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ROBUST LeGNSS POSITIONING SUBSYSTEM FOR UAV WITH CORRECTION AND OPTIMAL FILTERING

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Introduction

In recent years, the unprecedented evolution of unmanned aerial vehicle (UAV) technology has necessitated the development of more accurate and reliable positioning systems [1]. Central to this pursuit is the precision of positioning, which is critical for the effective operation of UAVs in various applications ranging from commercial deliveries to surveillance and environmental monitoring. Traditional positioning systems, primarily Global Positioning Systems (GPS or GNSS) and Inertial Systems (INS), face significant challenges in delivering the required level of accuracy due to factors such as signal degradation, environmental interference, and inherent sensor limitations.

In this context, synthesizing a robust LeGNSS positioning subsystem is a promising solution to overcome these hurdles. By integrating correction and optimal filtering of measurement errors, this subsystem aims to provide enhanced processing of redundant information crucial for UAV positioning. The proposed integration scheme leverages the strengths of both the GNSS and INS systems while effectively compensating for their weaknesses.

A comprehensive approach was adopted to analyse the proposed model of the LeGNSS positioning subsystem. Utilizing Matlab, arrays of data were created to simulate various aspects of UAV positioning, including RMS positioning errors from satellite and inertial information sources and the impact of external dynamic influences such as wind. This detailed simulation provides a foundation for understanding the complexities and challenges in UAV positioning and the efficacy of the proposed solution in real-world scenarios.

The introduction of LeGNSS, integrating low-earth orbit (LEO) satellite network data with GNSS and MEMS-based inertial systems, marks a significant advancement in UAV positioning technology. This paper aims to elucidate the development and implementation of the LeGNSS positioning subsystem, highlighting its potential to revolutionize UAV positioning through enhanced accuracy, reliability, and fault tolerance.

Problem statement

UAV positioning has been continually evolving, driven by the burgeoning demand for UAVs in many applications, ranging from commercial delivery and agricultural monitoring to military and search and rescue operations. However, the cornerstone of effective UAV operation, precise and reliable positioning, faces significant challenges, primarily due to the limitations of existing positioning systems like GNSS and INS.

GNSS Limitations: GNSS, while widely used for its global coverage and relatively high accuracy, has flaws [2]. The primary challenge lies in signal degradation. Signals transmitted from satellites to receivers on UAVs are prone to interference from various sources, including atmospheric conditions, urban canyons, and foliage. This interference can lead to significant errors in position estimation. Additionally, GNSS is susceptible to multipath errors, where signals reflect off surfaces before reaching the receiver, causing delays and inaccuracies in the calculated positions.

INS Limitations: On the other hand, INS, which calculates position based on motion and rotational sensors, is not reliant on external signals and is thus immune to signal degradation issues that plague GNSS. However, INS systems, especially those based on micro-electro-mechanical systems (MEMS), are subject to cumulative errors [3]. These errors arise from drift in inertial sensors over time. Without external reference points, the accuracy of INS degrades rapidly, making it unreliable for long-term positioning.

Integration Challenges: The integration of GNSS and INS has been recognized as a potential solution to address the individual limitations of each system. However, this integration is not straightforward. The challenge lies in effectively combining the data from both systems to provide a more accurate and reliable estimation of the UAV's position [4]. This approach requires sophisticated filtering and correction techniques to manage the noise and errors inherent in the data from each system. The integration must also account for dynamic environmental factors and operational conditions that can affect the performance of the positioning systems.

Dynamic Environmental Influences: UAV operations are often subject to dynamic environmental conditions, such as varying wind speeds and directions, which can further complicate positioning [5]. These factors can introduce additional errors in the positioning data, making it difficult to maintain the required level of accuracy for specific applications.

Robust Positioning Subsystem: To resolve these issues, we need a robust positioning subsystem that can effectively integrate GNSS and INS data, applying advanced correction and filtering techniques [6]. This subsystem must improve the accuracy and reliability of UAV positioning and be resilient to environmental influences and operational dynamics.

Research Gap: Existing research in UAV positioning has primarily focused on enhancing GNSS or INS independently or on essential integration of these systems [7]. There is a lack of comprehensive solutions that address the complex interplay of errors and environmental factors affecting integrated UAV positioning systems. The LeGNSS positioning subsystem aims to fill this gap by providing an advanced solution that integrates GNSS and INS data and enhances this integration with correction and optimal filtering techniques.

The vanguard of satellite innovation, as exemplified by enterprises such as SpaceX, heralds a promising trajectory for the progression of positioning systems. Their constellation, with approximately 1,700 satellites ensconced in lower Earth orbit, portends the inauguration of a satellite fleet exceeding 40,000. These satellites, traversing at proximally 1,200 km above the terrestrial surface, could employ signals akin to the quintessential GPS to ascertain terrestrial coordinates with remarkable precision. The confluence of this technological leap with the architectural framework proffered in this study has the potential to redefine the industry, offering a positional solution of unparalleled reliability and accuracy.

The challenges in UAV positioning stem from the limitations of GNSS and INS, the complexities of their integration, and the dynamic environmental factors affecting UAV operations [8]. The proposed LeGNSS positioning subsystem seeks to overcome these challenges by offering a sophisticated integration model that enhances UAV positioning systems accuracy, reliability, and fault tolerance. This research aims to contribute significantly to the field of UAV positioning, providing a robust solution that can be adapted to a wide range of applications.

Problem solution

Positioning and piloting paradigms, especially within the constraints of complex urban environments, have invariably encountered formidable challenges [9]. The vision is clear-cut for proposing satellite positioning to engineer systems that can deliver consistently exceptional performance, irrespective of environmental constraints.

The proposed solution to the challenges outlined in UAV positioning systems is the synthesis of a robust LeGNSS positioning subsystem [10]. This subsystem integrates correction and optimal filtering of measurement errors, enhancing the processing of redundant information critical for precise UAV positioning. The core of this solution lies in an advanced integration scheme utilizing the LeGNSS positioning subsystem [11].

To analyse the proposed model, Matlab was employed to create arrays of data simulating various aspects of UAV positioning. This solution includes positioning errors from satellite and inertial information sources and the impact of external dynamic influences, such as wind, on the UAV's flight modeling (fig. 1).

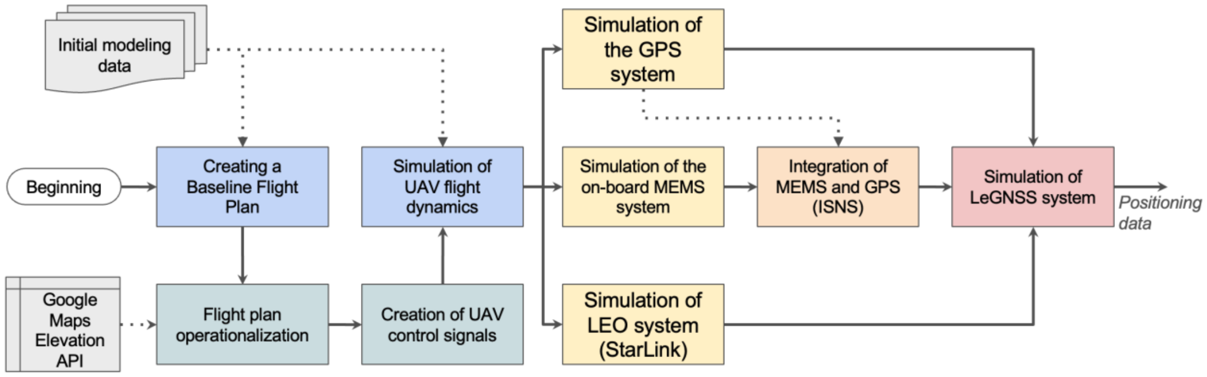

Fig. 1. Modeling algorithm for LeGNSS integrated multilayer positioning system in Matlab

This algorithm is designed to simulate the LeGNSS integrated positioning system operation for UAVs. It performs a sequence of steps to simulate UAV flight using various positioning models such as MEMS, GPS, LEO, and LeGNSS systems.

When simulating the flight dynamics of a UAV, it is important to consider aerodynamic forces, changes in air density, and other external factors, such as wind and turbulence, that affect the movement of the vehicle. Aerodynamic drag during flight can be accurately modeled using equation (1):

$$F_{drag} = -\frac{1}{2}\rho C_d A v^2, \tag{1}$$

Where ρ is the density of the air, C_d is the drag coefficient, A is the cross-sectional area, and v is the velocity. This equation allows us to consider the aerodynamic resistance of the air to create a more accurate simulation in different flight conditions. This helps determine the optimal control commands for UAVs to reach the routes' specified points effectively.

The use of Matlab tools for automated compilation and visualization of flight routes allows us to plan and evaluate the trajectory of UAVs in detail. The UAV flight simulation model includes integrating and processing data from several positioning systems, which provides a comprehensive analysis of the behaviour of onboard subsystems in different conditions. The use of pseudo-real data when simulating the operation of the integrated positioning system made it possible to create a detailed 3D flight model reflecting the realistic flight scenario of UAVs.

Simulation of flight dynamics requires using equations of motion, notably Newton's and Euler's (2-3), which allows to reproduce the dynamics of UAV movement.

$$\underline{r} = \frac{\underline{F}}{m} - \underline{g}\,, \tag{2}$$

$$\underline{\omega} = I^{-1}(T - \omega \times (I\,\omega)), \tag{3}$$

where r is the acceleration of the UAV center of mass, F is the moment of force, m is the mass, g is the acceleration of gravity, ω is the angular velocity, T is the moment of forces, and I is the inertia tensor.

For simulation purposes, gyroscope drift and accelerometer errors are characterized by exponential functions with a significant correlation period. Accordingly, they can be represented using the following differential equations:

$$\dot{\omega}_{\text{др}} = -\frac{1}{T_\omega}\omega_{\text{др}} + \frac{1}{T_\omega}q_\omega, \tag{4}$$

$$\Delta\dot{a} = -\frac{1}{T_a}\Delta a + \frac{1}{T_a}q_a, \tag{5}$$

where q – random component (white noise), T_a, T_ω – correlation time coefficient.

Simulation of random and systematic (deterministic) errors of sensors, particularly accelerometers, gyroscopes, and magnetometers, was generated through the error model (6), which considers errors arising from temperature changes, mechanical stresses, electromagnetic interference, etc.

$$\delta_{MEMS} = \delta_{bias}(t) + \delta_{scale} + \delta_{ortho} + \\ + \delta_{drift}(t) + \delta_{noise}(t), \qquad (6)$$

where *bias* is the error of the shift over time, *scale* is the deviation in the scale of the sensor data, *ortho* is the error of the non-orthogonality of the sensor axes, *drift* is the rate of change of sensor drift over time, noise is random fluctuations in measurements that cannot be predicted or corrected, (t) is a function of time (rate of change).

In pursuit of elevating the resilience and understanding of the positioning mechanism, we propose a fortified multi-sourced position methodology for UAVs predicated on the real-time assessment of redundant data. Central to this proposition is the advent of an algorithm optimized for the precise estimation of INS discrepancies, anchoring its foundation upon the Kalman filter paradigms.

At the heart of the LeGNSS positioning subsystem is the implementation of the Kalman filter, a critical component for combining data from the inertial MEMS positioning system, satellite positioning system, and LEO satellite network. The filter's correction coefficients, derived from the solution of the Riccati equation, play a vital role in updating the covariance matrix of estimation error (fig. 2). The Kalman filter effectively integrates new measurements, updating the estimate of the system's state and its uncertainty to minimize overall error.

The discrete simulation in the Matlab environment (R2023b) offers insights into the UAV positioning subsystem's operation. Multiple statistical evaluations were conducted to quantify the accuracy of the simulation results, comparing the variance of error estimation of the complex LeGNSS subsystem with other systems (fig. 3). These evaluations demonstrate the high quality of the LeGNSS error identification process and the reliability of the statistical modeling.

Including the algorithm of optimal filtering and positional correction in the complex system, the model reduces the system's overall error and the noise level of positioning estimates.

The error has a slight spike at the beginning of the simulation period. Still, it does not exceed the permissible limits and remains relatively low throughout the simulation period, indicating reliable system initialization. Transient peaks of error can be observed throughout the period. These peaks can be explained by changes in flight dynamics during difficult mission phases, signal failures, or temporary drifts of INS. After each short rise, there is a rapid decrease in the magnitude of the error.

This modeling demonstrates the efficiency of processing real-time positioning information. Despite some peaks, the overall trend of error curves is stable, which indicates the regular operation of the proposed LeGNSS system. Fig. 3 shows a detailed assessment of the positioning error in the proposed LeGNSS system, which is within 3 meters.

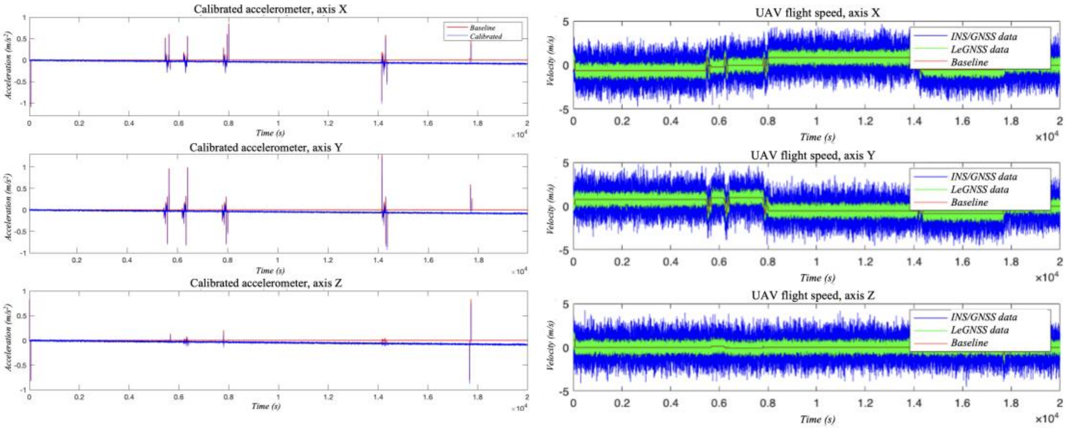

Fig. 2. Collection of data on UAV flight dynamics on simulation model

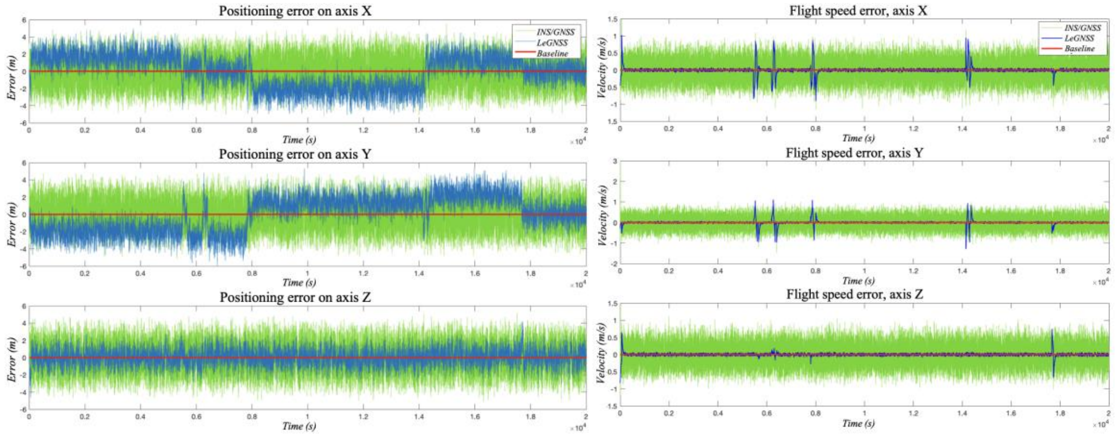

Fig. 3. System positioning error and speed on simulation model

Calculations of absolute RMS values of positioning error estimation for each of the studied systems based on the simulation results demonstrate improved accuracy of the LeGNSS positioning subsystem in comparison with the integrated INS/GNSS of increased accuracy by 9.02%, and by 26.4% compared to the onboard GPS receiver.

The results demonstrate the excellent efficiency of the complex LeGNSS subsystem of increased accuracy formed by the combination of the LEO (StarLink) low-orbit satellite communication system, the GNSS Global Satellite Positioning System (GPS), and the onboard MEMS measurement system. Internal data processing using algorithms for optimal data processing and filtering in the LeGNSS subsystem from different sources improves the accuracy of real-time UAV positioning and speed assessment.

The study assumes idealized conditions for receiving a satellite signal, which may not always correspond to real use cases. Error simulation of the MEMS system may not include all the details of specific sensors' drifts and measurement bias. Due to martial law in Ukraine, data collection has been hampered, including access to satellite signals due to potential restrictions (StarLink, etc.). In further research, it is possible to analyse the impact of complex environmental factors on the operation of LeGNSS to explore the possibility of expanding the list of satellite systems or sensors to improve the accuracy of positioning information.

The solution proffered within this document delineates a prospective framework for a synergized inertial and satellite positioning matrix [12]. This system is bolstered by incorporating correctional mechanisms and the concurrent filtration of high-frequency positioning discrepancies.

The proposed LeGNSS positioning subsystem marks a significant advancement in UAV positioning technology. Its ability to integrate multiple data sources with advanced filtering and correction techniques results in a reliable, continuous, and accurate positioning solution. This system's efficiency not only addresses the existing challenges in positioning but also opens ways for improved safety, accuracy, and operational efficiency in various sectors employing UAVs.

The findings of this study can be applied in various sectors, including unmanned aircraft systems, allowing for improved safety, accuracy, and operational efficiency of existing systems.

Conclusions

The combined strategy that merges inertial with satellite positioning, corrective mechanisms, and optimized filtration promises a significant uplift in system prowess. This is manifested in the precision of trajectory computations, attenuation of positioning signal anomalies, and a conspicuous decrement in ISNS inaccuracies.

The proposed LeGNSS positioning subsystem for UAVs demonstrates increasing accuracy for positioning estimation by 9.02% from GNSS/INS and by 26.4% compared to the onboard GPS receiver.

Furthermore, while the architectural proposition elucidated herein signals an advance towards enhanced positioning precision and robustness, it also delineates pathways for further evolution. These pathways may involve the integration of an intricate sensor error framework, refining the Kalman filter's matrix, and reconciling the frequency disparities intrinsic to both systems and perhaps the assimilation with alternative satellite clusters.

In sum, the proposed LeGNSS integration of inertial, GNSS, and LEO satellite positioning systems, augmented with corrective circuits and optimal filtration, signifies a profound advance for modern UAV positioning solutions.

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Dolintse B.I.

ROBUST LeGNSS POSITIONING SUBSYSTEM FOR UAV WITH CORRECTION AND OPTIMAL FILTERING

The integration of LEO satellites with GNSS/INS into a robust LeGNSS positioning subsystem for Unmanned Aerial Vehicles (UAVs) addresses the limitations of traditional GNSS and INS systems. The proposed LeGNSS integrates low-earth orbit (LEO) satellite data with GNSS and MEMS-based inertial systems to enhance UAV positioning accuracy, reliability, and fault tolerance. It aims to overcome challenges like signal degradation and sensor errors through advanced correction and optimal filtering techniques. The paper utilizes Matlab simulations to analyse UAV positioning, considering dynamic environmental factors like wind. It *emphasizes the integration of GNSS and INS systems to improve position estimation, highlighting the need for sophisticated filtering and error management. The study demonstrates improved positioning accuracy with the LeGNSS subsystem compared to traditional methods and suggests its application in various sectors employing unmanned aircraft. The research enhances UAV positioning technology and improves safety and operational efficiency.*

***Keywords**: LeGNSS, GNSS, LEO satellites, multi-source integration, positioning, uncrewed aerial vehicle, data analysis, error correction, optimal filtration.*

Долінце Б.І.

РОБАСТНА LeGNSS ПІДСИСТЕМА ПОЗИЦІОНУВАННЯ ДЛЯ БПЛА З КОРЕКЦІЄЮ ТА ОПТИМАЛЬНОЮ ФІЛЬТРАЦІЄЮ

Інтеграція супутників низької орбіти LEO з системами GNSS/INS у надійну підсистему позиціонування LeGNSS для безпілотних літальних апаратів, що усуває обмеження традиційних систем GNSS та INS. Запропонована підсистема LeGNSS інтегрує дані супутників LEO з GNSS та інерціальними системами на базі MEMS для покращення точності, надійності та захищеності від помилок у позиціонуванні БпЛА. Вона має на меті подолати типові виклики, такі як втрата сигналу та похибки датчиків, за допомогою передових методів корекції та оптимальної фільтрації інформації. Для дослідження використовуються моделі для симуляції в середовищі Matlab, що дозволяють провести аналіз точності роботи підсистеми позиціонування БпЛА з урахуванням динамічних факторів навколишнього середовища, як-от вітер. Фокус робиться на інтеграції систем GNSS та INS з LEO супутниками для покращення оцінки позиції, підкреслюючи необхідність в складній фільтрації та управлінні похибками. Дослідження демонструє покращену точність позиціонування за допомогою підсистеми LeGNSS у порівнянні з традиційними системами та пропонує її застосування у різних галузях, що використовують безпілотні літальні апарати. Результати сприяють покращенню технології позиціонування БпЛА та відкривають шляхи для підвищення безпеки та оперативної ефективності.

***Ключові слова**: LeGNSS, GNSS, супутники LEO, багатоджерельна інтеграція, позиціонування, безпілотний літальний апарат, аналіз даних, корекція помилок, оптимальна фільтрація.*