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Reliable Navigation in GPS-Denied Environments Using Doppler Assistance

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Abstract- — Reliable navigation in environments where Global Positioning System (GPS) signals are unavailable or degraded remains a critical challenge for autonomous systems, defense operations, and underground or indoor applications. This research proposes a robust navigation framework that leverages Doppler-based velocity estimation to enhance positioning accuracy in GPS-denied environments. The system integrates inertial measurement units (IMUs) with Doppler shift observations derived from radio frequency or acoustic signals to provide continuous and drift-reduced localization. A sensor fusion approach, combining Extended Kalman Filtering and machine learning-based error correction, is employed to mitigate accumulated drift and measurement noise. The proposed model is evaluated in complex scenarios such as urban canyons, tunnels, and indoor settings, demonstrating improved trajectory estimation and resilience compared to conventional inertial-only methods. Experimental results indicate that Doppler-assisted navigation significantly enhances reliability, reduces positional error, and ensures continuous operation in challenging conditions. This approach offers a scalable and efficient solution for next-generation navigation systems in autonomous vehicles and robotics.

Keywords: GPS-denied navigation, Doppler assistance, sensor fusion, inertial measurement unit, Extended Kalman Filter, autonomous systems, indoor localization.

I. INTRODUCTION

Accurate and reliable navigation is a fundamental requirement for modern autonomous systems, including unmanned aerial vehicles (UAVs), autonomous ground vehicles, marine vessels, and mobile robots. Traditionally, navigation systems rely heavily on the Global Positioning System (GPS) for real-time positioning and tracking. However, GPS signals are highly susceptible to blockage, interference, and intentional jamming, making them unreliable or completely unavailable in certain environments such as indoor spaces, underground tunnels, dense urban areas (urban canyons), and hostile or military zones. These limitations create a significant need for alternative navigation solutions capable of maintaining accuracy and reliability in GPS-denied environments.

In the absence of GPS, inertial navigation systems (INS), which use inertial measurement units (IMUs), are commonly employed to estimate position, velocity, and orientation. While INS can provide continuous navigation without external signals, it suffers from cumulative errors due to sensor noise and bias drift over time. This leads to a gradual degradation in positioning accuracy, especially during long-duration operations. Therefore, relying solely on inertial systems is insufficient for applications that demand high precision and long-term stability.

To address these challenges, recent research has focused on integrating additional sources of information to enhance navigation performance. One promising approach is the use of Doppler-based measurements, which exploit the frequency shift of signals caused by relative motion between a transmitter and receiver. Doppler assistance provides valuable velocity information that can be used to correct drift errors in inertial systems. By combining Doppler data with IMU readings through advanced sensor fusion techniques, it is possible to achieve more accurate and robust navigation in environments where GPS is unavailable.

This research proposes a Doppler-assisted navigation framework designed to improve localization accuracy and reliability in challenging conditions. The system integrates Doppler velocity estimation with inertial sensing and applies filtering techniques, such as the Extended Kalman Filter, to effectively fuse the data and reduce uncertainty. Additionally, machine learning methods can be incorporated to model and compensate for nonlinear errors and environmental variations, further enhancing system performance.

The proposed approach is particularly relevant for applications such as search and rescue operations, underground exploration, indoor robotics, and military missions, where reliable navigation is critical for safety and mission success. By addressing the limitations of existing methods, this work aims to contribute to the development of resilient, scalable, and high-precision navigation systems capable of operating effectively in GPS-denied environments.

II. RELATED WORKS

Highly Accurate GPS-Denied PNT Using Direct Doppler LiDAR Measurements Authors: Jeremy Templeton, Jasprit Singh Gill, Anurag Jakhotia, Joel Pazhayampallil presents a high-precision navigation system for GPS-denied environments using Doppler-enabled Frequency Modulated Continuous Wave (FMCW) LiDAR. The authors address limitations of traditional systems like inertial navigation systems (INS), which suffer from drift, and visual odometry, which fails under poor lighting or terrain conditions. Their approach integrates IMU data with Doppler velocity measurements in a nonlinear filtering framework to estimate motion accurately. The system achieves very low cross-track error (around 0.1%), demonstrating high robustness across different terrains and environmental conditions. A key contribution is its independence from platform-specific inputs such as wheel sensors, making it scalable across vehicles, drones, and soldiers. The study highlights Doppler sensing as a powerful enhancement for reliable positioning, navigation, and timing (PNT) in challenging environments like battlefields and urban canyons.

2. Degeneracy-Resilient Navigation Using FMCW LiDAR with Doppler Velocity: Katya M. Papais, Wenda Zhao, Timothy D. Barfoot This research introduces a navigation system designed for geometrically challenging environments where traditional localization methods fail. The authors use FMCW LiDAR to extract Doppler velocity measurements, enabling motion estimation even in feature-sparse areas. Unlike conventional ICP-based approaches, which depend heavily on geometric features, this method uses correspondence-free motion estimation combined with uncertainty modeling. The system is capable of detecting degeneracy conditions and adapting accordingly to maintain stable localization. Experimental validation across multiple real-world environments demonstrates improved reliability and robustness. The integration of Doppler information plays a key role in maintaining navigation performance where geometry alone is insufficient. This work is highly relevant for autonomous navigation in environments such as airports, underground tunnels, and planetary exploration.

3. Cooperative Localization of a GPS-Denied UAV Using DOA Measurements Authors: James Russell, Mengbin Ye, Brian D. O. Anderson, Hatem Hmam, Peter Sarunic This paper proposes a cooperative navigation strategy where a GPS-enabled UAV assists a GPS-denied UAV using Direction of Arrival (DOA) measurements. The system estimates the transformation between local and global coordinate frames using linear algebra and optimization techniques. In noisy environments, the authors apply semidefinite programming (SDP) and Procrustes analysis to improve accuracy. The approach demonstrates how collaboration between multiple agents can overcome the limitations of standalone navigation systems. It also highlights the importance of integrating external measurements with inertial data. This method is particularly useful for swarm robotics and coordinated drone operations in GPS-denied environments such as disaster zones or military missions.

4. Nonlinear Deterministic Observer for UWB-IMU Sensor Fusion Authors: Hashim A. Hashim, Abdelrahman E. E. Eltoukhy, Kyriakos G. Vamvoudakis, Mohammed I. Abouheaf develops a nonlinear observer-based navigation framework that fuses Ultra-Wideband (UWB) and IMU data. The model is formulated on the Special Euclidean group, enabling accurate estimation of position, velocity, and orientation. The proposed observer guarantees exponential convergence and robustness against noise, making it suitable for real-time applications. The authors validate their method using real-world drone datasets, showing improved accuracy compared to traditional filters. The integration of UWB signals helps correct inertial drift, a major issue in GPS-denied navigation. This work contributes to the development of low-cost and efficient navigation systems for indoor robotics and UAV applications.

5. Vision-Aided Navigation Using Landmark Feature Identification Author: Tennyson Samuel John This thesis explores vision-based navigation as an alternative to GPS by using image processing techniques to detect and track landmarks. The system integrates camera data with IMU measurements through sensor fusion, enabling localization without satellite signals. Algorithms such as CAMSHIFT and ADCOM are used for feature tracking, while navigation filters estimate position based on landmark observations. The study demonstrates that vision-based measurements can act as surrogate GPS signals in structured environments. The approach is particularly useful for indoor navigation and urban environments where GPS signals are weak or unavailable. It also emphasizes the importance of feature detection and robustness to noise in real-world scenarios.

6. Navigation Sensors and Systems in GNSS-Denied Environments Author: George T. Schmidt This paper provides a comprehensive overview of navigation technologies used in GNSS-denied environments. It discusses the limitations of GPS and highlights alternative systems such as inertial sensors,

Doppler velocity sensors, and integrated navigation frameworks. The author emphasizes the importance of sensor fusion in improving accuracy and reliability. Various case studies demonstrate how combining multiple sensors can compensate for individual weaknesses. The paper also explores advancements in navigation algorithms and hardware systems, making it a foundational reference for researchers. It underscores Doppler velocity as a key component in enhancing navigation performance.

7. Landmark-Based Secure Navigation in GPS-Denied Environments Authors: Ganesh Sapkota, Sanjay Madria This research proposes a landmark-based navigation framework enhanced with Extended Kalman Filtering (EKF) for predicting safe trajectories. The system integrates landmark detection with hazard mapping to ensure safe navigation paths. It evaluates performance using metrics such as Average Displacement Error and Final Displacement Error. The results show improved accuracy and safety in dynamic environments. The study highlights the role of predictive modeling in navigation systems and demonstrates how combining mapping and filtering techniques enhances reliability. This approach is useful in military and emergency scenarios where both accuracy and safety are critical.

8. UWB Positioning Enhancement Algorithm in GPS-Denied Environments Authors: Yuansheng Huang, Bo Cao, Ao Wang focuses on improving positioning accuracy using Ultra-Wideband (UWB) technology. The authors propose a novel algorithm to reduce noise and enhance localization precision. UWB is particularly effective in indoor environments due to its high resolution and resistance to interference. The study demonstrates improved positioning accuracy compared to traditional methods. The integration of UWB with other sensors provides a reliable alternative to GPS. This work contributes to indoor navigation systems, especially in industrial and smart building applications.

9. GPS-Denied Navigation Using Nonlinear Stochastic Observer Hashim A. Hashim This paper introduces a stochastic observer-based framework for estimating navigation states in GPS-denied environments. The system models motion dynamics using Lie group theory and incorporates IMU data with landmark measurements. It addresses sensor noise through stochastic filtering techniques, ensuring bounded estimation errors. The approach is validated using quadrotor datasets, showing strong performance in real-world scenarios. The study provides a mathematically rigorous solution to navigation challenges and highlights the importance of nonlinear modeling.

10. Doppler Navigation Using LEO Satellites Authors: Ariel Baron, Pini Gurfil, Héctor Rotstein This research explores Doppler-based navigation using Low Earth Orbit (LEO) satellites as an alternative to GPS. The system estimates position and velocity by analyzing Doppler shifts in satellite signals. The authors evaluate the accuracy and feasibility of this approach, demonstrating its potential for global navigation without reliance on traditional GPS infrastructure. The study shows that Doppler measurements can provide reliable positioning even in signal-degraded environments. This work is highly relevant for future navigation systems, especially in defense and space applications.

III. PROPOSED METHOD

The proposed system presents a robust and scalable framework for reliable navigation in GPS-denied environments by integrating Doppler-assisted velocity estimation with inertial sensing and intelligent data fusion techniques. The architecture is designed to overcome the limitations of standalone inertial navigation systems, particularly the issue of cumulative drift over time, by incorporating external motion cues derived from Doppler shift measurements.

The system consists of three major components: data acquisition, sensor fusion and processing, and localization output. In the data acquisition stage, an Inertial Measurement Unit (IMU) collects acceleration and angular velocity data, while Doppler measurements are obtained from radio frequency (RF) or acoustic signals. These Doppler signals provide real-time velocity information based on frequency shifts caused by relative motion between the transmitter and receiver. Optionally, additional sensors such as barometers or magnetometers can be included to enhance environmental awareness.

In the processing stage, raw sensor data undergo preprocessing steps such as noise filtering, bias correction, and normalization. The cleaned data is then fed into a sensor fusion module that employs an Extended Kalman Filter (EKF) to combine IMU and Doppler observations. The EKF estimates the system’s state variables, including position, velocity, and orientation, while minimizing uncertainty and correcting drift errors. To further enhance accuracy, a machine learning-based error correction module is integrated into the framework. This module is trained on historical navigation data to learn nonlinear error patterns and compensate for residual inaccuracies in real time.

The localization output stage generates continuous position estimates, which can be visualized or used for navigation control. The system is designed to operate in real time, ensuring uninterrupted navigation even in challenging environments such as indoor spaces, tunnels, and dense urban areas. Additionally, a confidence estimation mechanism is included to assess the reliability of predictions and trigger alerts when uncertainty exceeds predefined thresholds.

The proposed framework is adaptable to various platforms, including autonomous vehicles, drones, and robotic systems. By leveraging Doppler assistance and advanced data fusion techniques, the system achieves improved accuracy, robustness, and resilience compared to traditional GPS-independent navigation methods. This makes it a promising solution for next-generation navigation systems operating in complex and GPS-restricted environments.

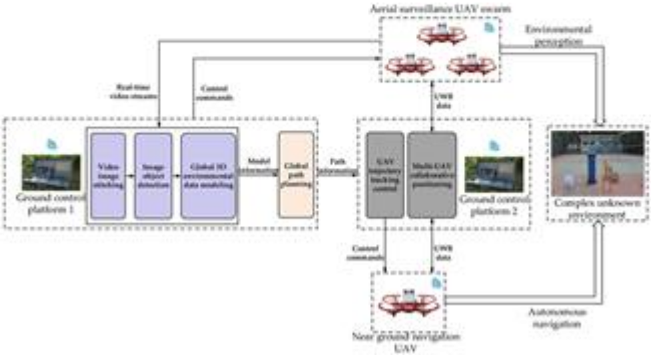

Fig.1.System Architecture

The proposed Doppler-assisted navigation system for GPS-denied environments is organized into several functional modules, each responsible for a specific task to ensure accurate and reliable localization.

The first module is the Data Acquisition Module, which gathers raw data from various onboard sensors. This includes the Inertial Measurement Unit (IMU) for capturing acceleration and angular velocity, and Doppler sensors that measure velocity through frequency shifts of signals. Additional sensors such as magnetometers or barometers may also be incorporated to improve environmental awareness and system robustness.

The second module is the Preprocessing Module, where the collected data is cleaned and prepared for analysis. This involves noise filtering, outlier removal, bias correction, and normalization of sensor readings. Since raw sensor data is often noisy and inconsistent, this step is essential to ensure the reliability of subsequent processing stages.

The third module is the Sensor Fusion Module, which plays a critical role in combining data from multiple sources. An Extended Kalman Filter (EKF) is used to integrate IMU and Doppler measurements, estimating the system's position, velocity, and orientation. This module helps reduce cumulative errors and improves overall accuracy by leveraging the complementary strengths of different sensors.

The fourth module is the Machine Learning-Based Error Correction Module, which enhances the system's performance by learning and correcting nonlinear errors. Trained on historical navigation data, this module identifies patterns in drift and sensor inaccuracies, providing real-time corrections to the estimated states.
Finally, the Localization and Output Module generates the final position estimates and provides navigation outputs. It also includes a confidence assessment mechanism to evaluate the reliability of predictions and trigger alerts when uncertainty exceeds acceptable levels. Together, these modules form an efficient and robust navigation framework for operation in GPS-denied environments.

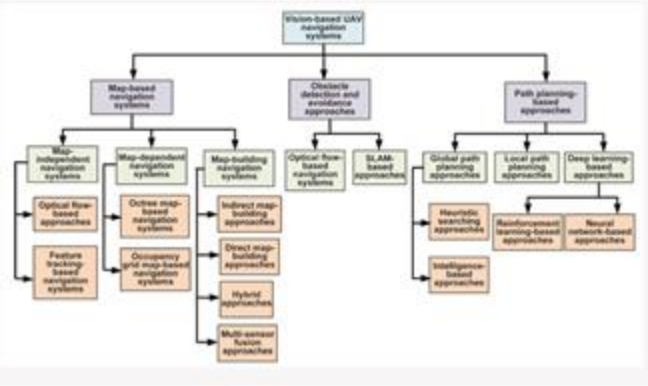

Fig.2.Methodology workflow of the Reliable Navigation in GPS-Denied Environments Using Doppler Assistance

Overall Working Flow of the Proposed System:
The overall workflow of the proposed Doppler-assisted navigation system is designed to ensure continuous, accurate, and reliable localization in GPS-denied environments through a sequence of coordinated steps. The process begins with the data acquisition phase, where multiple onboard sensors collect real-time information. The Inertial Measurement Unit (IMU) captures acceleration and angular velocity, while Doppler sensors measure velocity based on frequency shifts caused by relative motion. Additional supporting sensors, such as magnetometers or barometers, may also contribute contextual environmental data.

Once collected, the raw sensor data enters the preprocessing stage, where it is cleaned and standardized. This includes noise filtering, bias correction, and removal of outliers to ensure data consistency. Proper preprocessing is essential to reduce errors that could propagate through the system and affect localization accuracy.

The processed data is then passed to the sensor fusion stage, which is the core of the workflow. Here, an Extended Kalman Filter (EKF) integrates IMU and Doppler measurements to estimate the system's state, including position, velocity, and orientation. This fusion process helps compensate for the drift commonly associated with inertial systems by incorporating real-time velocity corrections from Doppler observations.

Following sensor fusion, the system applies a machine learning-based error correction stage. In this step, trained models analyze residual errors and nonlinear patterns in the estimated states, refining the predictions further. This enhances accuracy, especially in complex and dynamic environments.
Finally, the refined data is sent to the localization and output stage, where continuous position estimates are generated and visualized. The system also evaluates confidence levels and provides alerts if uncertainty exceeds predefined thresholds. This complete workflow ensures robust, real-time navigation performance in environments where GPS signals are unavailable or unreliable.

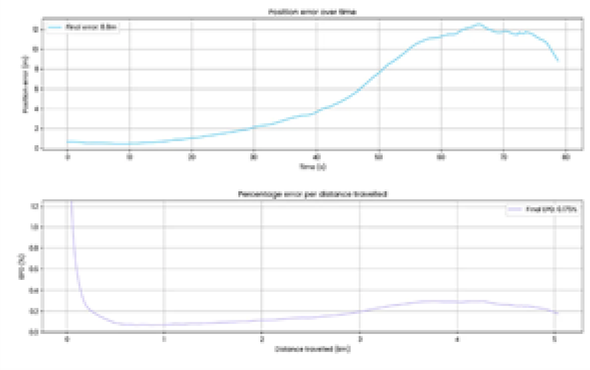

Fig.3.Performance Evaluation of Reliable Navigation in GPS-Denied Environments Using Doppler Assistance

$$f_d = \frac{v}{c} f_c$$

The Doppler frequency shift equation represents the change in frequency observed at the receiver due to the relative motion between the transmitter and receiver. In this equation, f_ddenotes the Doppler frequency shift, vrepresents the relative velocity between the transmitter and receiver, cis the speed of light, and f_cis the carrier frequency of the transmitted signal. When the receiver moves toward the transmitter, the frequency increases, while movement away from the transmitter causes a decrease in frequency. In GPS-denied navigation systems, Doppler measurements are used to estimate velocity and direction of motion. These velocity estimates play a crucial role in maintaining continuous navigation performance when satellite positioning signals are unavailable.

$$x_{k+1} = x_k + v_k \Delta t$$

The position update equation is used to estimate the new position of a moving object based on its previous position and velocity. In this equation, x_krepresents the position at the current time step, v_kdenotes the velocity of the object, and Δtrepresents the time interval between two measurements. The result x_(k+1)gives the updated position of the object after the time interval. In navigation systems operating in GPS-denied environments, velocity information obtained from Doppler measurements or inertial sensors is used in this equation to update the position continuously. This process allows the navigation system to track the movement of the platform even when external positioning signals are unavailable.

$$Error = \sqrt{(x_{est} - x_{true})^2 + (y_{est} - y_{true})^2}$$

The navigation error equation calculates the positional error between the estimated position and the true position of a moving object. In this equation, x_estand y_estrepresent the estimated coordinates produced by the navigation system, while x_trueand y_truerepresent the actual coordinates. The equation computes the Euclidean distance between these two points, which represents the positioning error. This metric is commonly used to evaluate the performance of navigation algorithms. In GPS-denied navigation systems, this equation helps measure how accurately the Doppler-assisted navigation method estimates the true location compared to reference measurements obtained from ground truth data or high-precision sensors.

V. FUTURE WORK

Future research should focus on enhancing the robustness and accuracy of Doppler-based navigation systems across diverse GPS-denied scenarios. One key direction involves the fusion of

Doppler radar/sonar with complementary sensors such as IMUs, LiDAR, and visual odometry to create tightly coupled multi-modal navigation frameworks that reduce cumulative drift errors over extended missions.

Advancing machine learning integration presents another promising avenue, where deep neural networks can learn environmental velocity signatures and compensate for multipath interference, signal degradation, and dynamic obstacle interference in real time.

Research should also explore miniaturization and energy efficiency of Doppler hardware for deployment on micro-UAVs, underwater gliders, and handheld soldier systems operating in tunnels, underwater, or urban canyons.

Developing adaptive Doppler filtering algorithms capable of handling non-stationary environments — such as turbulent airflows, ocean currents, or underground voids — will be critical for consistent performance. Additionally, standardizing simulation benchmarks and real-world test datasets for GPS-denied Doppler navigation will accelerate reproducible research.

Finally, extending these systems for collaborative multi-agent navigation, where swarms of vehicles share Doppler-derived velocity estimates to improve collective localization, represents a transformative long-term research goal.

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