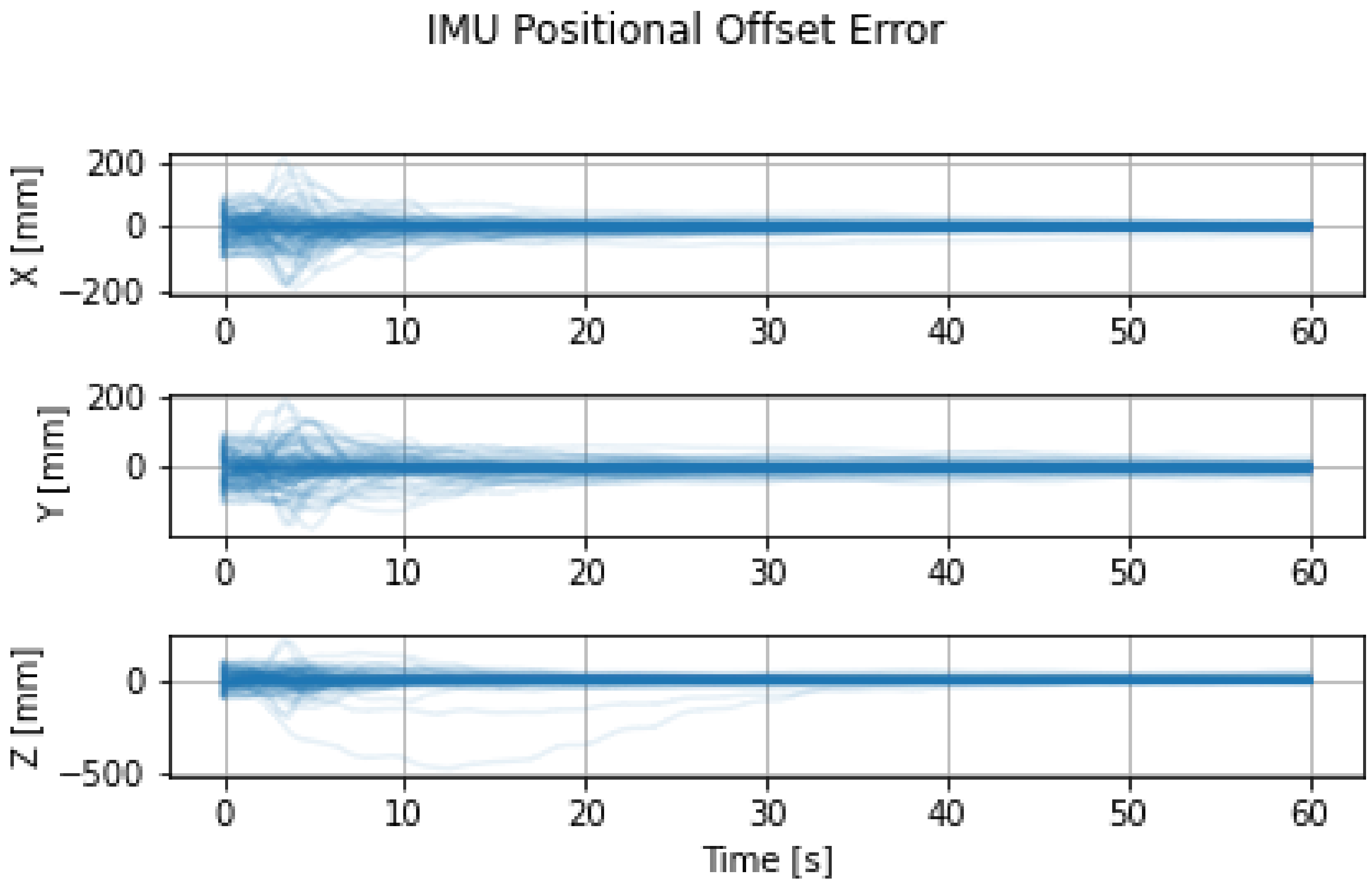
Monte Carlo Simulations

- Monte Carlo Simulation
  - Parallelized for faster processing
  - Random draws for
    - Initial intrinsic and extrinsic errors
    - Sinusoidal sensor motion errors
    - Target measurement errors
    - Shifts in extrinsic calibration parameters
  - 1000 runs for convergence testing

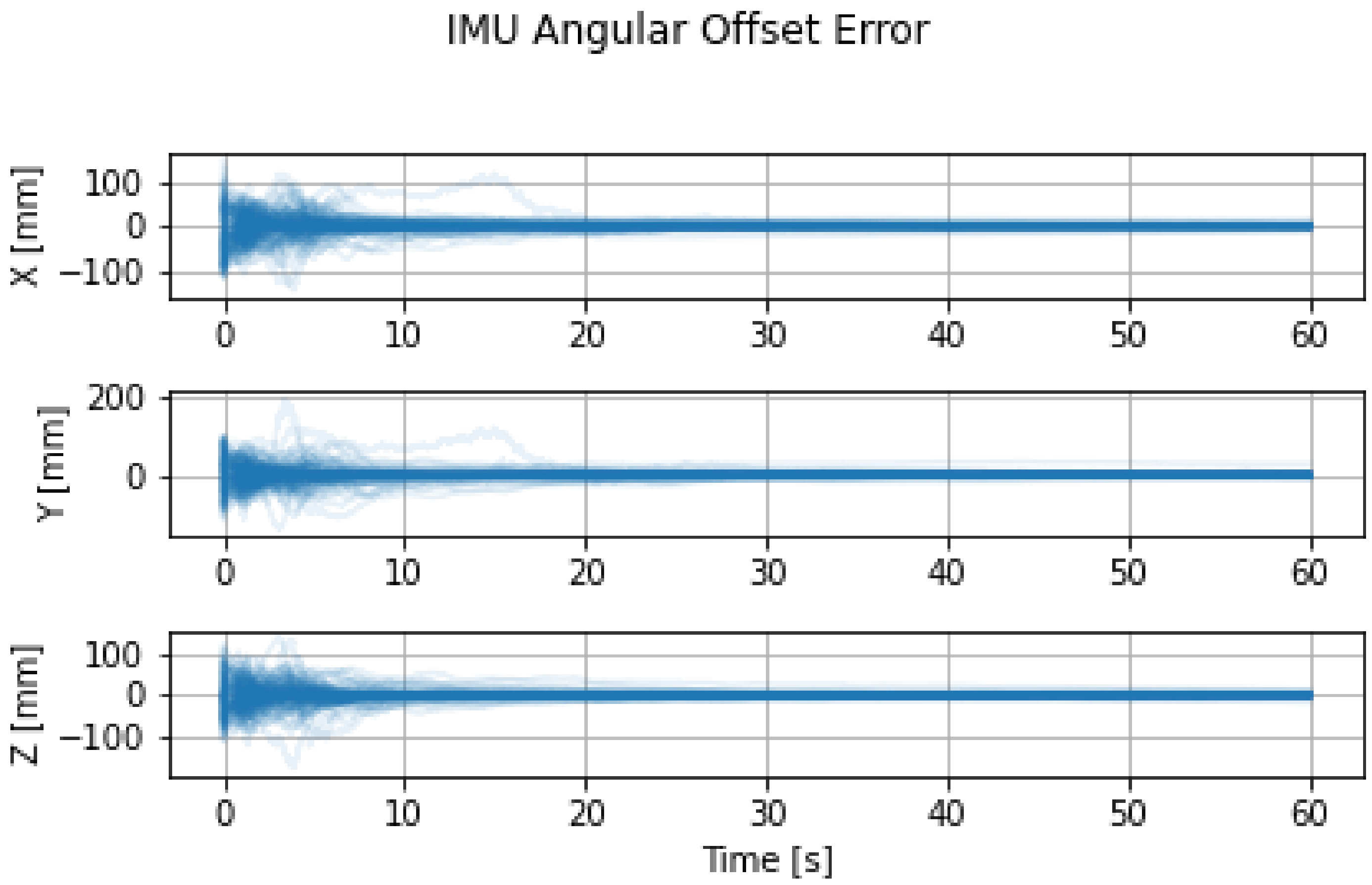
Monte Carlo Results

- Sensor Calibrations
  - Showed consistent and timely convergence
- Settle and Shift Detection
  - Showed ability to detect and react to settling and shifts
  - Consistent convergence after shifts in sensor calibrations

Monte-Carlo Results



Monte-Carlo Results



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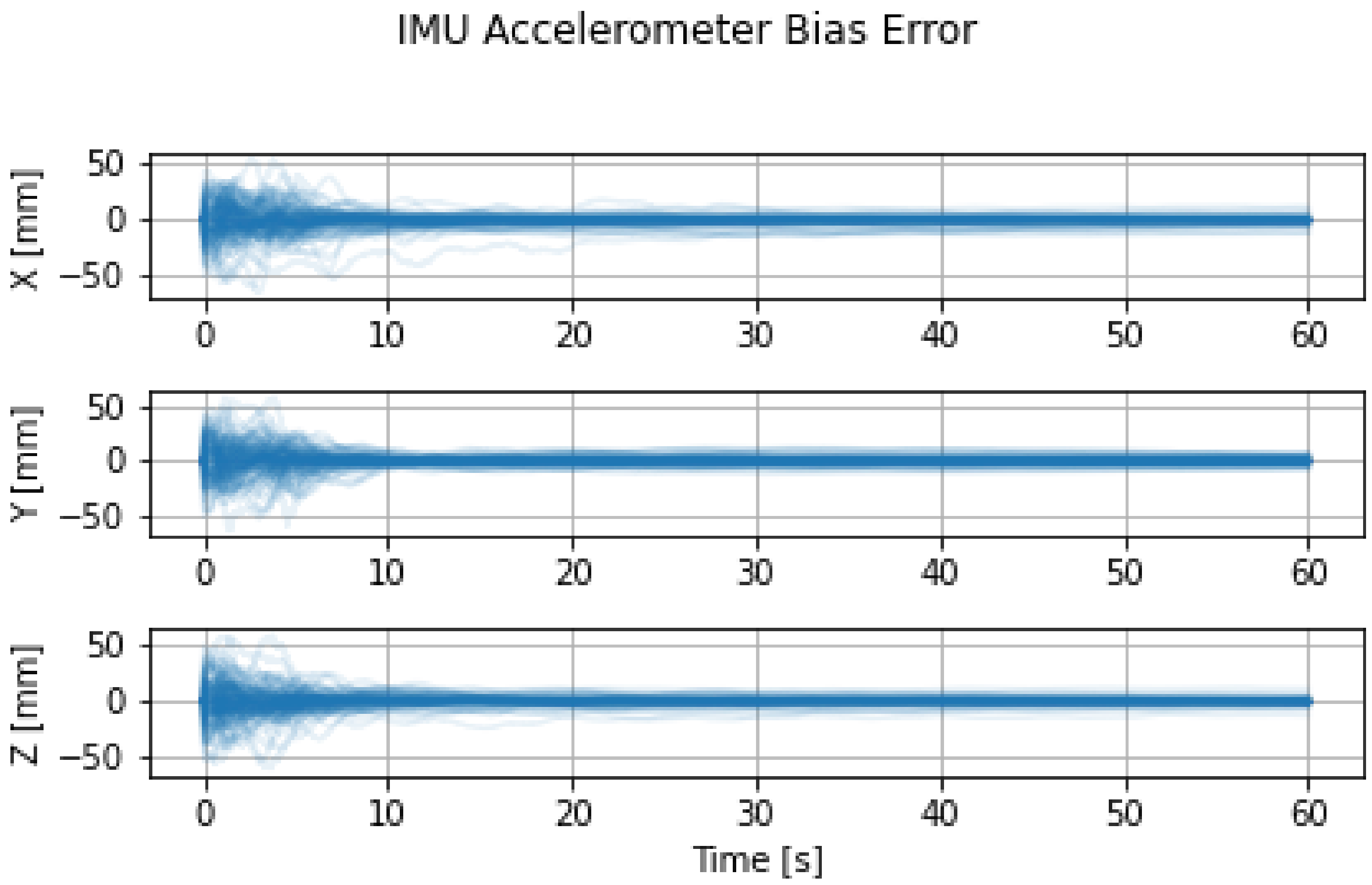

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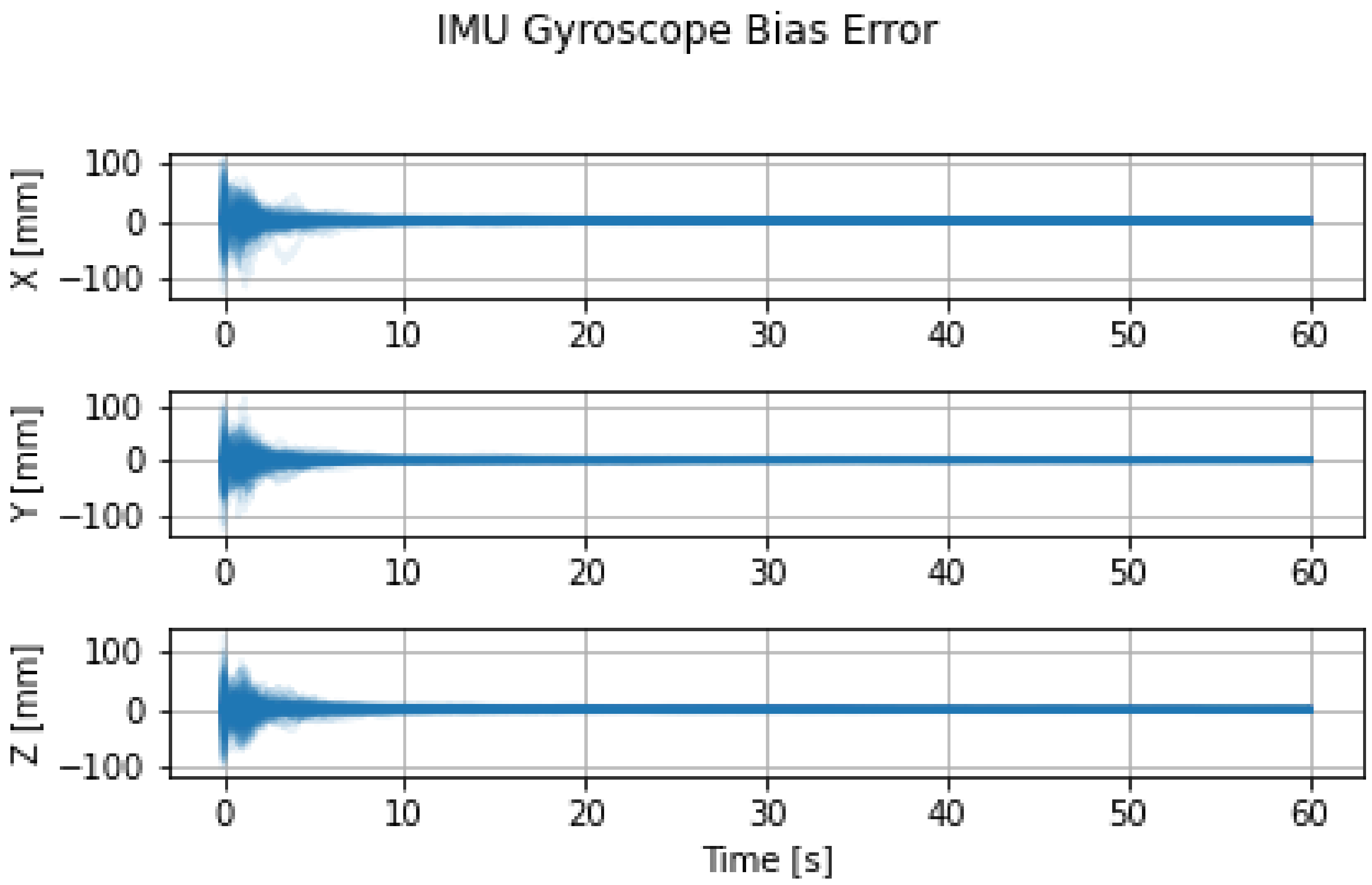
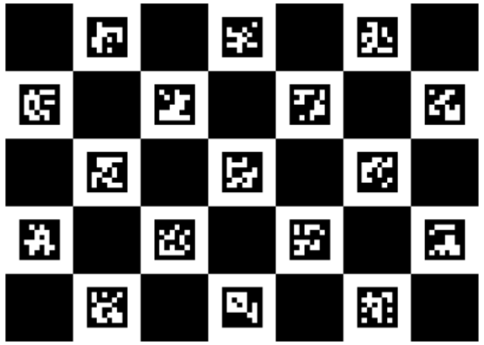
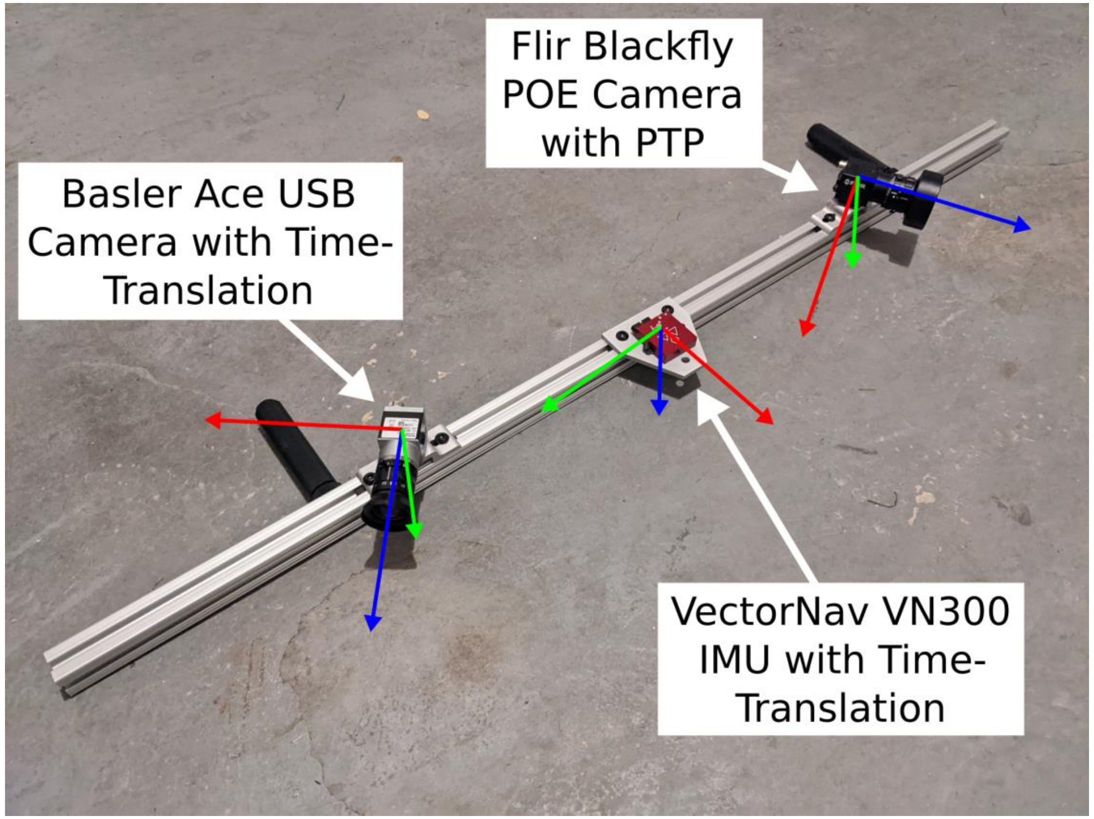


Experimental Setup

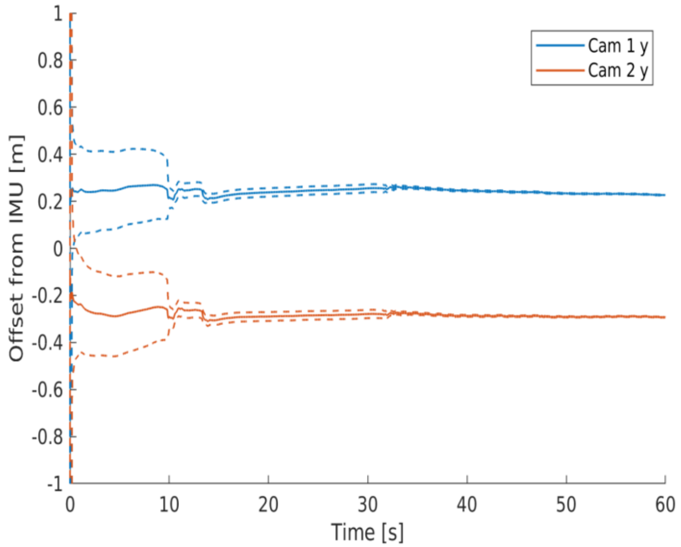
- IMU
  - VectorNav VN300
  - GPS-aided INS solution as truth
- Cameras
  - Gig-E Flir Blackfly S
  - USB 3.0 Basler Ace
- Target
  - ChArUco Board

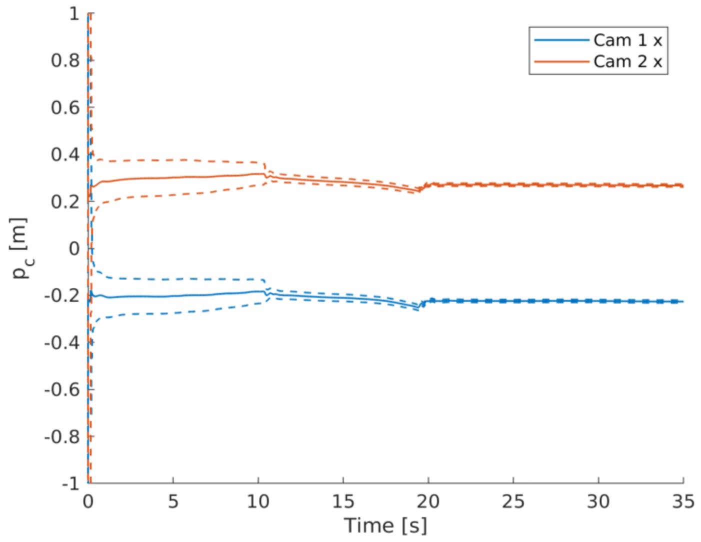


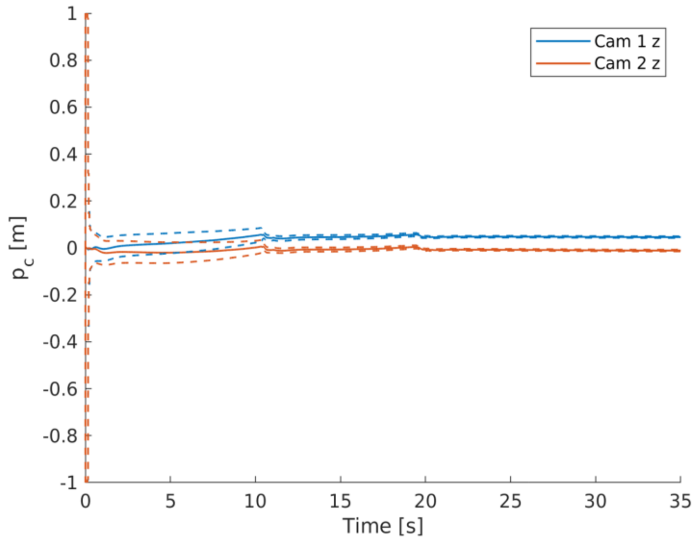


Experimental Results

- Overlapping Fields of View
  - Convergence for extrinsic and intrinsic parameters







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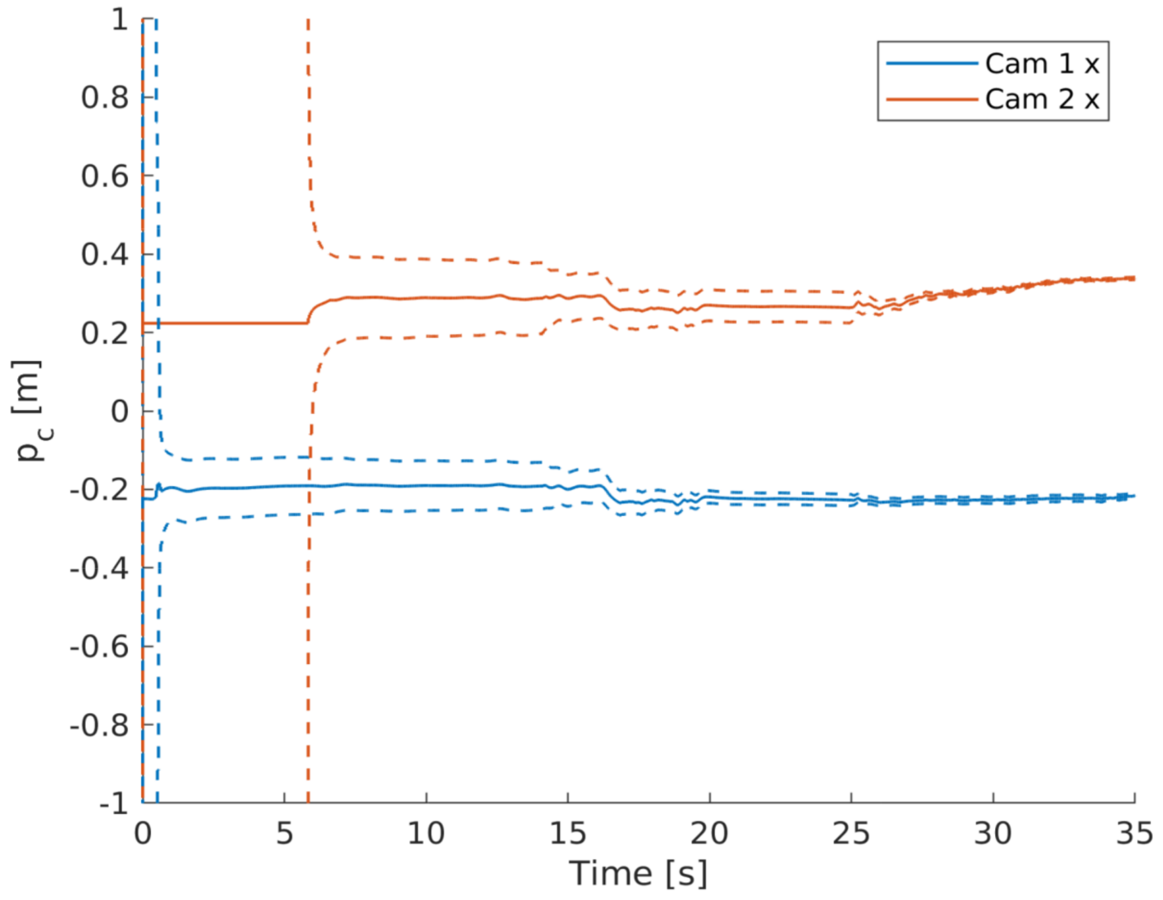

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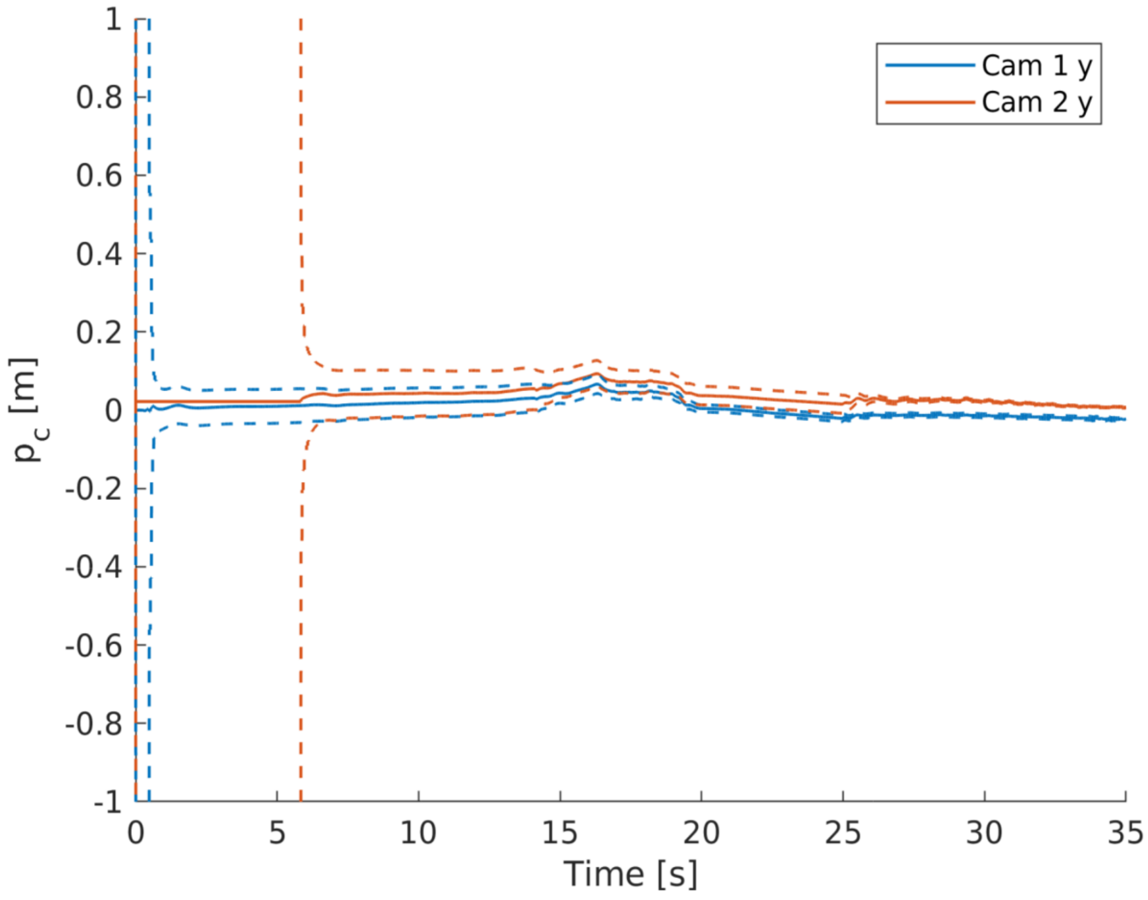

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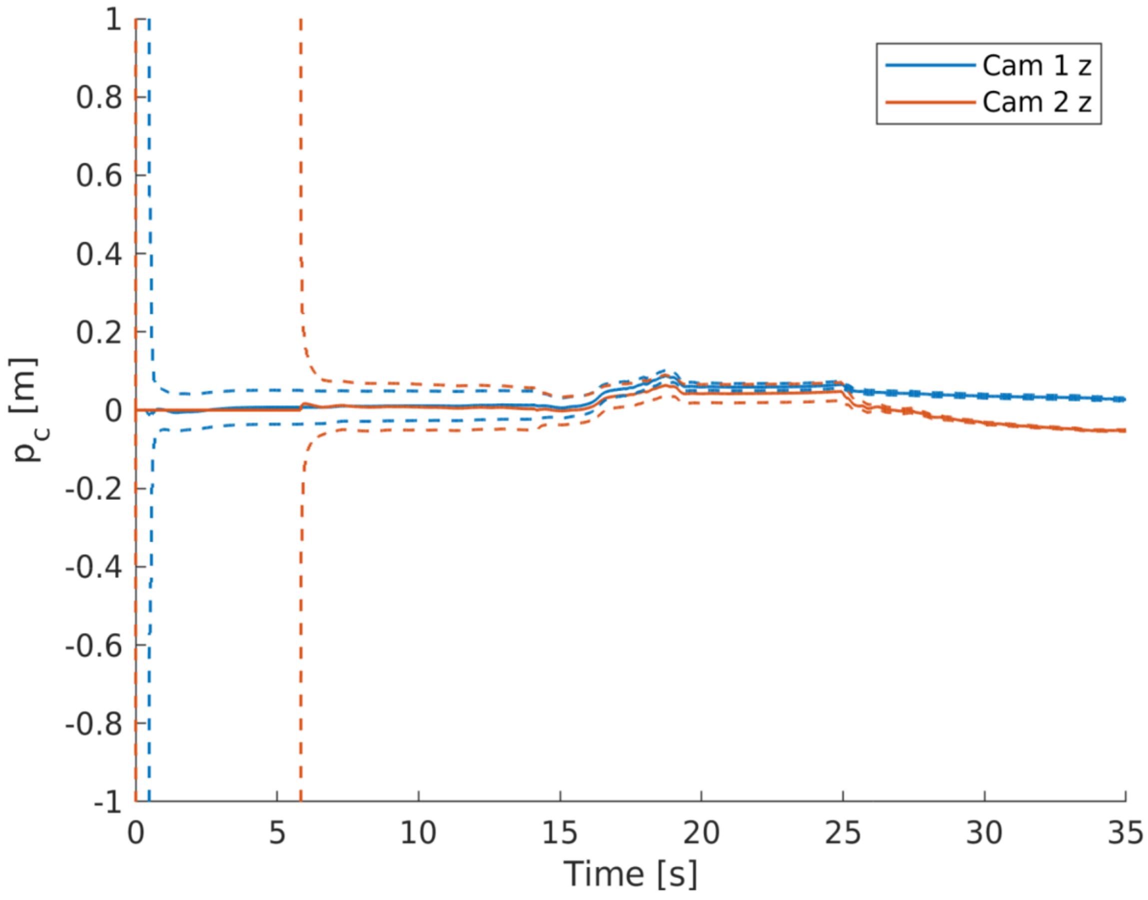
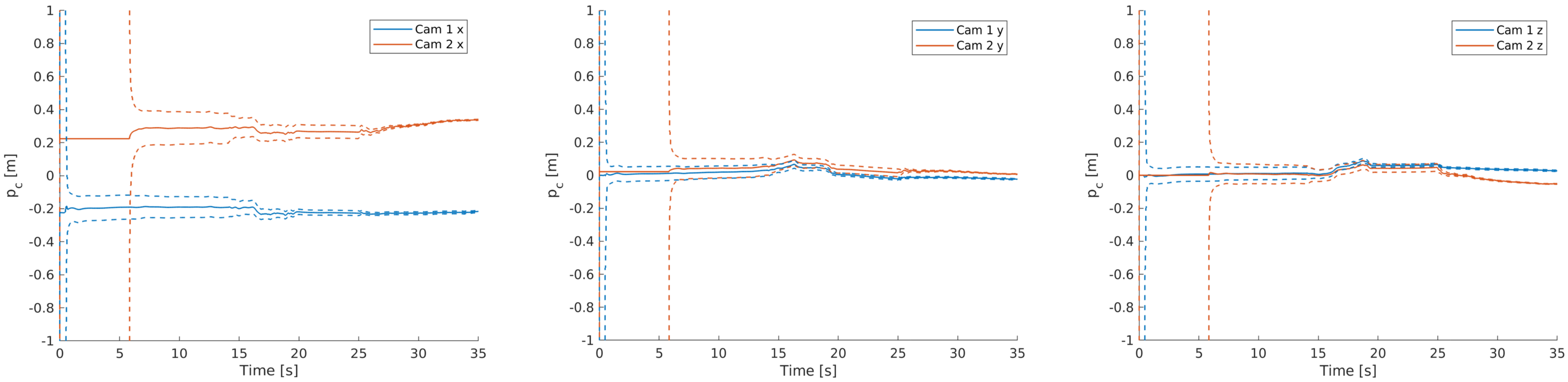


Experimental Results

- Non-Overlapping Fields of View
  - Separate parameter convergence as targets becomes visible
  - Allows for large angular motions while still utilizing fiducial markers



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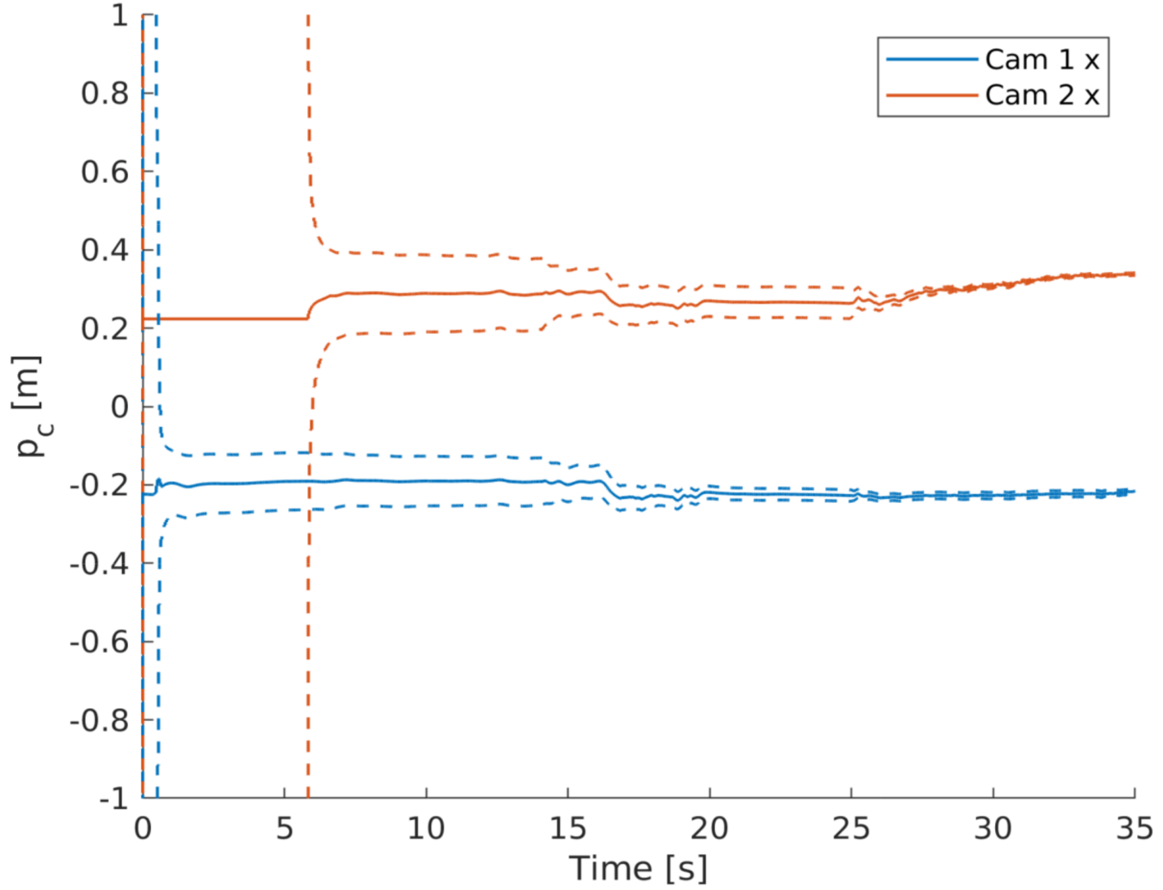

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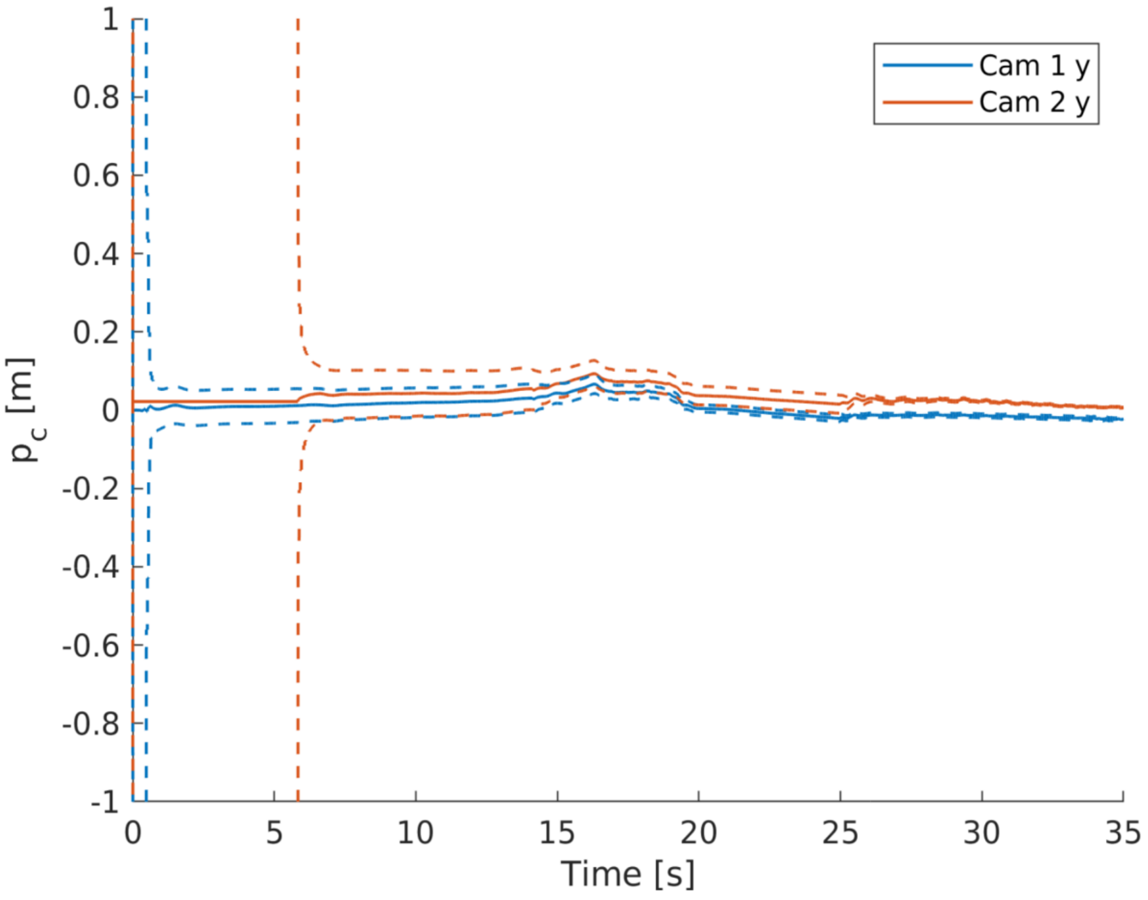

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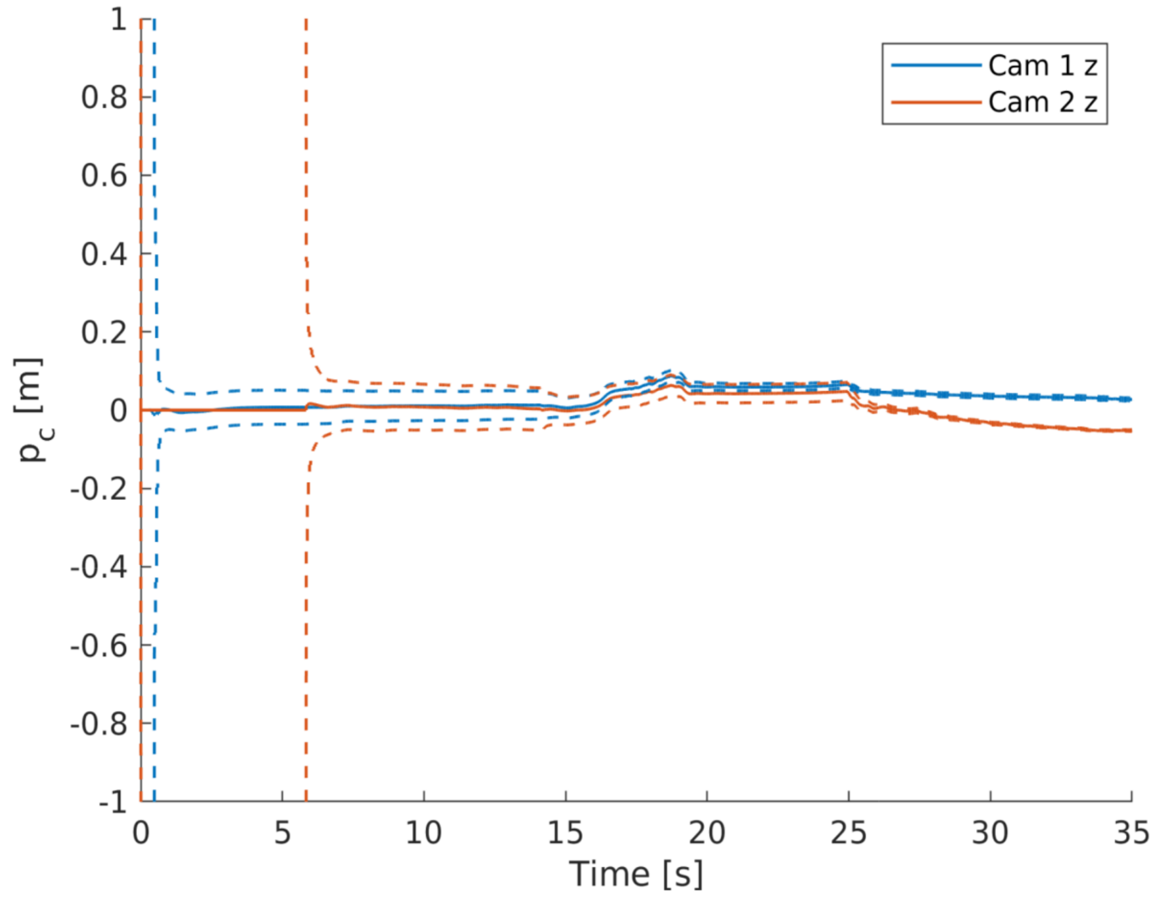

Contributions

- Extended online IMU-camera calibration framework for multiple cameras
- Derived Jacobians and update equations for quaternion-based fiducial measurement and update
- Included time-translation filters for non-PTP sensors
- Provided open-sourced EKF simulation and ROS node implementation

Current Work

- Multi-IMU Inertial Odometry
  - Using multiple, low-cost IMUs to improve localization performance
  - Using higher-order states for rotation estimates
  - Online extrinsic and intrinsic IMU calibration

Future Work

- Integrating Multi-IMU calibration work into filter
- Using feature detection and tracking over fiducials
- Additionally testing of time translation/calibration
- High-fidelity Monte-Carlo simulation
    - Procedurally-Generated environments/images
    - Timing delays and stutters

Open-Sourced Code

- Code repository is available online
- Monte Carlo Simulation
  - Python
  - Multithreaded
  - Faster than real-time
- ROS Node
  - C++ and ROS Kinetic
  - Real-Time (Measurement Limited)
- https://github.com/unmannedlab/multi-cam-imu-cal

Presentation References

1. Chustz, G., & Saripalli, S. (2021). ROOAD: RELLIS Off-road Odometry Analysis Dataset. *ArXIv*. http://arxiv.org/abs/2109.08228
2. Mishra, S., Osteen, P. R., Pandey, G., & Saripalli, S. (2020). Experimental evaluation of 3D-LIDAR camera extrinsic calibration. *IEEE International Conference on Intelligent Robots and Systems*, 9020–9026. https://doi.org/10.1109/IROS45743.2020.9340911
3. Jiang, P., Osteen, P., Wigness M., and Saripalli S., (2020). RELLIS-3D: A Multi-modal Dataset for Off-Road Robotics.

Questions

Code Repository

Unmanned Systems
Lab Website

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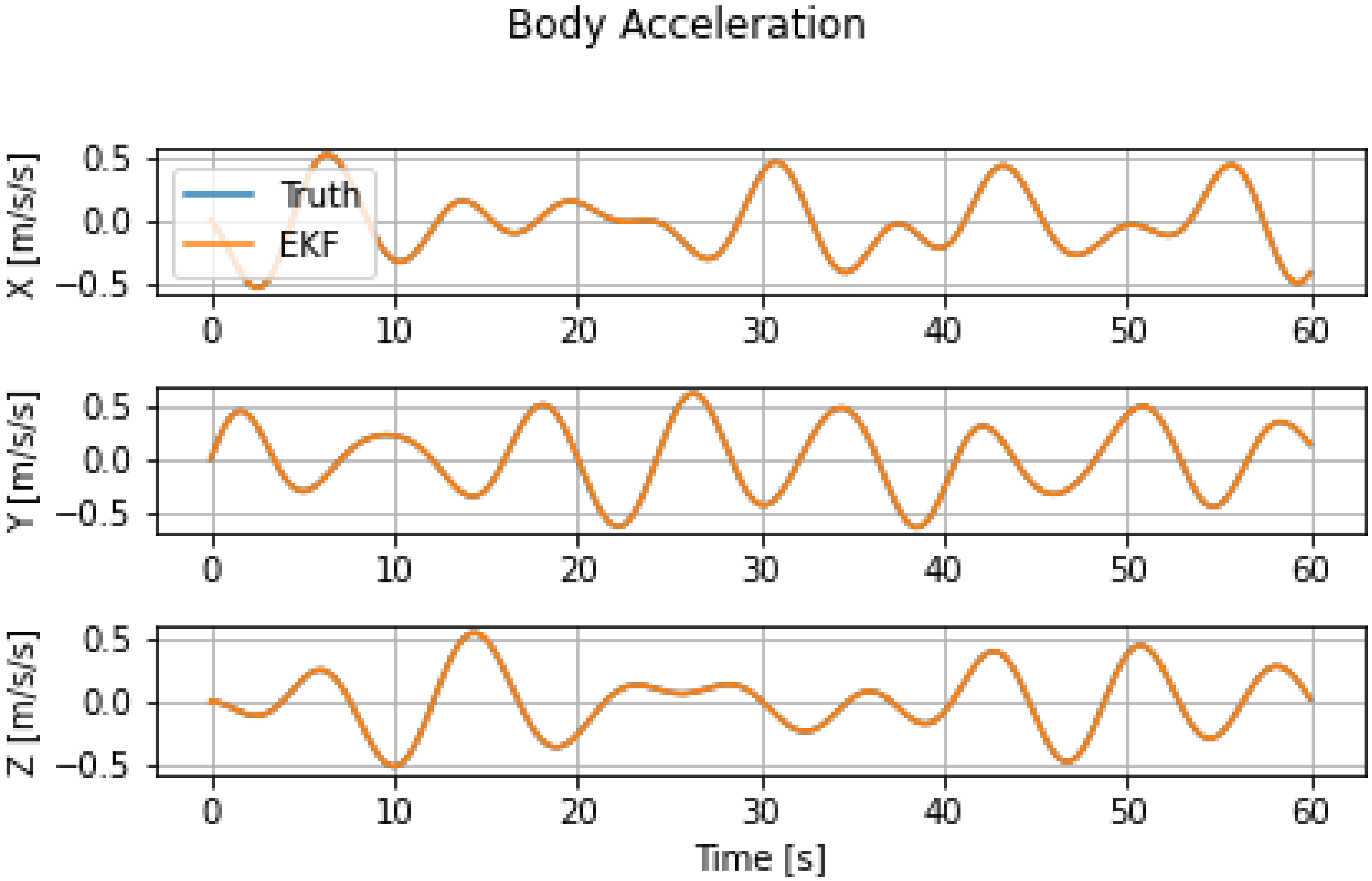
Backup: Single Run Results



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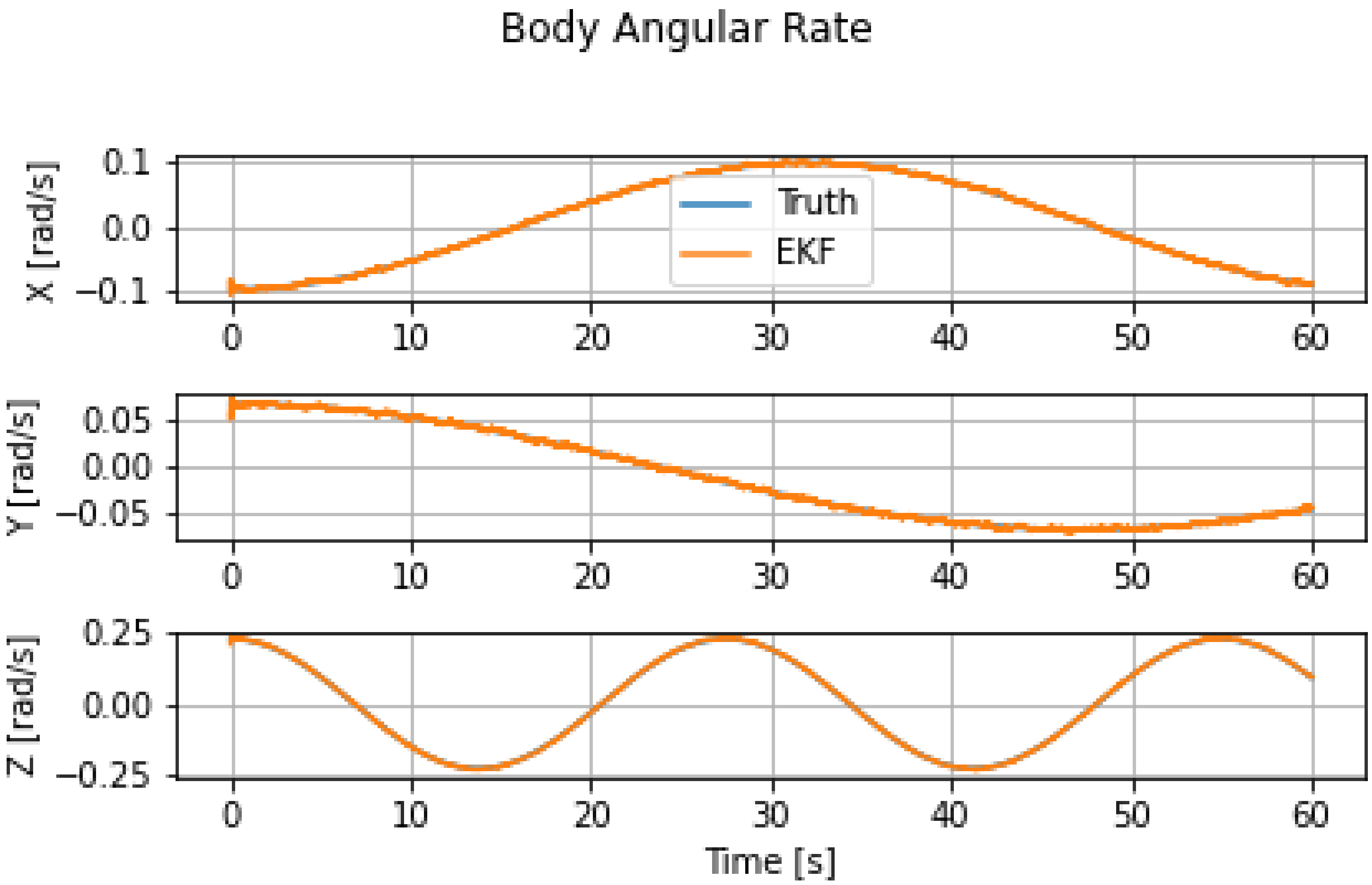

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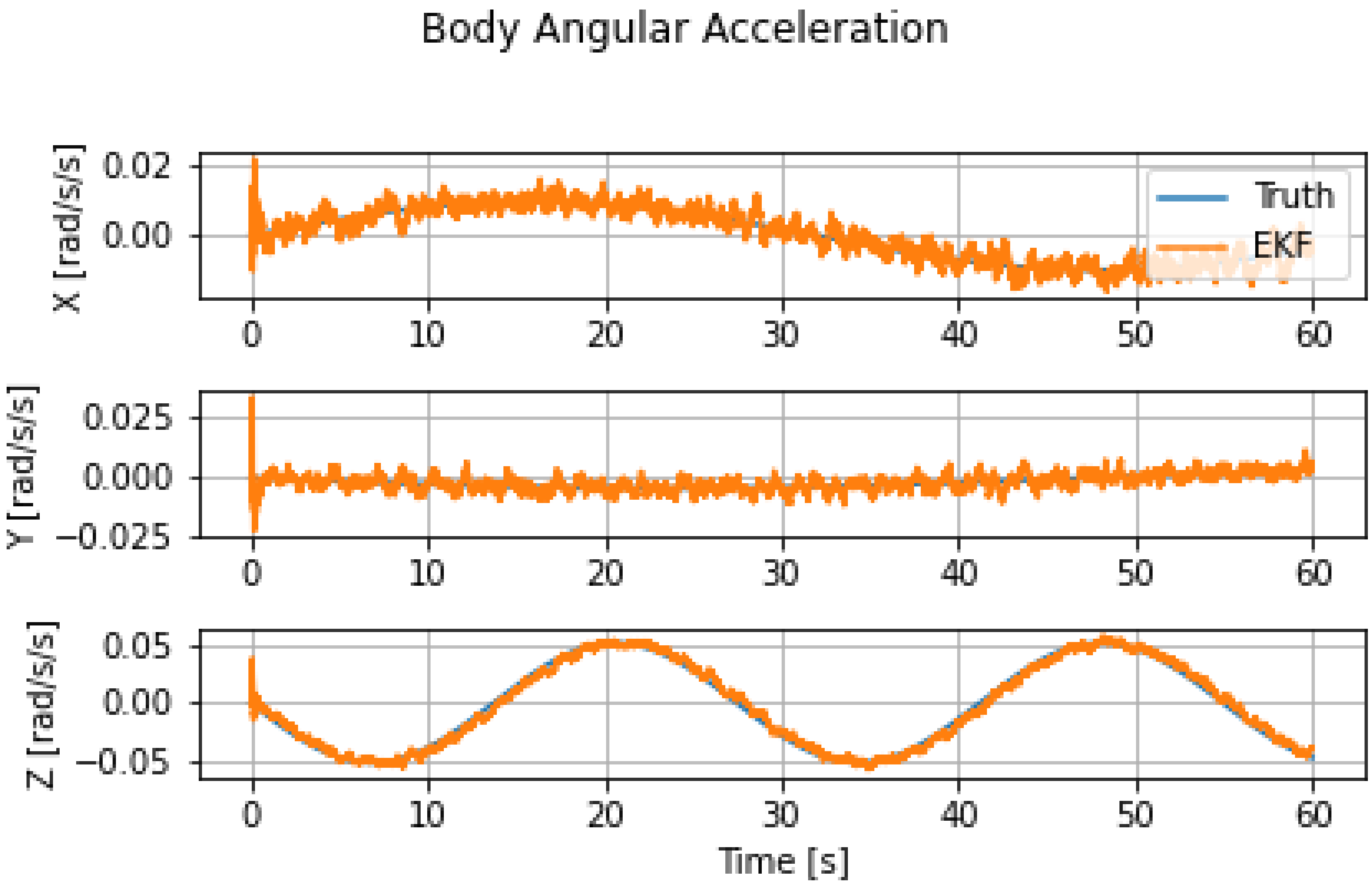

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