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Article

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ENHANCING ACCURACY OF INFORMATION PROCESSING IN ONBOARD SUBSYSTEMS OF UAVS

The object of research is the onboard subsystems of Unmanned Aerial Vehicles (UAVs). The research is aimed at analyzing UAVs, specifically the integration and enhancement of satellite-based positioning systems, including Global Navigation Satellite Systems (GNSS) and Inertial Navigation Systems (INS).

The problem concerns traditional satellite-based positioning services, especially those relying solely on medium earth orbit (MEO) satellites, which are insufficient for specific requirements. The study aims to address the limitations of these systems on onboard subsystems of UAVs, especially in challenging environments laden with jammers and interference, and to provide a more accurate, robust, and continuous positioning solution.

The research proposes a «multilayer system of systems» approach that integrates signals from various sources, including low Earth orbit (LEO) satellites, ground-based positioning, navigation, and timing (PNT) systems, and user-centric sensors. The combined approach, termed LeGNSS/INS, leverages the strengths of each component, providing redundancy and enhanced accuracy. The system's performance was evaluated using pseudo-real output data, demonstrating its ability to generate quasi-real dynamic trajectories for UAV flight. The error analysis showed that the proposed method consistently outperforms traditional GNSS systems, especially in challenging environments.

The enhanced performance of the LeGNSS/INS system can be attributed to integrating multiple satellite systems with INS and applying optimal filtering techniques. The research also employed mathematical modeling to represent the dependencies and interactions when combining data from different sources, such as GPS, LEO, and INS. The Kalman filter is a mechanism to fuse data from multiple sources optimally.

The insights from this study apply to various sectors, including aviation, maritime navigation, autonomous drones, and defense. The enhanced positioning accuracy can significantly improve safety, navigation precision, and operational efficiency. However, the study assumes idealized conditions for satellite signal reception, which might not always be accurate in real-world scenarios. Challenges, such as the martial law conditions in Ukraine affecting data collection and potential satellite signal restrictions, were also highlighted. Further research can delve into the impact of more complex environmental factors and the integration of additional satellite systems or sensors to enhance accuracy further.

Keywords: *LeGNSS, INS, LEO satellites, UAV, multi-constellation positioning system, precise positioning, drone management.*

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1. Introduction

The advancement of satellite-based positioning systems has been pivotal in various sectors, from autonomous vehicles to drone management. Ensuring accurate positioning and navigation, these systems have become integral to modern technological applications. However, the enhancing accuracy of information processing on multi-constellation positioning systems, particularly the LeGNSS/INS system, poses significant challenges. Addressing these challenges is crucial to maintaining the reliability and accuracy of positioning information.

Existing works on improving the accuracy of processing information about positioning in the onboard subsystems of Unmanned Aerial Vehicles (UAVs) demonstrate a wide range of solutions that use means of information interference and interference on positioning systems such as compensation method, least-squares, filtering, optimal information processing, maximum likelihood method, and others [1–4].

Combining these techniques with other methods can significantly enhance positioning systems' efficiency, resilience, and reliability. In addition to classic global navigation systems, existing studies suggest using geostationary satellites as sources of navigation information to increase the accuracy of information about object positioning [5]. Early developments of positioning subsystems for UAVs used a simple integration of inertial sensors and GPS [6]. Still, the approaches became more complex over time, allowing for the simultaneous processing of more diverse sources of positioning information. Specifically, papers [7, 8] discuss the architecture of multi-constellation positioning systems. Article [9] focuses on ensuring positioning accuracy with the help of interference mitigation techniques in multi-frequency and multi-constellation positioning systems. The issues of information interference and its impact on positioning accuracy are considered in [10]. It proposed using redundant information and advanced information processing techniques to improve the resilience of positioning systems [11].

Advanced techniques in satellite positioning, especially in the transport sector, can address various challenges, particularly in ensuring accurate positioning, resource allocation, and improving safety in applications that rely on Global Navigation Satellite Systems (GNSS) signals and services, including aviation, maritime navigation, and land transportation systems [12].

A multi-constellation system performs better than a GPS-only constellation, and jamming the GNSS range has more critical consequences than jamming the range of the low Earth orbit (LEO) system. In addition, existing studies of the effects of interference signals on receivers demonstrate the advantages of using multi-constellation techniques and considering different types of interference signals in designing GNSS receivers for mission-critical applications [13].

The satellite constellations achieve nearly continuous global coverage by utilizing the unique characteristics of LEO dynamics. These LEO satellites operate closer to Earth, allowing faster data transmission and reduced latency. Unlike geostationary satellites, which remain fixed over a specific location, LEO satellites orbit the Earth more rapidly, necessitating a constellation to maintain consistent coverage. The combined impact of these factors ensures the efficient operation and positioning of LEO satellites within their constellations.

This positioning system, backed by extensive LEO satellite constellations, is poised to drive technological advancements, and elevate safety and efficiency across various domains.

This research aims to experimentally evaluate the accuracy of navigation information in the proposed model of an Inertial LEO-enhanced Global Navigation Satellite System (LeGNSS/INS) with increased resistance to external interference. This will ensure accurate positioning data, which is crucial for applications such as autonomous and uncrewed aerial vehicles in urban areas.

The proposed inertial multi-constellation positioning system, integrated with prominent satellite constellations such as SpaceX (4487 satellites), OneWeb (720 satellites), and Telesat (117 satellites) [14], promises ground-breaking precision in positioning information. This massive number of satellites provides better geometry than GPS and enables the use of lower-cost receivers with higher accuracy.

This enhanced accuracy ensures robust global broadband access, bridging the digital divide, and has profound implications for sectors reliant on navigation, including aviation, maritime, and autonomous vehicles.

2. Materials and Methods

In the rapidly evolving domain of satellite-based positioning systems, understanding the resilience and performance of these systems against potential threats, such as information jammers and interference, is paramount. This study focused on an experimental assessment of the effects of bias and jamming on the inertial multi-constellation positioning system, specifically the LeGNSS/INS system. As a part of this study, several experimental tests were conducted to evaluate the performance of the proposed LeGNSS/INS system, which combines the filtering approach and variance component estimation methods for multi-constellation positioning. Our experimental framework was anchored on the use of semi-real navigation information.

The main idea of the innovation is to overcome the well-known inertial system drift problem using a custom Kalman filter, an intelligent algorithm, and a set of additional sources of positioning data. All electronics will not make any sense in conditions of aggressive electromagnetic interference. Therefore, in addition to technical solutions for processing information in the UAV navigation subsystem, it is also necessary to provide robust radio shielding, which should receive attention.

This approach was chosen to balance the authenticity of real-world data and the controllability of simulated environments. To further enhance the realism of our experiments, a Simulink emulator was employed. This tool was instrumental in generating quasi-real dynamic trajectories, which closely mimic real-world satellite movements and behaviours while allowing for the controlled introduction of variables like jammers and interference.

Satellite-based positioning services relying solely on medium earth orbit satellites are insufficient for the requirements discussed in this work. Therefore, our task is to transition towards a comprehensive «multilayer system of systems» approach [15]. This approach would enhance MEO signals with those from LEO satellites (Fig. 1) and information from the inertial positioning subsystem. Additionally, let's propose integrating signals from ground-based positioning, navigation, and timing (PNT) systems and user-centric sensors.

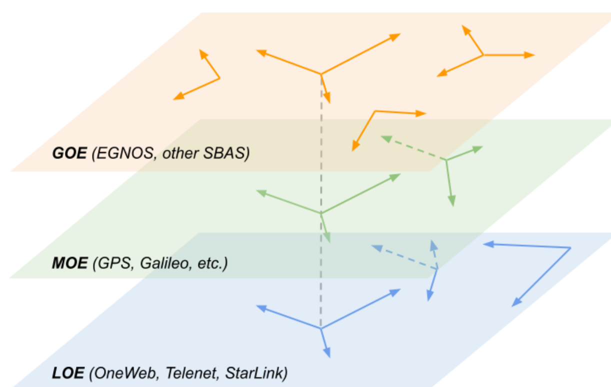

Fig. 1. Illustration of satellite-based «multilayer system of systems» approach

The slight degradation in their coverage has brought a significant reward in operational feasibility [16]. At the same time, during the analysis and processing of the received positioning information, it is required to consider that satellite navigation platforms contain their orbital positioning errors. Thus, the orbital errors of ephemeris broadcasting usually do not exceed 10 m [17]. For analyzing the proposed LeGNSS/ISN model of positioning subsystem in Simulink, created a testing positioning data array and used average root mean square (RMS) values of orbit positioning errors Table 1 for all orbital types of satellites [13].

But in the case of using low-cost positioning systems (such as in smartphones) for UAVs, receivers are better suited for dynamic applications – the mean shift between reference and measured trajectories varied from 1.23 to 5.98 m [18].

RMS of GPS, BDS, and GLONASS pseudo-range residuals of the smartphone in different ranges compared in Table 2 [19–22].

Table 1

Averaged RMS values of orbit errors for all orbital types of satellites

Satellite Type	Along (cm)	Cross (cm)	Radial (cm)	3D (cm)	Clock (ns)
BDS GEO	110.5	0.3	0.3	110.5	0.11
BDS IGSO	0.9	0.9	0.3	1.3	0.10
BDS MEO	0.7	0.6	0.3	1.0	0.09
GPS	0.6	0.2	0.1	0.7	0.07
LEO	1.3	0.6	1.2	1.9	0.20

Table 2

Averaged RMS pseudo-range residual values of low-cost receiver

Satellite Type	Min (cm)	Max (cm)
BDS GEO	260	360
BDS IGSO	255	465
BDS MEO	276	696
GPS	277	573
LEO	650	950

Beyond the primary evaluation, our study also delved into a comparative analysis. Let's compare the performance of the LeGNSS/INS system, equipped with cluster constellations and redundant information processing, against traditional global positioning systems. At last, let's present an explored scenario where information from multiple positioning systems was processed simultaneously.

When combining data from multiple systems like GPS, LEO, and INS, the dependencies and interactions between these systems can be represented through mathematical formulas. The position obtained from each system can be defined as P_{GPS}, P_{LEO1}, P_{LEO2}, and P_{INS}.

The merged position $P_{LeGNSS/INS}$ (1) can be a weighted average of the positioning from each system:

$$P_{LeGNSS/INS}= \\ =w_{GPS}\cdot P_{GPS}+w_{LEO1}\cdot P_{LEO1}+w_{LEO2}\cdot P_{LEO2}+w_{\mathrm{INS}}\cdot P_{\mathrm{INS}}, \quad (1)$$

where w represents the weight or trust level of each system's position estimate.

The error in the position estimates from each system can be represented as e_{GPS}, e_{LEO1}, e_{LEO2}, and e_{INS}. The combined error $e_{LeGNSS/INS}$ can be a function of particular errors:

$$e_{LeGNSS/INS}=f(e_{GPS},\ e_{LEO1},\ e_{LEO2},\ e_{INS}). \quad (2)$$

The Kalman filter provides a mechanism (3) to optimally fuse data from multiple sources. The state update equation in the presence of multiple measurements is:

$$\widehat{P_{k|k}}=\widehat{P_{k|k-1}}+K_k\sum_i\left[z_{k,i}-H_i\widehat{P_{k|k-1}}\right], \quad (3)$$

where $z_{k,i}$ is the measurement from the i-th system, and H_i is the observation model for that system. Also, the velocity and acceleration from each system can be combined.

When combining data from multiple systems (4), the fused positioning data can be represented as:

$$D_{LeGNSS/INS}=\alpha\cdot D_{GPS}+\beta\cdot D_{LEO1}+\gamma\cdot D_{LEO2}+\delta\cdot D_{INS}, \quad (4)$$

where α, β, γ, δ are fusion coefficients that determine the contribution of each system to the fused data.

The above formulas represent the dependencies and interactions when combining GPS, LEO, and INS data. The actual values of the weights, fusion coefficients, and other parameters would depend on the specific application, the quality of the measurements from each system, and the desired accuracy and reliability of the combined data.

3. Results and Discussion

The results demonstrate the efficacy of combining multiple satellite systems with INS and enhancing the results using optimal filtering. The combined system offers a robust, continuous, and accurate positioning solution, leveraging the strengths of each component and providing redundancy.

While traditional GNSS systems offer reasonable accuracy, our combined system outperforms standard configurations, especially in challenging environments. This improvement aligns with recent literature emphasizing the benefits of multi-system integration and advanced filtering techniques.

The provided modeling was performed using pseudo-real output data, which allowed the mathematical simulation of the operation of the integrated system and the demonstration of a 3D model of the UAV flight (Fig. 2) with such a navigation information correction system.

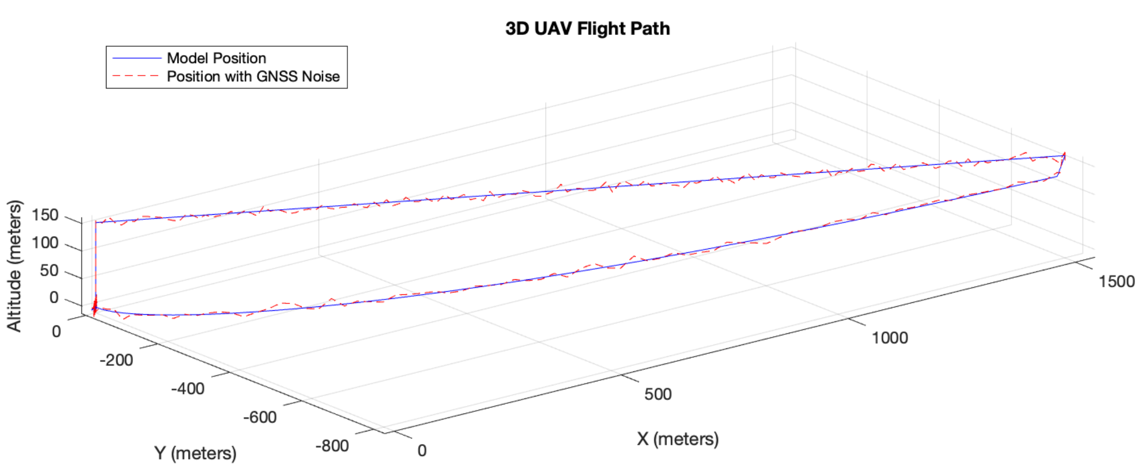

Fig. 2. UAV flight path generating with quasi-real dynamic trajectories

At the onset of the modeling period, the error remains relatively low, indicating the system's robust initialization and the effectiveness of the initial calibration. Throughout the timeline, transient peaks in error can be observed. These peaks might be attributed to complex environmental conditions, signal disruptions, or temporary INS drifts. Post each short peak, a rapid decline in error magnitude is evident.

This showcases the efficacy of correcting the information about position estimates in real time. Despite occasional peaks, the general trend of the error curve is stable, suggesting the consistent performance of the proposed LeGNSS/INS system. Fig. 3 presents a detailed assessment of the modeling error in the proposed LeGNSS/INS system, which is within 3–4 meters and is weakly dependent on GPS signal loss.

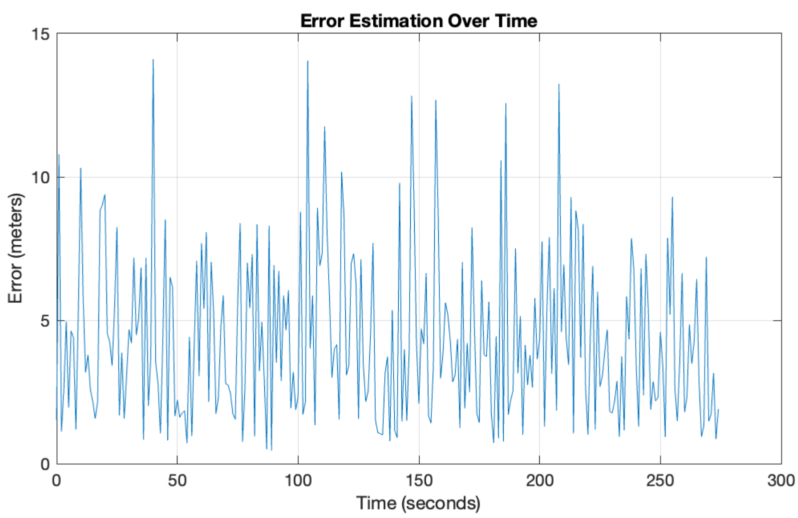

Fig. 3. Modeling error of proposed LeGNSS/INS system

The insights from this study can be applied to various sectors, including aviation, maritime navigation, autonomous drones, and defense. The enhanced positioning accuracy can improve safety, precision, and operational efficiency.

The study assumes idealized conditions for satellite signal reception, which might not always hold in real-world scenarios. The INS system's error propagation was modelled linearly, which might not capture all the nuances of real-world INS drifts. Because of the martial law in Ukraine, data collection has been challenged, including access to satellite signals due to potential restrictions (StarLink, OneWeb, etc.).

Further research can analyze the impact of more complex environmental factors on the combined system's performance and further explore the integration of additional satellite systems or sensors to enhance positioning information accuracy. Further adjustment of optimal filtering parameters can achieve excellent smoothness and precision of received positional information.

4. Conclusions

This study introduced the LeGNSS/INS platform, a new approach combining different satellite information sources to improve positioning accuracy, especially in high-interference environments. The system is a «multilayer system of systems» that uses multiple satellite constellations in combination with INS, applying a Kalman filter for data processing. As a result, LeGNSS/INS consistently demonstrated a robust nature and better performance than traditional systems, particularly in environments with significant interference.

The proposed LeGNSS/INS system exhibited a robust initialization, with transient peaks in error effectively corrected in real-time, ensuring consistent performance throughout. Detailed assessments revealed an impressive modeling error within the 3–4 meters range, demonstrating its resilience even during GPS signal loss. These achievements in positioning accuracy have broad applications across various sectors, enhancing safety, precision, and operational efficiency. However, while the system works effectively in ideal satellite signal reception conditions, real-world scenarios and nonlinear INS drift may bring challenges that require further research.

Further works can focus on the more profound integrative studies with the inertial multi-constellation positioning system, building upon the foundational assumptions presented in our work. It is recommended to enhance the current positioning simulation and exploring the untapped potential of inertial multi-constellation positioning systems in processing positioning information across LEO constellations. Integrating auxiliary techniques with existing satellite capabilities may offer a viable solution to the convergence issue of further improving cold start performance.

Insights obtained from this experimental study can provide a valuable basis for future designs and optimizations of LeGNSS/INS-based positioning systems. Consequently, research and prototype development to bolster positioning precision and simulation performance will be a pivotal direction for future research.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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