https://doi.org/10.31256/Mx7Zx4J In: UK-RAS22 5th UK Robotics and Autonomous Systems Conference, Aberystwyth, 26 August 2022.

Failure Mode Analysis (FMA) for Visual-Based Navigation for UAVs in Urban Environment

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***Abstract*— Visual-based navigation systems for Unmanned Aerial vehicles (UAVs) have become an interesting research area focused on improving robustness and accuracy in the urban environment. However, a lack of integrity can damage UAVs, limiting their potential usage in civil applications. For safety reasons, integrity performance requirements must be met. In literature, such systems require significant attention for their ability to perform fault analysis, referred to as failure mode. In this paper, we have conducted a failure mode analysis in urban environments for UAVs to identify threats and faults presented in existing Visual-inertial Navigation Systems. In addition, we propose a federated-filter-based fault detection and execution system to improve navigation performance under faulted conditions.**

Keywords—visual-based navigation, integrity, failure mode analysis, urban environment, GNSS

I. INTRODUCTION

Recently, the use of unmanned aerial vehicles (UAVs) has increased in various applications, outdoor and indoor. With computer vision and artificial intelligence advancements, vision-based navigation systems are widely adopted by existing researchers. However, there are still challenges that need to be overcome by researchers, especially while UAVs navigate in urban environments such as dense buildings, GNSS signal denial, signal blockage, multipath effect, and limited satellite visibility [1]. Visual-Inertial Navigation Systems (VINS) provide complementary techniques to reduce drift error from IMU predictions alone. However, VINS still suffer from accumulated errors that can be reduced by integrating GNSS data in the urban environment and thus still do not satisfy system integrity requirements. To satisfy integrity requirements [1] which are Integrity Risk, Alert Limit (AL), and Time to Alert (TIA) in challenging environments, integrity monitoring for multi-sensor data fusion with integrity monitoring systems are essential. Integrity analysis requires a general review of threats and faults, which can be classified as

- Failure modes and effects analysis (FMEA)
- Fault tree analysis (FTA)

[9] has recently reviewed the tightly coupled GNSS/INS fusion technique, which has reduced mean positioning error from 8.31 to 3.21 meters but is still not enough for autonomous driving. Hence, in this scenario, the visual-inertial navigation system can be suitable for implementing drones [9] and self-driving cars [10].

The study presented here investigates the failure modes in the VINS system when each component exits the protection level (PL) [1] in the urban scenario and proposes a solution technique to overcome the errors to increase system integrity.

In the proposed system, a Federated Filter has been used to detect and exclude step errors for GNSS and IMU, along with positioning errors caused by high-level feature domain biases. The decentralised configuration of the federated filter makes the system more robust with fault-tolerant capability. Thus, we have used NR (No Reset) mode technique [10] to improve failure detection and correlation. In addition, we have carried out a chi-square test with the faulted condition to enhance fault tolerance. The experiment results show high efficiency and effectiveness in various faulted conditions.

II. PROPOSED CONCEPT

To improve the performance of vision-based navigation systems for UAVs concerning integrity, it is necessary to have good knowledge of all potential threats and faults. Commonly integrity monitoring in visual navigation faces several challenges and requires new solutions. Figure 1 illustrates familiar error sources in visual positioning that need to be considered to ensure the system's integrity [3]. Integrating multiple sensors can enhance performance and reduce the impact of failure in the system.

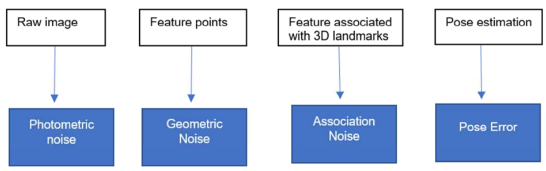

Fig. 1. Error state propagation of visual positioning

To analyse the integrity of the system, the threats in the system should be identified. For an integrated GNSS/VINS system, failure modes [2] can be categorised as-

- GNSS sensor failure modes
- VINS reference system failure modes
  - ✓ VINS operational hardware failure modes
  - ✓ VINS operational software failure modes
- Integrated GNSS/VINS system failure modes

FMEA involves identifying all the failure modes with their causes, characteristics, and probability of occurrence in the above system. FMEA analysis for GNSS/VINS system provides essential failure modes such as convergence failure, quantifying errors, motion blur, and overexposure. One of the standard methods to analyse faults is evaluating metrics such as the probability of failure, which can be represented by fault tree analysis (FTA). It helps to break down failure events to determine the probability of loss of integrity using a fault tree diagram. We have adopted muti-fault conditions to allocate risks using FTA for the integrated system. Besides, we have categorised the faulted conditions according to the work environment, sensors type, error type, error effects and user-end faults. These allow us to evaluate maximum faults in VINS systems. For instance, pose errors mentioned in Figure 1 can be the effect of feature extraction domain, large bias measurements, and error correlation. So, performing integrity analysis for the mentioned system requires the Fault Detection and Execution (FDE) method [4]. For visual positioning, fault can occur in different domains resulting in failures such as feature extraction steps, outlier and positioning errors, linearised biases, and imperfect calibration.

TABLE I. EXISTING INTEGRITY MONITORING SOLUTION

Reference	System Integration	Impact	Experiments to Ensure the Integrity	Error Type
J. Al Hage et al. [5]	Stereo camera + GNSS	Track lane markers using a camera and monitor estimated position residuals to remove faulty measurements	Multi-sensor data fusion fault detection and exclusion technique	Positioning error measurements
E. Shytermeja et al. [6]	Fish-eye camera + GNSS+ IMU	The camera is used to check the GNSS signal in the urban line	Receiver autonomous integrity monitoring technique and Isotropy-based protection level	Multipath error and incongruent GNSS pseudo-range measurement
Zhu et al. [7]	Camera +GNSS	Covariance estimation and covariance intersection technique for estimation	Not considered	Not Considered
Bhamidipati et al. [8]	Fish-eye camera+ GNSS	Errors in measurement from both sensors have calculated PL for position solution.	Graph-base monitoring algorithm	Data association error

Table 1: shows some existing systems with the integrations of different sensors implemented with integrity analysis and associated errors. However, the above techniques are limited to specific scenarios such as multipath, error correlation, ramp error, and bias. A few research studies have been conducted on integrity monitoring based on the visual-inertial navigation system, but neither proposes a step-by-step FMEA systemic approach. Additionally, the existing systems mentioned above have not discussed sensor failures in reference systems. Therefore, adopting the FMEA approach allows the systems to identify faults in reference systems with sensors and consider correlation and propagation of error sources [3].

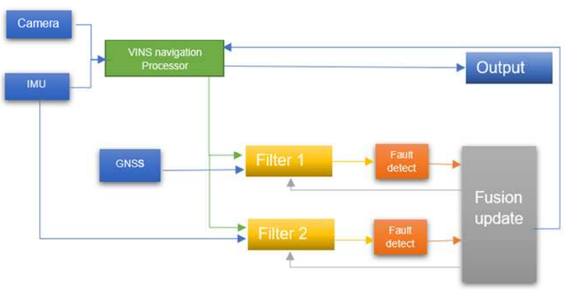

Fig. 2. System architecture

To overcome the challenges UAV suffers in the urban environment, a hybrid federated-filter-based multi-sensor fusion technique has been designed, shown in Figure 2, in multiple-faulted conditions to detect and exclude errors. Along with two local filters and one master filter, GNSS and IMU are the adding sensors to bound VINS error. The FDE scheme has been designed based on the measurements after the chi-square test.

III. RESEARCH LIMITATIONS AND FUTURE WORK

The proposed system is in a progressive condition where we plan to add more sensors to enhance the performance of the visual navigation system and ensure a more precise position. In future, we will test our system with a challenging urban UAV driving scenario that includes high-rising buildings, outdoor open sky, and a high dynamic environment on Cranfield University premises.

IV. CONCLUSION

This paper proposes a federated-filter-based GNSS/VINS system to detect and execute multiple faults in VINS, GNSS and IMU. We have conducted Failure Mode Analysis and Fault Tree Analysis to ensure the high integrity of the system. We have created a simulated environment in MATLAB/Simulink for the synthetic dataset and used Open-VINS open-source environment to carry out the VINS system experiment. This study has shown a practical pathway to conduct further research on analysing individual sensor faults to detect them to increase the system's safety.

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