UDC 004.942 DOI: 10.18372/2073-4751.74.17878

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ARCHITECTURE OF INTEGRATED NAVIGATION SYSTEMS WITH ENHANCED COORDINATE ACCURACY AND FAULT DETECTION

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Introduction

The rapid advancements in the field of uncrewed aerial vehicles (UAVs) have necessitated the development of more accurate and reliable navigation systems. Uncrewed Aerial Vehicles (UAVs) have emerged as pivotal tools for precision agriculture, infrastructure, and construction. Drones equipped with high-precision navigation systems facilitate detailed site inspections, risk assessments, and progress monitoring, eliminating the need for manual, time-consuming surveys. Additionally, in the emergency response sector, drones with accurate navigation can swiftly locate disaster-stricken areas or lost individuals, optimizing rescue operations or resolving security missions.

The efficacy of UAVs is largely contingent upon their navigation accuracy, ensuring they can operate autonomously over long distances with pinpoint precision. Integration of Global Navigation Satellite Systems (GNSS) with Inertial Navigation Systems (INS) has been identified as a promising solution to achieve this high level of navigational accuracy. However, while the potential benefits of GNSS/INS integration are vast, there are inherent challenges. A primary concern is the maintenance of navigation precision even after prolonged operation. Additionally, the computational demands of the integrated navigation algorithm should be minimal to ensure the UAV's onboard processing systems are manageable.

Previous research in this domain has primarily focused on either GNSS or INS in isolation. While both systems have their merits, their limitations can be mitigated when used both. The GNSS, for instance, offers global coverage but can be susceptible to signal blockages or interference. On the other hand, INS operates independently of external signals, providing continuous navigation capability, but its accuracy can degrade over time due to inherent sensor errors.

This article delves into the centralized Kalman filter method to fuse the GPS and INS systems under a loose coupling premise [1]. The objective is to harness the strengths of both systems while compensating for their weaknesses. Furthermore, the feedback emendation method is introduced to counteract the potential decline in navigation accuracy over extended periods. The subsequent sections will comprehensively explore the proposed integration method, its computational advantages, and its potential to revolutionize precision agriculture through enhanced UAV navigation.

INS/SNS integration benefits advantages from both systems. Their combination gives a continuous, high-bandwidth, complete navigation solution with high long- and short-term accuracy. SNS measurement creates borders for inertial solution drift, and INS smooths the INS/SNS solution with possible signal outages. INS/SNS integration is suitable for many applications in practice with a low-cost budget. For example, it can navigate ships, airlines, aircraft, helicopters, UAVs, small boats, vehicles, or personal navigation.

Moreover, the integration of other navigation sources, such as Geostationary Navigation and GSM Positioning System at land surfaces [2], Long Baseline Location (LBL), or Ultra Short Baseline Location (USBL) at sea, into the system further enhances its reliability and resilience [3].

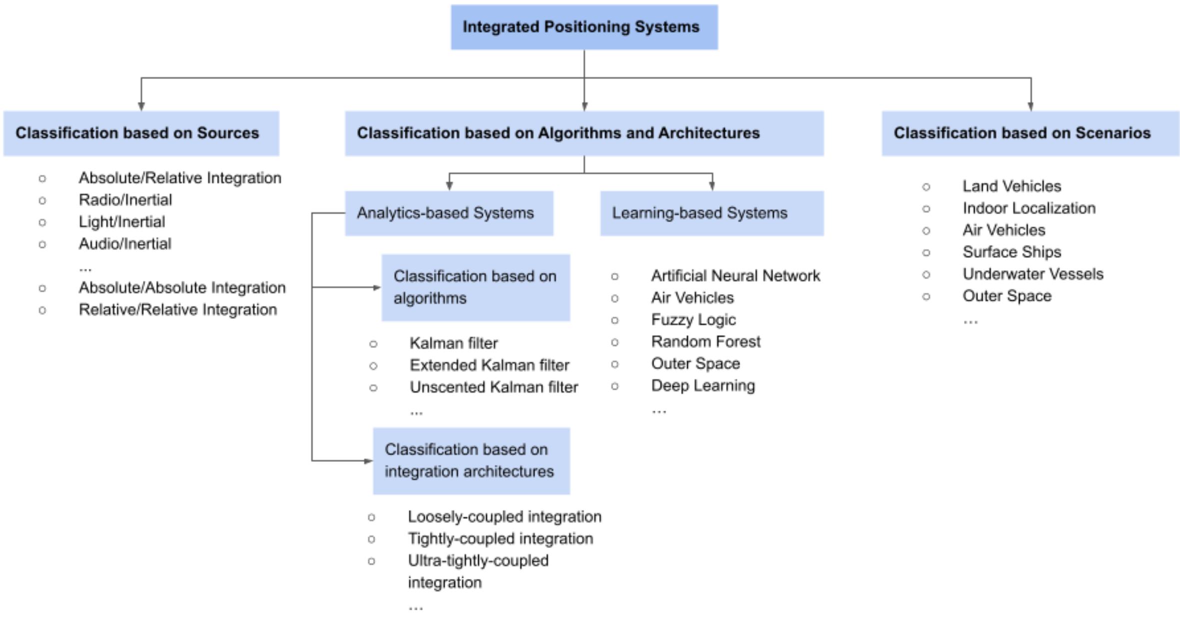

Fig. 1. Overall classification of integrated positioning (navigation) systems

Another approach is using simultaneous localization and mapping (SLAM) and data fusion techniques tailored explicitly for object detection and environmental scene perception in UAVs [4]. Preliminary tests of this multi-source navigation system have shown promising results, with the capability to isolate fault sources in seconds and maintain positioning accuracy effectively. Integrating such advanced navigation methodologies will ensure their safe and efficient operation as UAVs expand.

Researchers of integrated positioning and navigation systems use a variety of approaches to classify systems. Figure 1 shows a general classification that covers the main existing approaches to system development and sheds light on the complex interaction of different navigation technologies [5]. As illustrated in their work, this classification encompasses a range of systems from standalone GNSS to multi-sensor integrated systems, emphasizing the role of sensors like IMUs, LiDAR, and cameras in conjunction with GNSS [6]. This classification is a foundational reference for our study, highlighting the importance and complexity of integrating diverse navigation tools for optimal performance.

Problem statement

Integrating multiple sources to achieve precise and reliable navigation has become paramount in the rapidly evolving landscape of navigation and positioning systems, especially for uncrewed aerial vehicle (UAV) applications. The fusion of the Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS) has been widely recognized as a promising approach to enhance the accuracy and reliability of navigation solutions. However, the integration process is challenging [7].

The primary concern arises from the potential degradation in the precision of navigation parameters over extended periods of operation. This is further exacerbated by the complexities associated with the integration algorithms, which often demand significant computational resources. The challenge is to develop an integrated navigation algorithm that is both efficient and reliable, ensuring that the precision of navigation parameters does not diminish over time, even after prolonged operation.

Another significant challenge is the threat of spoofing signals. Spoofing involves broadcasting counterfeit signals, often more robust than genuine ones, intending to mislead GPS receivers [8].

Such malicious activities can severely compromise the integrity of navigation systems, leading to potentially catastrophic outcomes, especially in critical applications like UAVs used in agriculture, surveillance, and delivery. The need for effective countermeasures, such as blocking techniques, to mitigate the risks associated with spoofing signals is more pressing than ever [9]. These countermeasures should be capable of identifying and nullifying unwanted signals, ensuring that only genuine GPS signals are processed.

Furthermore, the existing multi-source fusion navigation systems, which often rely on methods like the Kalman filter or the least square method, have limitations [10]. At the system and subsystem levels, the navigation source is the minimum fault unit that can be detected. This necessitates the establishment of a robust navigation source fault detection and verification model. Moreover, there's a need to reconstruct the fusion model of the system based on the detection results to ensure optimal performance.

Researchers have been working diligently to mitigate the urban canyon effect. Some of the notable advancements include:

- *Improved Signal Processing* by refining the algorithms that process satellite signals, the accuracy of position determination has been enhanced.
- *Integration with Other Systems* combining satellite navigation with other systems like Wi-Fi and inertial sensors has shown promise in improving accuracy in challenging environments.
- *Advanced Receiver Design* that is designed to be more resilient to signal interruptions, ensuring consistent performance even in urban canyons.

Following these challenges, this research aims to delve deeper into the intricacies of multi-source fusion navigation systems, exploring innovative solutions to enhance the precision and reliability of UAV navigation. The goal is to develop adaptive methods that address the challenges above and pave the way for the next generation of resilient and efficient navigation systems for UAVs.

The basic configuration in Fig. 2 shows an integration algorithm that compares the inertial navigation solution with the outputs of GNSS user equipment and estimates correction to the inertial position, velocity, and attitude. The correction stage is usually processed by a Kalman filter, which forms an inertial navigation solution. This architecture depends on GNSS signal availability because the solution is continuously produced [11]. Schemes combine INS and SNS to resolve weakly bound, tightly bound, and deeply integrated circuits. They are divided by type of feedback, open and closed systems.

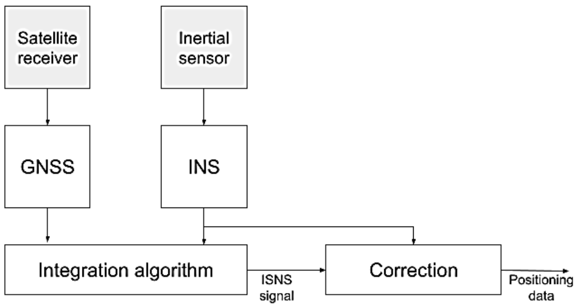

Fig. 2. Universal INS/GNSS integration system architecture.

In modern navigation methodologies, we utilize redundant information as a backup mechanism instead of leveraging it to enhance the system's overall performance and precision. While providing a safety net in case primary data sources fail, this approach misses out on the potential benefits that could be derived from the redundant data. By integrating and processing this surplus information, we can refine the accuracy and reliability of the navigation system. This would make the system more robust against errors and inaccuracies and optimize the use of available data, ensuring that no valuable information goes to waste [6].

Problem solution

In the realm of integrated Inertial Satellite Navigation Systems (ISNS), the Kalman filter has emerged as a pivotal tool for predicting and estimating the state of a system. The Kalman filter uses a series of mathematical equations to evaluate unknown variables based on probability theory. However, while the filter is adept at handling uncertainties and inaccuracies in measurements, its ability to detect soft faults remains a significant.

Unlike hard faults, which are abrupt and easily detectable, soft faults manifest gradually and can be elusive. These faults can arise from various sources, such as sensor drifts, minor system degradations, or external interferences [12]. In its standard form, the Kalman filter primarily focuses on minimizing the error between the predicted and actual measurements. This error often termed the “residual”, is a crucial parameter for fault detection. When the residual exceeds a certain threshold, a fault is typically flagged.

However, the challenge arises when the residual remains within acceptable bounds, but a soft fault gradually affects the system. The traditional Kalman filter might not recognize this subtle degradation, leading to compromised system performance over time [13]. The inability to detect and address these soft faults can reduce navigation accuracy, posing risks, especially in critical applications like aviation or autonomous driving.

To reduce this limitation in GNSS with Kalman filter can be proposed following solutions:

Adaptive Thresholding. An adaptive approach can be employed instead of a static threshold for residuals. This would involve continuously updating based on the system's recent performance, making it more responsive to soft faults.

Augmented State Estimation. Adding additional states to the filter that specifically model potential fault scenarios makes the filter more sensitive to deviations caused by soft faults.

Data Fusion. Integrating data from multiple sensors or sources can provide a more holistic view of the system's state. By comparing the outputs of different sources, inconsistencies arising from soft faults can be more easily identified.

AI Integration. Modern machine learning algorithms can be trained to recognize patterns associated with soft faults or spoofing attacks. The system can benefit from predictive modelling and pattern recognition by integrating these algorithms with the Kalman filter.

Blocking to mitigate spoofing signals is a crucial aspect of GPS equipment operation, primarily when used by critical infrastructure. Spoofing signals can mislead GPS receivers by broadcasting counterfeit signals, which can be stronger than authentic ones. To counteract this, blocking techniques are employed. These techniques involve using specialized hardware or software that can identify and block unwanted signals, ensuring that only genuine GPS signals are processed by implementing effective blocking mechanisms, the integrity and reliability of GPS data can be maintained, and safeguarding critical infrastructure from potential threats posed by spoofing attacks.

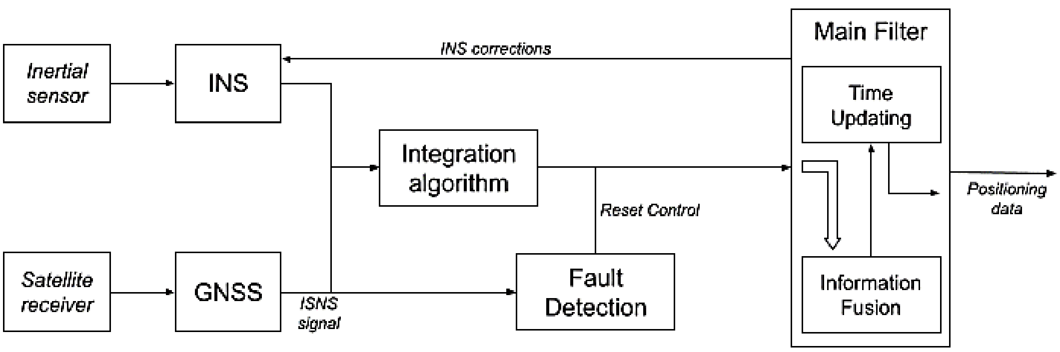

Fig. 3. Architecture of integrated positioning system based on ISNS with Kalman filtering and fault detection

In the context of our research, we utilize a multi-source fusion navigation system, which primarily employs the KF or the least square method to achieve the fusion solution [14].

The smallest detectable fault unit is identified as the navigation source at both the system and subsystem levels. This necessitates the creation of a model for detecting and verifying navigation source faults. Subsequently, based on the outcomes of this detection, the system's fusion model is restructured. For this study, we have proposed an architecture of ISNS with KF integrated technique to the multi-source GNSS fusion navigation system with a blocking algorithm for mitigating fault and spoofing signals Figure 3.

Conclusions

Satellite navigation has historically faced many obstacles, especially in challenging environments like urban settings. The aspiration for the future is unambiguous: satellite navigation systems that consistently deliver unparalleled performance, regardless of the surroundings.

The proposed solution presented herein introduces a potential architecture for an integrated inertial and satellite navigation system scheme. This architecture of ISNS is enhanced with corrective circuits and simultaneous filtration of high-frequency measurement errors.

To improve the positioning system's fault tolerance and precision, a robust multi-source integrated navigation method for UAVs based on real-time redundant information evaluation was proposed. A pivotal component of this proposal is the introduction of an algorithm for the optimal estimation of INS error, grounded in the principles of the Kalman filter. The proposed system architecture, both for the estimated process and the measurements, is meticulously tailored to align with the requirements of the KF.

The integrated approach, combining inertial and satellite navigation systems with corrective circuits and optimal filtration, promises a significant enhancement in system performance. This includes improved accuracy in determining flight trajectories, reduced peaks in navigation signals, and a marked reduction in ISNS error.

Remains an untapped reservoir of potential in the form of redundant information. Historically viewed as mere backup data, this information can be a game-changer. By effectively harnessing this data, it can be transformed from a passive element to an active contributor, significantly augmenting navigation precision. Future research could focus on creating innovative algorithms and models that effectively utilize this redundant data.

Moreover, while the proposed solution offers a promising architecture for enhanced accuracy and reliability, there are avenues for further refinement. These include incorporating a more detailed sensor error model, refining the matrix of the Kalman filter, and addressing the frequency disparities inherent in both systems or integrating with alternative satellite constellations.

Recent advances in satellite technology are opening with SpaceX a promising path for improving navigation systems. They have some 1,700 satellites in Earth's low orbit, meaning they circle the planet with about 1,200 km from the Earth's surface, and ultimately plan to launch more than 40,000 satellites. Their satellite signals could be used similarly to traditional GPS to accurately determine a location on Earth. Their signals could be used similarly to classic GPS to determine the object's location accurately. This integration could revolutionize the industry by offering a more reliable and accurate navigation solution, especially when combined with the architecture proposed in this research.

The proposed architectural approach for integrating inertial and satellite navigation systems, augmented with corrective circuits and filtration, represents a significant stride in the field. As we look ahead, continued research and innovation promise to further refine and enhance the precision and reliability of satellite navigation systems.

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The integration of GNSS/INS is becoming increasingly pivotal for the precise operation of uncrewed aerial vehicles, especially in agriculture. This integration is underscored by two primary necessities: the assurance that after prolonged operation, the accuracy of the navigation parameters remains uncompromised and the implementation of an integrated navigation algorithm that is both straightforward and dependable, demanding minimal processing power from the onboard chips. This article first introduces the centralized Kalman filter approach, employed to merge GPS and INS systems, based on a loosely coupled framework. This amalgamation is streamlined, significantly curtailing the computational demands of the system, and *reducing its intricacy. Subsequently, the discrepancies in the INS system's navigation parameters, as gauged by the discrete Kalman filter algorithm, are rectified using a feedback amendment method. This strategy effectively counters the degradation in navigational accuracy that typically ensues from extended operational periods.*

Keywords: *positioning and navigation, multi-source integrated navigation, uncrewed aerial vehicle, data analysis, error correction, filtration, fault detection, fault tolerance.*

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АРХІТЕКТУРА ІНТЕГРОВАНИХ НАВІГАЦІЙНИХ СИСТЕМ З ПОКРАЩЕНОЮ ТОЧНІСТЮ КООРДИНАТ ТА ВИЯВЛЕННЯМ ПОМИЛОК

Інтеграція GNSS/INS стає все більш важливою для точної роботи безпілотних літальних апаратів, особливо в аграрній сфері. Ця інтеграція базується на двох основних потребах: забезпеченні того, що після тривалої роботи точність навігаційних параметрів залишається незмінною, та впровадженні інтегрованого навігаційного алгоритму, який є простим та надійним, вимагаючи мінімальної обробки від бортових мікросхем. У цій статті спочатку представлено підхід централізованого фільтра Калмана, який використовується для об'єднання GPS та INS систем на основі слабко зв'язаної структури. Це об'єднання є оптимізованим, що значно зменшує обчислювальні потреби системи та зменшує її складність. Після цього розбіжності в навігаційних параметрах INS системи, які оцінюються за алгоритмом дискретного фільтра Калмана, виправляються за допомогою методу виправлення зворотного зв'язку. Ця стратегія ефективно протистоїть зниженню навігаційної точності, яке зазвичай виникає після тривалого періоду роботи.

Ключові слова: *позиціонування та навігація, багатоджерельна інтегрована навігація, безпілотний літальний апарат, аналіз даних, корекція помилок, фільтрація, виявлення помилок, відмовостійкість.*