RESEARCH STATEMENT

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Research Background

My research goal is to enable accurate and high-integrity navigation for safety-critical applications such as aviation, automated vehicles and urban air mobility (UAM). Integrity measures the trust that can be placed on the correctness of the navigation solution. To ensure high navigation integrity, integrity monitoring schemes need to be implemented. Integrity monitoring includes the fault detection & exclusion (FDE) capability and provides an upper bound on the navigation error with a high confidence level (e.g., 99.99999%), namely a protection level (PL). The PL is computed by considering the effect of undetected faults and wrong exclusion events on the navigation error. Therefore, this bound is more reliable than a 95% error bound or a 3-sigma bound. Figure 1 illustrates the concept of integrity using automated driving as an example.

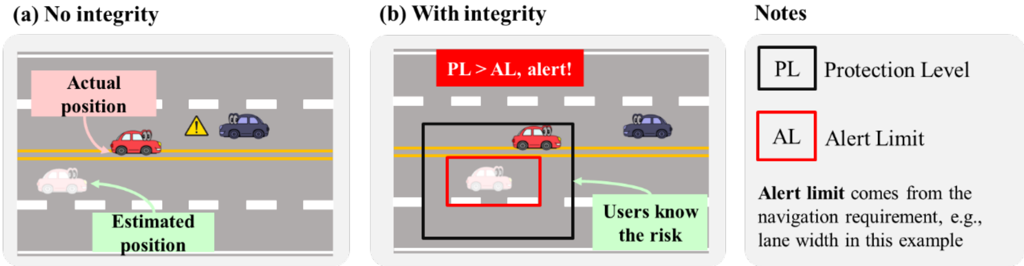

Figure 1: Illustration of the navigation integrity concept. If integrity monitoring is enabled, the users will know the navigation error bound, and they can determine whether the navigation solution is reliable by comparing this error bound with the alert limit, i.e., the maximum acceptable error.

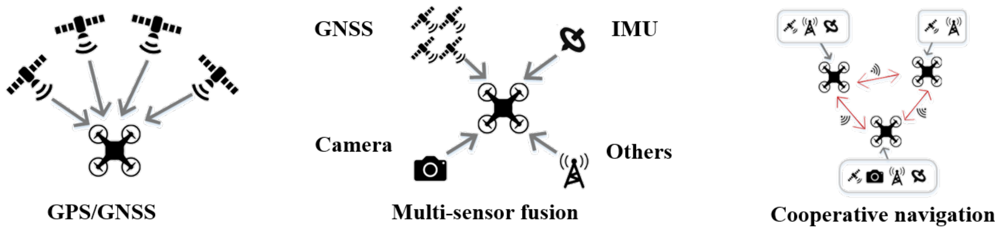

Figure 2: Illustration of different navigation systems.

My research work focuses on designing, implementing, and evaluating integrity monitoring algorithms for different navigation systems, including: (a) GNSS single point positioning, (b) GNSS precise positioning with ambiguity resolution (RTK and PPP-RTK), (c) GNSS/INS tight integration, (d) visual navigation, (e) cooperative navigation, etc. Figure 2 illustrates different types of navigation systems. I will describe my research contributions below.

Integrity Monitoring for GNSS-based Navigation

Nowadays, GNSS has been playing a crucial role in various safety-critical navigation applications. GNSS single point positioning is widely used in the aviation field, and the corresponding state-of-the-art integrity monitoring scheme is advanced receiver autonomous integrity monitoring (ARAIM). However, single point positioning cannot meet the stringent navigation requirements in UAM and automated driving applications. Therefore, it has become a solid demand to investigate integrity monitoring approaches for GNSS precise positioning systems such as RTK and PPP-RTK. Our research on GNSS integrity was supported by Honeywell, Geely, Natural Science Foundation of China (NSFC), CAAC East China Regional Administration, etc. Our contributions on this topic are described as follows.

1. Characterizing Signal-In-Space Range Errors of Beidou from an Integrity Perspective

ARAIM relies a ground monitor to generate and update integrity support message (ISM), which carries information defining signal-in-space range errors (SISREs) and fault statistics. Prior studies mainly focused on estimating the ISM parameters for GPS, Galileo, and GLONASS. Because China's Beidou system is also expected to serve civil aviation, we analyzed the long-term SISRE performance of Beidou by following the ISM data analysis standards. The contributions of our work are (a) conservatively estimating the user range accuracy (URA) and prior fault probabilities of Beidou satellites, and (b) analyzing the effect of fault definitions and thresholds on the estimates of URA and fault probabilities [1, 2].

2. Reducing Computational Load of Multi-Constellation ARAIM with Fault Grouping

The computational issue of ARAIM becomes critical when multiple constellations are involved and fault exclusion is enabled. Therefore, we proposed an implementation of fault hypothesis grouping to lighten the computational load of multi-constellation ARAIM while not degrading the navigation performance [3]. Unlike most of the prior approaches that were limited to dual-constellation scenarios, our implementation can support up to four constellations. In addition, we consider both ARAIM fault detection (FD) and ARAIM fault detection & exclusion (FDE) scenarios to potentially accommodate most ARAIM services. Moreover, the new fault grouping scheme includes a logic to re-allocate the false alert budget and an automatic logic to determine whether a fault grouping operation will degrade the navigation performance. As a consequence, simulation results suggest that our implementation can effectively reduce the ARAIM computational load while benefiting or maintaining the navigation performance.

3. Solution Separation-based Integrity Monitoring for GNSS Precise Positioning with Ambiguity Resolution

Intelligent transportation systems will greatly benefit from accurate and high-integrity localization information. Therefore, it is worth investigating the integrity monitoring approaches for GNSS precise positioning systems such as RTK and PPP-RTK. We proposed a solution separation-based integrity monitoring algorithm for GNSS precise positioning with ambiguity resolution [4]. Benefit from a two-layer hypothesis structure, the proposed integrity monitoring algorithm can accommodate (a) measurement faults, (b) product faults, and (c) incorrect ambiguity fixes, simultaneously. This algorithm includes not only the fault detection function but also the capability to evaluate the protection levels.

In addition, we have implemented various integrity monitoring algorithms for PPP-RTK in the project "Design and Evaluation of Integrity Monitoring Algorithms for GNSS PPP-RTK" from Geely Co Ltd. (ranked among the Fortune Global 500). Experimental results from 50,000-kilometer highway road tests proved the promising performance of our PPP-RTK integrity monitoring algorithm.

Integrity Monitoring for Multi-Sensor Integrated Navigation

Autonomous vehicles and UAM usually navigate themselves by integrating multiple sensors to improve navigation performance, and they require the corresponding integrity monitoring approach to ensure navigation safety. Therefore, we investigated the solution separation-based integrity monitoring approaches for multi-sensor integrated navigation systems. This research was supported by Honeywell and Natural Science Foundation of China, and our contributions are described as follows.

1. Solution Separation-based Kalman Filter Integrity Monitoring for Multi-Sensor Integrated Navigation Against All Sources of Faults

Attracted by the outstanding performance of solution separation-based ARAIM, researchers started to apply solution separation to Kalman filter-based navigation systems. On this basis, we implemented solution separation-based Kalman filter integrity monitoring to protect multi-sensor integrated navigation against all sources of faults [5]. As compared to existing approaches, our implementation has two advantages. First, we consider the faults in state initialization and state prediction phases (e.g., IMU failures in GNSS/INS tight integration) aside from those at the measurement-update stage. Second, our implementation can accommodate the cases where the all-in-view filter is not optimal in a least squares sense (e.g., the filter uses a self-tuning gain matrix).

The solution separation-based Kalman filter integrity monitoring algorithm was implemented to various navigation systems, such as GNSS/INS tight integration and GNSS/INS/vision integration [5]. Simulation results prove the effectiveness of the integrity monitoring algorithm and also suggest that in a GNSS/INS integrated navigation system, IMU failures can severely degrade navigation integrity. Given that UAM and automated cars will be equipped with low-cost IMUs, the probability of IMU faults must be considered. Therefore, we proposed a new approach to enhance navigation integrity for UAM and automated cars by integrating multiple IMUs with GNSS in a centralized Kalman filter [6].

2. Integrity Monitoring for Feature-based Visual Navigation

Camera- or laser- based visual navigation can greatly augment navigation performance in GNSS challenging environments. However, visual navigation systems are vulnerable to the outliers caused by incorrect data association, moving objects, etc. To ensure the integrity of visual navigation, we proposed a solution separation-based integrity monitoring algorithm for feature-based stereo visual navigation systems [7]. In this algorithm, the navigation states are estimated using the feature correspondences and an iterative least-squares estimator. In addition, we proposed a feature grouping method to reduce the computational load and analyzed its effect on the integrity performance [7].

Similar to GNSS, visual navigation also relies on the integrity support message to achieve integrity monitoring. Therefore, we analyzed the behaviors of the feature matching errors and accordingly inserted several fault detectors to the visual navigation front end [8]. Benefit from these detectors, the statistical characteristics of the feature matching errors become less sensitive to the operational scenarios. Therefore, we can preliminary establish an error model of visual navigation for integrity monitoring tasks.

Integrity Monitoring for Multi-Agent Cooperative Navigation

As shown in Figure 2, cooperative navigation exploits the navigation information in multiple agents and the inter-agent relative measurements to achieve navigation performance improvement. Since 2021, I have been involving in the research on cooperative navigation in our lab as a student leader. Our research goal is to realize efficient and reliable cooperative navigation. Our research efforts are summarized as follows.

1. Event-Triggered Fusion Topology Adaption for Efficient Multi-Agent Cooperative Navigation

Fusion topology of the cooperative navigation system defines how the navigation information is exploited. For example, a fully-centralized fusion topology fuses all the information with one estimator, which can produce the optimal navigation performance at a cost of heavy computational load and communication cost. Given specific navigation performance requirements and resource constraints, the fully-centralized topology is not always the best choice. Therefore, we proposed the idea of event-triggered fusion topology adaption to realize efficient cooperative navigation in dynamic operation scenarios. To achieve this, we first developed a method to estimate the achievable performance of different fusion topologies [9]. On this basis, we then proposed an efficient approach to optimize the fusion topology [10, 11].

2. Integrity Monitoring of Multi-UAV Relative Navigation for Collision Avoidance

Accurate and reliable relative navigation is a prerequisite to safely maintain multi-UAV close formation and to achieve UAV-UAV collision avoidance. We implemented a solution separation-based integrity monitoring approach to GNSS-based relative navigation systems to enhance navigation integrity [12]. This approach estimates a safe distance between UAVs from the perspective of navigation uncertainty. In addition, given that the UAVs may fly in urban areas, this work considers the spatial correlation among the satellite faults that are caused by multipath/NLOS effects.

3. Fault Detection and Exclusion for Multi-UAV Cooperative Navigation

To achieve efficient and reliable cooperative navigation, we investigated different fusion topologies with least-squares estimators and designed the corresponding fault detection & exclusion (FDE) algorithm. This work considers not only the measurement faults occurring within one UAV or one satellite but also the faults in the UAV-UAV relative measurements. Simulations based on the Spirent Sim3D software proved the effectiveness of the FDE algorithm.

Bayesian Receiver Autonomous Integrity Monitoring

The baseline ARAIM algorithm evaluates the integrity risk/protection level using only prior information, including the measurement model, the error model, and the prior fault probabilities. To explore the benefits from user measurements, prior studies introduced the concept of Bayesian receiver autonomous integrity monitoring (Bayesian RAIM), which evaluates the integrity risk in a posterior probability sense. However, prior approaches cannot obviously outperform the ARAIM method in terms of integrity risk.

Therefore, we proposed a new Bayesian RAIM approach to offer a tight upper bound on the posterior integrity risk [13]. Our contributions are deriving the posterior probability density of the true state and developing a tight upper bound on the posterior integrity risk. The major difference between our approach and the existing ones lies in that our approach searches the worst-case fault distributions to directly maximize the posterior integrity risk instead of the posterior probabilities of each hypothesis. Simulation results suggest that the new Bayesian RAIM approach offers significantly lower integrity than the ARAIM method.

Hands-on Experience

Over the past years, I have gained some hands-on experience with UAV, ground robots and navigation sensors. When I was an undergraduate, I participated in several projects about quadrotors and toy cars. For example, I developed a prototype of ARAIM with a Octocopter (DJI 1000) and deployed lane-tracking algorithms to a toy car (Donkey car). Recently, I have established a prototype multi-sensor integrated navigation platform. As shown in Figure 3, this platform includes a GNSS receiver, two IMU sensors (a Xsens Mti-1 and a Fiber-optic IMU), and two global-shutter cameras. Hardward time synchronization is achieved with GNSS pulse per second (PPS) signals and an MCU (STM32). The synchronization error is typically below 1 millisecond. This platform currently supports two functions: (a) data collection, and (b) ground truth generation. In the future, I will implement multi-sensor integrated navigation algorithms and the corresponding integrity monitoring methods to this platform.

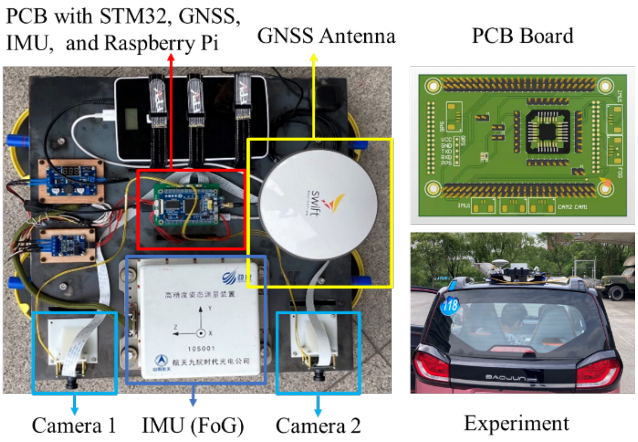

Figure 3: Prototype of multi-sensor integrated navigation with GNSS, IMUs, and global-shutter cameras.

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