

UAV High-Precision Navigation review: Research Advances in Multi-Sensor Fusion Technology with IMU, Vision and UWB

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Abstract: Precise positioning systems are crucial for unmanned aerial vehicle (UAV) autonomous operations, playing an indispensable role in various practical applications. Notwithstanding their widespread utility, traditional Global Navigation Satellite System (GNSS) implementations encounter substantial constraints when operating in signal-deprived settings, including densely built-up urban corridors and enclosed interior spaces. Multi-sensor fusion technology effectively integrates complementary advantages of Inertial Measurement Unit (IMU), vision, and Ultra-Wideband (UWB) sensors. This approach significantly enhances positioning accuracy and system reliability while improving adaptability to complex operational environments. This study systematically reviews high-precision UAV navigation systems incorporating IMU, vision, and UWB technologies. It provides in-depth analysis of respective advantages and limitations of each technology, while offering perspectives on future development directions.

Keywords: High-precision UAV Navigation; Multi-sensor Fusion; GNSS-denied Navigation; IMU; Vision; UWB.

1. Introduction

In recent years, UAV has demonstrated significant advantages across various fields such as power inspection, agricultural management, aerial photography, and national defense. Owing to their flexibility and cost-effectiveness, UAV has become an important subject of research.

In the operation of an UAV, both its positional coordinates and heading orientation play a critical role. The reliable operation of UAV in these scenarios highly depends on accurate real-time position and heading information. Precise positioning is fundamental to the autonomous decision-making and safe flight of UAVs during task execution [1]. For applications such as pesticide spraying and route patrol, high-precision positioning systems are critical for avoiding path overlap and maintaining flight stability. In rescue missions, these systems provide accurate absolute coordinates of targets, thereby effectively guiding rescue efforts. Furthermore, high-precision positioning facilitates the sharing of location information among multiple UAVs, ensuring consistent relative positioning and enhancing the synchronization and performance of collaborative operations [2].

Nevertheless, current UAV positioning systems still face a number of challenges. Traditionally, the GNSS has been widely adopted for UAV positioning due to its strong global coverage, continuous operation, and ease of use [3]. Nevertheless, GNSS signals often encounter weakening, disruption, or complete unavailability in challenging scenarios including urban canyon regions, dense forested zones, and EMI-prone areas (with electromagnetic interference), which can diminish positioning precision and introduce risks of mission compromise [4,5]. Furthermore, accurately determining the attitude, particularly the heading of UAV, remains a significant challenge. Calculating the heading of UAV requires precise measurements of the relative positions of antennas or sensors, making it highly susceptible to errors. This limitation underscores the need for

more robust and complementary positioning technologies to ensure reliability in challenging scenarios. Consequently, high-precision integrated navigation systems that fuse GNSS with other technologies have become a prominent research focus. These systems leverage the complementary strengths of different sensors to provide continuous and reliable positioning and attitude information, even when GNSS signals are compromised [6].

Substantial research efforts have been dedicated to fusion of different positioning technology to achieve high-precision positioning and heading estimation for UAV. A common approach integrates IMU with others to enhance reliability [7]. Furthermore, to improve performance in GNSS-challenged environments, visual solutions are increasingly being incorporated [8]. There is also growing interest in leveraging UWB technology as a solution for high-precision UAV navigation [9]. This approach has demonstrated considerable potential, with numerous studies reporting excellent performance in UAV flight tests.

Multi-sensor fusion greatly improves UAV positioning accuracy and adaptability. However, real-time fusion of high-rate multi-sensor data needs much computing. This raises model complexity and hardware cost, especially on lightweight platforms with limited computing power [10]. To solve this problem, recent studies have optimized and innovated navigation algorithms and filtering methods. These improvements raise real-time performance and make fusion positioning more suitable for resource-limited platforms [11]. They offer a practical way to achieve high-precision navigation in highly dynamic and complex environments.

This paper provides a comprehensive survey of recent advances in high-precision navigation technologies for UAV. It begins by examining the development of multi-sensor fusion with IMU. The review then extends to vision assisted multi-sensor fusion Navigation System. Furthermore, the potential of UWB-based positioning is discussed. Finally, the paper concludes by identifying prevailing challenges and

suggesting promising directions for future research in UAV high-precision positioning.

2. Multi-Sensor Fusion-Based High-Precision UAV Positioning Algorithm

2.1. Multi-Sensor Fusion With IMU

An IMU consists of an accelerometer and a gyroscope. It estimates position, velocity, and attitude by integrating sensor data. Unlike GNSS, IMU works without external radio signals. Thus, it can operate in signal-blocked or enclosed spaces such as tunnels, indoors, or urban canyons. It also resists interference well. In addition, IMU gives high short-term accuracy. It is compact and consumes little power. These traits make it suitable for drones, where weight and energy matter.

However, IMU errors grow over time. Long-term accuracy drops quickly because integration accumulates small biases and noise. To solve this, IMU is often fused with other sensors. Absolute or stable measurements help correct IMU drift. Meanwhile, IMU's high update rate makes up for the slow response of other sensors in dynamic scenes.

Studies show that proper multi-sensor fusion can raise drone positioning accuracy and robustness. IMU is combined with ranging using an Extended Kalman Filter (EKF) in [7]. It achieves anchor-free high-precision relative positioning for dual micro aerial vehicle formation in GNSS-denied environments. An in-flight alignment model based on vector observations was established by using the Lie group [12]. It improves the performance of the rapid and accurate airborne alignment for cost-effective INS/GPS integration in short-endurance, high-rotation scenarios. To address the problem of large error in low-cost MEMS-IMU sensors, Fernandes *et al.* proposed an EKF filtering-smoothing framework based on Lie groups, which achieves tight coupling integration of GNSS/INS and meets the high-precision post-processing navigation requirements for short-duration, high-dynamic UAV [13]. An integration of WiFi and IMU UAV positioning system is proposed which achieves high indoor positioning accuracy [14]. By fusing IMU with ultrasonic sensors and designing an Adaptive Extended Kalman Filter (AEKF) along with a virtual observation process, Yang *et al.* significantly enhanced the UAV's position update rate, accuracy, and system stability [15]. A novel parametric alignment method is proposed to address the challenge of achieving high-precision initial heading estimation for systems equipped only with a single-antenna GNSS and a low-cost MEMS-IMU, in the absence of an absolute heading reference [16]. These studies demonstrate that integrating IMU with other sensors effectively enhances the measurement accuracy and overall reliability of high-precision sensing systems in drones.

Furthermore, existing studies have introduced innovative approaches for IMU fault detection and isolation (FDI) [17-19]. Concurrently, other research focuses on high-precision positioning technology that integrates IMU and GNSS for UAVs and examines spoofing techniques to counter UAV threats [2]. Overall, IMU is widely employed in high-precision navigation systems for UAVs.

2.2. Multi-Sensor Fusion with Vision

Besides IMU, another common multi-sensor fusion method for UAVs is vision-based high-precision navigation systems. Vision sensors extract features such as edges and semantics from the environment. They use changes in geometric texture

information to provide relative-scale position estimates. Vision sensors leverage rich environmental data to complement other sensors, overcoming the limitations of single-sensor systems. However, vision sensors have several drawbacks. They are highly sensitive to lighting conditions. Reliability decreases under strong light, low light, or rapidly changing illumination. Performance also declines in environments with insufficient visual features. Moreover, vision processing involves high computational complexity. In dynamic scenes with many moving objects, it can cause significant errors.

Research has made notable progress in addressing these challenges. Xiong *et al.* proposed a lightweight onboard relative positioning system designed specifically for micro-UAV swarms fusing data from a monocular camera with a compressed YOLOv7-tiny neural network for relative angle calculation, UWB for distance and IMU for self-state estimation [2]. A novel GNSS/IMU/Vision ultra-tightly integrated navigation system with a fuzzy control method is proposed to increase the anti-interference capabilities of traditional GNSS/IMU ultra-tightly integrated navigation systems under high-dynamic or harsh conditions [20]. A C#-based simulation environment is used to validate the algorithm's performance under strong GNSS signal noise in this research. To design a lightweight intelligent fusion algorithm for adaptive collaboration of multi-sensors to enhance navigation stability under dynamic interference, Wang *et al.* constructs a new hybrid fusion framework using lightweight CNN for visual feature extraction and balances accuracy and efficiency via deep learning and adaptive filtering, offering a reliable solution for UAV navigation in complex environments [21]. To address the problem that GNSS signals are easily disturbed near high-voltage lines, a vision-radar fusion assistance system is proposed and validated in real high-voltage environments [22]. Its system demonstrates reliability and practicality, providing a complete solution for automated power inspection.

Based on these research, vision-based high-precision UAV navigation systems demonstrate significant applicability in environments with strong signal interference or limited GNSS propagation. Innovations of algorithms such as visual SLAM and deep learning-based feature extraction enhance environmental perception accuracy. In filtering methods, novel filters improve the robustness of multi-sensor data fusion. By integrating multi-sensor data, these systems effectively enhance navigation accuracy and robustness, providing reliable auxiliary support for autonomous UAV operations under dynamic or challenging conditions.

2.3. Multi-Sensor Fusion With UWB

At present, high precision navigation systems that fuse IMU or vision have formed a mature research field. They are widely used in UAV positioning and navigation. These methods combine inertial continuity, visual spatial detail, and GNSS global position. They give good accuracy in open areas and keep strong robustness in some GNSS-denied scenes.

At the same time, to meet special needs in different tasks, many studies have added UWB to high-precision navigation design. Relevant research has applied UWB technology to unmanned aerial vehicle landing systems. Zeng *et al.* constructed a high-precision UAV landing system by integrating dual UWB tags with IMU navigation technology, which achieves 61% improvement in positioning accuracy, and provides an illumination-independent solution for

autonomous landing on mobile platforms [23]. To address the precise landing requirements of UAVs on mobile platforms, Hashim *et al.* proposes an illumination-independent positioning scheme based on UWB and IMU fusion which maintains stable positioning performance in dynamic landing scenarios through multi-sensor data coordination and effectively overcomes the limitations of traditional vision-based methods that rely on lighting conditions [24]. UWB measures signal travel time to reach centimeter or even millimeter accuracy. It works well indoors, underground, or where GNSS is fully denied. With controlled multipath, it gives stable and low-delay positioning. Ochoa-de-Erbe-Landaberea *et al.* significantly reduces positioning errors in traditional four-anchor UWB systems by deploying compact architecture and innovative filtering algorithms [25]. These studies provide reliable technical solutions for the autonomous landing of unmanned aerial vehicles on mobile platforms, particularly suited to scenarios with restricted GNSS signals such as ship decks and chemical plant tanks.

Compared with GNSS global positioning, UWB focuses more on local positioning. They provide continuous and reliable pose estimation where GNSS is unavailable within a small area. However, UWB has limited range and is affected by multipath and Non-Line-of-Sight (NLOS) conditions. It also has higher hardware and deployment costs. To enhance UAV positioning accuracy and address the limitations upon, recent research has prioritized multi-sensor fusion schemes based on UWB technology. By integrating UWB with heterogeneous sensors such as IMUs and vision systems, this approach effectively compensates for UWB error accumulation in NLOS scenarios, significantly improving positioning robustness and precision in complex environments. To address the positioning errors caused by NLOS conditions in UWB-based drone systems, reference Li *et al.* developed an integrated optimization scheme [26]. Xu *et al.* also proposes a novel time delay calibration method for positioning base stations by the analysis of base station deployment optimization based on the Chan algorithm and site characteristics [27]. It maintains positioning accuracy during UWB data outages by combining adaptive machine learning with robust filtering techniques. Zhang *et al.* effectively addresses the high-precision positioning challenges in agricultural greenhouse environments through intelligent fusion of UWB and IMU technologies, which demonstrates strong adaptability to temperature/humidity variations and metal structure interference [28]. This line of research has substantially advanced UWB-based UAV navigation technologies through multidimensional innovations. These advancements hold significant value for both theoretical development and practical applications.

In general, UWB technology plays a critical role in indoor positioning scenarios. Current research emphasizes deep multi-sensor fusion methods for specific application contexts. This strategy represents a significant developmental trend in high-precision navigation.

3. Conclusion

This in-depth study reveals the inherent mechanisms of multi-sensor fusion positioning through systematic analysis of IMU, vision, and UWB technologies. The research demonstrates that such integration not only achieves data-level complementarity but also enables spatiotemporal benchmark unification and error model optimization. Particularly in GNSS-denied environments, the deep fusion

of multi-source heterogeneous data provides new perspectives for establishing robust positioning systems, significantly advancing perception theories for intelligent unmanned systems.

Current research still faces fundamental challenges: temporal-spatial registration accuracy directly affects fusion outcomes, while existing methods show limited tolerance for minor synchronization errors. The performance degradation mechanisms of sensors in complex environments require deeper investigation, especially error propagation patterns of UAV positioning system based on vision in textureless scenes and UWB in NLOS conditions. Moreover, the inherent contradiction between computational complexity and real-time requirements presents ongoing engineering challenges.

Future research should focus on intelligent adaptive fusion algorithms using deep learning, incorporate emerging sensors like event cameras and millimeter-wave radar, establish seamless positioning systems across scales, and develop energy-efficient architectures for resource-constrained platforms. These advancements will extend the technology's applications to autonomous driving, smart warehouses, and emergency rescue operations, particularly in extreme environments where precise positioning is critical.

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