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Attitude Estimation Algorithms and Comprehensive Error Analysis in the Generic Multi-sensor Integration Strategy

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Abstract

Modern multi-sensor integrated kinematic position/attitude systems serve a diverse range of industries, including precision agriculture, construction, mobile mapping, and autonomous driving. These industries have diverse needs that must be met by their position/attitude systems, which emphasizes the need for PosAtt systems that are highly customizable and robust. Lower-cost sensors have become increasingly prevalent in modern position/attitude systems, and accurately modeling the systematic errors in these sensors is of paramount importance for high-accuracy applications.

This dissertation focuses on extending and refining the tools for comprehensive error analysis in the Generic Multi-sensor Integration Strategy (GMIS), with a particular focus on statistical analysis in pre-and post-processing environments. This research leverages the strengths of the GMIS to rigorously characterize the sensor performance and systematic errors of tactical grade MEMS IMU sensors, even in situations where a reference solution is unavailable.

The principal research contributions of this dissertation are as follows:

1. A generalized framework for imposing system state equality constraints in a Kalman Filter, which allows for the direct estimation of the constrained observation, predicted system state, and process noise residuals, along with their associated covariance matrices. This framework opens opportunities for comprehensive error analysis in system state constrained Kalman Filters, including: residual analysis, reliability analysis, and Variance Component Estimation (VCE).
2. The formulation of three unique attitude models under the GMIS framework: the Roll-Pitch-Heading (RPH) model, the Direction Cosine Matrix (DCM) model, and the Quaternion model. This research defines each attitude model's corresponding system model, system state constraints, and IMU observation models within the GMIS. This work uniquely uses the process noise residual vector to conduct VCE to directly compare the performance of each different attitude model. Each of the three attitude models used in this research performed similarly over a road test dataset, and the DCM model in particular exhibited resistance to a sudden trajectory variation that was captured by the IMU.
3. The formulation of Multi-IMU (MIMU) array modeling in the GMIS, allowing for the separate estimation of IMU systematic errors and stochastic properties for every sensor in the MIMU array. This work allows for a detailed, time-varying analysis of constituent IMU sensors' stochastic properties via VCE alongside rigorous Fault Detection and Exclusion (FDE) for each sensor in a MIMU array. None of this is possible under other data fusion methods for MIMU arrays. The *a posteriori* position/attitude standard deviations were compared between a MIMU and Single-IMU (SIMU) solution for the same road test dataset, and the MIMU solution provided an average accuracy improvement of ca. 14-16% in the estimated position, 30% in the estimated roll and pitch, and 40% in the estimated heading.

4. A generalized framework for the pre-analysis of online sensor calibration procedures under the GMIS. The proposed framework uses a candidate trajectory with a defined sensor configuration to estimate the following quantities: minimum significant values for individual systematic error parameters; minimum detectable values for observation biases from each sensor; and observability analysis for each sensor systematic error being modeled in the Kalman Filter. This framework allows for the establishment of best field procedures and sensor configurations without requiring the construction and testing of physical systems. This framework was used to evaluate three different case studies to determine the observability of IMU systematic error states, alongside their minimum estimable values and minimum detectable errors under different calibration maneuvers. Across all three case studies, the accelerometer biases generally had minimum estimable values within 1 cm/s and the gyroscope biases generally had minimum estimable values within 3.5 '/s. The scale factor errors of accelerometers and /gyroscopes and the lever arm vectors with respect to the reference-IMU had their observability much more dependent upon the specific calibration maneuver being used.

This research specifically targets two environments:

1. A system design environment, where it is valuable to determine optimal sensor configurations to maximize the reliability of any estimated solutions.
2. A post-processing environment, where comprehensively characterizing system performance is useful in diagnosing problems in the sensor platform when navigating particularly challenging environments.

   Both environments benefit greatly from the detailed analysis that this research makes possible.

This research takes great strides towards establishing the GMIS as a fully matured strategy for sensor integration that has much more modeling flexibility than traditional approaches. The only remaining challenge is addressing the increased computational load of the GMIS relative to the TMIS, and this is a high priority for future work.

The following further research would help to expand upon the contributions made in this dissertation:

1. Building support for other filter types, such as the Unscented Kalman Filter (UKF) under the GMIS, as well as optimal smoothing techniques.
2. Conducting a formal evaluation of the impact of using multiple IMU sensors, to investigate the relative benefits of increasing the number of sensors, changing the array configuration (i.e. axis direction and sensor placement), and changing the quality of sensors in the sensor array.
3. Expanding the capabilities of the PosAtt Engine that was developed for this research to include all GNSS constellations, and allow for more broad sensor configurations (e.g. multiple GNSS receivers, etc.).

The contributions of this dissertation lay a strong foundation for future research in adaptive filtering techniques, rigorous fault detection and exclusion, and comprehensive stochastic modeling of the sensors that are being used in a position/attitude system.