FY24 R&TD Innovative Spontaneous Concepts (ISC)

Approach for Low-Cost High-Performance Gyro System Enabled by Bias Self-Calibration

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Strategic Focus Area: Innovative Spontaneous Concepts

Objectives: The proposal aims to develop a method for integrating low-cost gyroscopes that can self-calibrate their biases independently, without relying on additional sensors, while ensuring continuous measurement capability. Additionally, the proposal seeks to explore similar techniques for accelerometers to create a compact, fault-tolerant, cost-effective, and high-performance Inertial Measurement Unit (IMU) system.

Background: Gyro noise and bias often limit performance in navigation systems, with high-performance gyroscopes typically exhibiting undesirable Size, Weight, and Power (SWaP) characteristics. MEMS Coriolis Vibratory Gyroscopes (CVGs), known for their compact size, low cost, and bias self-calibration through electronic mode switching, present a potential solution. This proposal introduces an innovative approach that simultaneously self-calibrates multiple non-CVG and CVG gyroscopes in a primary/auxiliary configuration. The concept can also be extended to accelerometers and Inertial Measurement Units, which usually include 3-axis gyroscopes and 3-axis accelerometers. This bias self-calibration process does not disrupt the normal operation of the gyroscopes or accelerometers and can be conducted continuously. By simultaneously estimating and correcting correlated biases and optimally filtering gyro and accelerometer noise, this approach significantly enhances the performance of the “IMU System”, which comprises numerous small IMUs, surpassing the performance of individual IMUs. This novel approach is crucial for non-aided navigation solutions, such as Venus Balloon missions, Europa Ocean exploration, and lunar and Martian lava tube exploration. It also offers robust performance reliability, as the “IMU System” is inherently fault tolerant.

Approach and Results: The distinctive feature of continuous bias self-calibration for inertial sensors is its ability to estimate and correct sensor biases independently of the underlying host body motion, while maintaining uninterrupted normal operation for providing inertial motion measurements. This study utilizes two types of bias self-calibration approaches, both employing a set of “Primary” sensor units, and a set of “Auxiliary” sensor units mounted on a moving host body. For the gyro-only scenario, we use one or more CVGs (Coriolis Vibratory Gyro) as auxiliary gyros, leveraging the CVG’s electronic “mode-switching” capability to gain observability of the biases for all gyros (CVG or otherwise) in the system. In the case of IMU (which typically includes 3-axis gyros and 3-axis accelerometers), we propose using periodic mechanical switching (orientation changes) of the auxiliary IMUs to similarly achieve bias observabilities for all IMUs in the system. With the bias observability obtained through either switching method, we design Kalman filters to continuously estimate the biases of all sensors. The bias-corrected measurements from the sensors are then optimally combined to produce a virtual sensor measurement with significantly improved measurement noise performance, as well as much reduced biases regardless of any corrections among the biases. This combined performance improvement in both bias and noise results in a virtual sensor capable of continuous operation without bandwidth reduction, offering superior performance compared to individual sensors and inherent fault tolerance, as faults in part of the sensor system only result in limited performance degradation. Simulation studies have been conducted for both the electronic switching CVG gyro case and the mechanical switching IMU case [1]. For the full IMU case with mechanical switching, considerable effort was invested in developing desktop testbeds and a testbed using a rate table. These testbeds employ several automotive-grade MEMS IMUs on both the primary and auxiliary sides of the system, with mechanical switching achieved through two orthogonal precision rotation stages. Measurements from all the IMUs and stage rotation information are collected, and the bias self-calibration algorithm—including stage motion transient exclusion, IMU bias estimation filters, and host body motion state estimation—is used to process the raw IMU measurement data, generating virtual IMU outputs for body angular velocity and body-specific force measurements continuously.

Significance/Benefits to JPL and NASA: This novel approach is crucial for non-aided navigation solutions or for the case when aiding sensors are only available infrequently. As this approach can potentially improve the virtual sensor performance significantly over the individual sensors, it supports utilizing low-cost sensors that are often low SWaP for high performance navigation applications. Another benefit is the sensor reliability as the sensor system and its algorithm support graceful performance degradation. For JPL, the self-calibratable gyros and IMUs can be useful in many applications, including Mars/Lunar Rovers, Landers, Helicopters, Venus Balloon, Europa Ocean Exploration, Underground Exploration Robots, and small projectiles that requires navigation solutions. The mechanical switching needed can be part of the sensor cluster system, or it can also be part of the host body that may already have components with relative orientation changes over time, such as, for instance, wheels or manipulators on a rover or a gimbaled payload on a spacecraft. For NASA, this innovation, being a generic gyro and IMU sensor technology, can be useful in many applications, including space, aeronautical, and underwater applications.

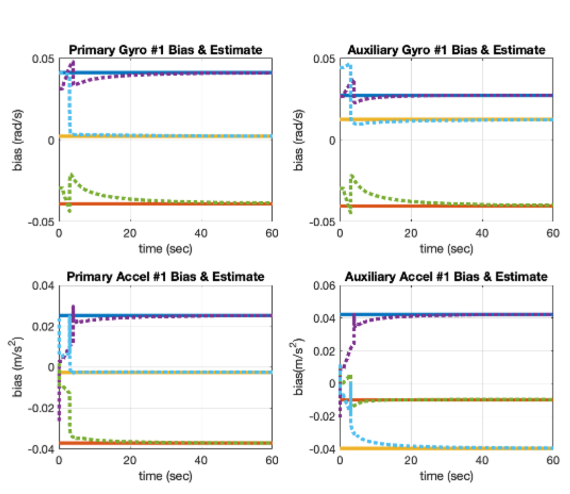

Figure 1. Simulation results for IMU self-calibration - bias estimation.

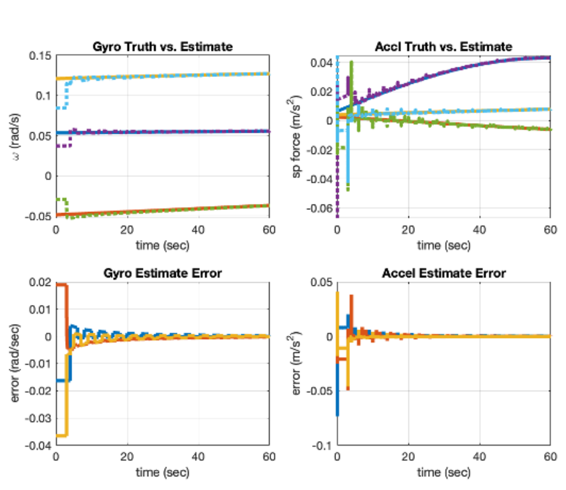

Figure 2. Simulation results for IMU self-calibration – body motion estimation.

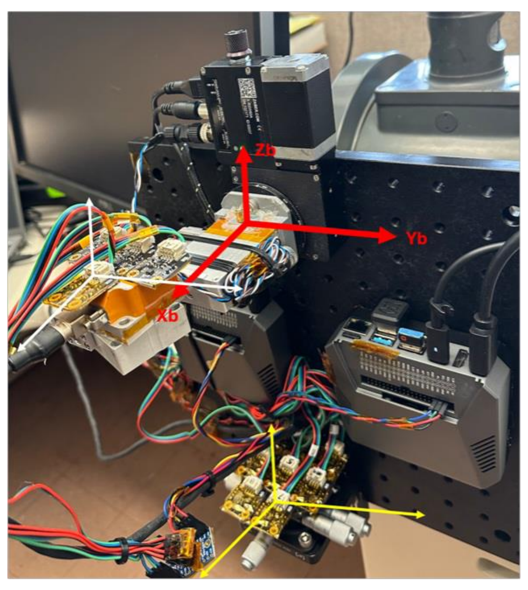

Figure 3. Desktop testbed with primary IMUs and auxiliary IMUs on the stages.

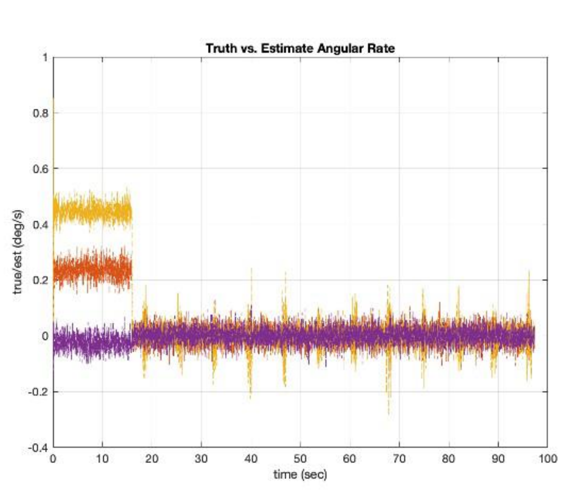

Figure 4. Desktop testbed results of gyro measurements: raw vs. post bias-calibration.

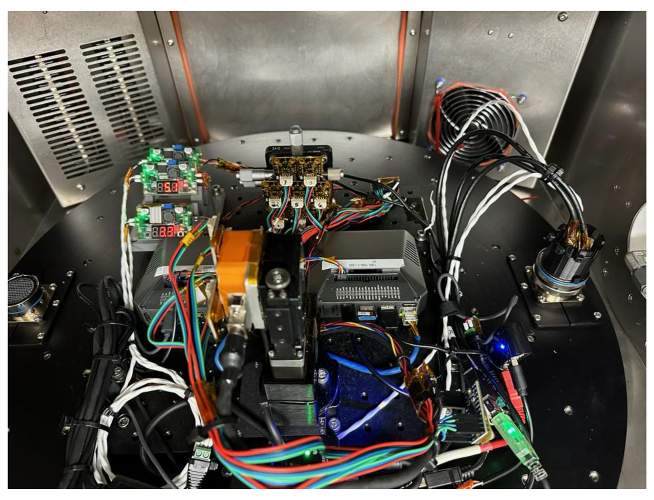

Figure 5. Rate table testbed setup with the same primary and auxiliary IMUs

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RPD-000 Clearance Number: CL#00-0000

Publications:

J. Y. Liu, “A High Performance IMU System via Continuous Bias Self-Calibration with Mechanical Switching,” to be submitted to 12th IEEE Int. Symposium on Inertial Sensors and Systems. 2025.

J. Y. Liu and E. Konefat, “Test Results for a Low Cost and Hight Performance IMU System via Bias Self-Calibration,” to be submitted to 2025 IEEE/ION Position, Location and Navigation Symposium. 2025.

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