# A survey on Multi-Sensor Integrated Navigation/Positioning Systems using Data Fusion

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**ABSTRACT - This project presents a novel type of dynamic pattern, called an incremental FPGrowth Frequent Pattern Analysis, which reports information about the frequent generalizations of an item set that are characterized by minimal redundancy, or minimum level of abstraction, in the event that the item set becomes infrequent over time. It suggests Frequent Pattern Growth, a method that avoids item set mining and post-processing by taking advantage of a support-driver term set generalization technique, as a solution to the problem of Frequent Pattern Growth mining. This work addresses the discovery of a smart subset, called the, in order to limit the amount of created patterns by focusing attention on the minimally redundant frequent generalizations. In response to these challenges, this study aims to develop an innovative approach to overcome the shortcomings of existing systems. Through this work, our study critically examines these limitations and proposes innovative solutions to overcome these challenges. By integrating advanced machine learning techniques and multimodal data fusion methods, ensuring more.**

## 1.LITERATURE SURVEY

### I. TOWARDS MULTI-MODAL PERCEPTION-BASED NAVIGATION: A DEEP REINFORCEMENT LEARNING METHOD

We present a novel navigation system of unmanned ground vehicle (UGV) for local path planning based on deep reinforcement learning. The navigation system decouples perception from control and takes advantage of multi-modal perception for a reliable online interaction with the surrounding environment of the UGV, which enables a direct policy learning for generating flexible actions to avoid collisions with obstacles in the navigation. By replacing the raw RGB images with their semantic segmentation maps as the input and applying a multimodal fusion scheme, our system trained only in simulation can handle real-world scenes containing dynamic obstacles such as vehicles and pedestrians. We also introduce a modal separation learning to accelerate the training and further boost the performance. Extensive experiments demonstrate that our method closes the gap between simulated and real environments, exhibiting the superiority over state-of-the-art approaches. Please refer to https://vsislab.github.io/mmpbnv1/ for the supplementary video demonstration of
UGV navigation in both simulated and real-world environments. r, it is still challenging to design an autonomous navigation system of unmanned ground vehicle (UGV) reliable for complex real-world environments which often contain many highly dynamic obstacles. This requires the navigation system to intelligently cope with various interactions with the obstacles at real-time rate. There exist some works relying on deep learning (DL) for autonomous navigation in complex environments. However, DL-based methods quintessentially focus more on the perception of the environment and do not explicitly learn the navigation policy [3], [4]. Few DL-based methods (e.g. [5]) directly learn the policy using offline annotations in a regular real-world environment. However, such policy annotations are not only time-consuming and laborious to generate, particularly at a large scale in highly dynamic environments, but also subject to a fixed, limited and discrete set of action states. Consequently, the learned policy may not meet the requirements of navigation in a dynamic and complex environment of the real world. By contrast, reinforcement learning (RL) directly learns the policy for the current environment through a reward mechanism [6]. It is actually more consistent with human's policymaking process where we make policies by interacting with the surrounding environment and directly adapt the policy model through trials and errors in accordance with the immediate response of the environment. Moreover, RL does not specifically require the supervision based on the policy annotations provided by human subjects. Previous work has used either LiDAR data [7], [8] or RGB images [9], [10] to learn policy for robot navigation via RL. To take advantage of the two complementary modalities of data, this work proposes a multi-modal perception-based navigation system.

### II. UNDERWATER POSITIONING ALGORITHM BASED ON SINS/LBL INTEGRATED SYSTEM

This study explores the collaborative assistance of a Strap-Down Inertial Navigation System (SINS) and a Long Baseline (LBL) underwater positioning algorithm based on Time of Arrival (TOA). The algorithm incorporates an equivalent sound velocity solution and a 3-D LBL underwater positioning approach with SINS assistance. The proposed method rapidly determines the ideal equivalent sound velocity for calculating distances in underwater positioning, mitigating errors due to uneven sound velocity distribution and sound ray bending. It exhibits high flexibility and adaptability. Simulation results indicate that compared to traditional algorithms, the improved method significantly corrects cumulative errors, extending the operational duration of Autonomous Underwater Vehicles (AUVs). As an autonomous navigation system, SINS continuously provides information on the carrier's attitude, velocity, and positioning. However, positioning errors accumulate over time. When AUVs move to effective LBL underwater acoustic positioning regions, errors can be calibrated. Yet, LBL positioning systems themselves have limitations, influenced by nonlinear underwater sound velocity profiles and measurement errors due to refraction, reflection, and multipath phenomena. To address these challenges, an algorithm incorporating an equivalent sound velocity based on interactive SINS assistance is introduced. This method boasts simplicity in calculation, sensitivity in acquiring suitable equivalent sound velocity for slope distance calculations, and flexibility without requiring specific environmental forms. By correcting cumulative SINS errors, the results are well-suited for AUV positioning navigation. While the collaborative SINS and LBL positioning system is effective for positioning tasks, it is crucial to manage the cumulative errors in SINS velocity and navigation orientation over time.

## III. POSITION, NAVIGATION, AND TIMING (PNT) THROUGH LOW EARTH ORBIT (LEO) SATELLITES: A SURVEY ON CURRENT STATUS, CHALLENGES, AND OPPORTUNITIES

The Low Earth Orbits (LEO) are becoming increasingly crowded with satellites, catering to applications such as broadband and narrowband communications, Earth observation, synthetic aperture radar, and Internet of Things (IoT) connectivity. While these targeted applications are prevalent, there is an untapped potential for LEO in the realm of positioning, navigation, and timing (PNT) systems, often referred to as LEO-PNT. Currently, there are no commercial LEO-PNT solutions, and research on LEO-PNT concepts lacks cohesion. Our survey aims to address these knowledge gaps by exploring the components of a LEO-PNT system, its technical design steps, challenges, viable physical layer parameters, tools for design optimization (including hardware and software simulators), models for wireless channels in satellite-to-ground and ground-to-satellite propagation, and the commercial prospects of future LEO-PNT systems. The survey is conducted by a team of authors with diverse expertise in wireless communications, signal processing, navigation and tracking, physics, machine learning, Earth observation, remote sensing, digital economy, and business models. Over the past decade, investments in the space industry have shifted from Medium Earth Orbit (MEO) satellite-based constellations to Low Earth Orbit (LEO) satellite-based systems. Various LEO systems now offer services ranging from broadband connectivity (e.g., Iridium, OneWeb, Starlink) and IoT applications (e.g., Hiber, Myriota) to Earth observation and synthetic aperture radar (EO-SAR) applications (e.g., Iceye, HawkEye), leading to a paradigm shift in communication and sensing applications. The global research focus is now turning towards a similar paradigm shift in positioning applications, namely the LEO positioning, navigation, and timing (LEO-PNT) concept. Traditional satellite-based positioning systems predominantly rely on Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) satellite systems, such as the US Navstar GPS, European Galileo, Russian GLONASS, and Chinese Beidou. Additionally, augmented satellite systems like the European Geostationary Navigation Overlay Service (EGNOS), GPS-Aided GeoAugmented Navigation system (GAGAN), and Wide Area Augmentation System (WAAS)/Canadian WAAS (CWAAS) are in use. Typically, MEO orbits range from around 2,000 km to 35,786 km above sea level, while GEO orbits are precisely located at 35,786 km above sea level.

## IV. MULTISOURCE INFORMATION FUSION NETWORK FOR OPTICAL REMOTE SENSING IMAGE SUPER-RESOLUTION

Super-resolution algorithms based on deep learning are effective in enhancing the details of optical remote sensing images (ORSI) for further analysis. Recent studies have explored deep unfolding methods to bridge the gap between optimization-based and learning-based approaches. However, existing unfolding methods often overlook the utilization of intermediate network features between different iteration stages, leading to limitations in super-resolution results. To address this issue, we propose a Multi-Source Information Fusion Network (MSFNet) for ORSI super-resolution. Our approach incorporates three key strategies to enhance super-resolution performance: a feature extraction strategy, an information fusion strategy, and a structured unfolding network. Firstly, we introduce multi-scale implicit constraints to the objective function, recognizing the value of image information at various scales for mining potential features. Secondly, we unfold the optimization process into a neural network using the Alternating Direction Method of Multipliers (ADMM), effectively leveraging prior information for image reconstruction. Thirdly, we introduce a row-column decoupling Transformer module for feature fusion, enhancing feature extraction across scales and channels. Experimental evaluations on three remote sensing image datasets demonstrate the effectiveness of the proposed algorithm. Results indicate improved image reconstruction performance. In the realm of remote sensing, image super-resolution is a critical technology, addressing challenges in optical remote sensing image resolution through both hardware and algorithmic approaches. Hardware methods offer direct improvements but are limited by long production cycles and high costs. In contrast, SR algorithms provide a more cost-effective and flexible alternative. The degradation of remote sensing images is primarily caused by atmospheric turbulence, noise, and down sampling factors, leading to the loss of image details. Traditional SR algorithms, including interpolation-based, optimization-based, and learning-based methods, address these challenges. While interpolation is fast, it has limitations in reconstruction performance. Optimization-based methods offer interpretability and improved performance, and our proposed MSFNet contributes to advancing the capabilities of learning-based approaches in the field of ORSI super-resolution.

## V. MULTIAGENT INFORMATION FUSION FOR CONNECTED DRIVING

This paper provides a comprehensive review of state-of-the-art multi-sensor fusion approaches applicable to next-generation intelligent transportation systems, where connected vehicles collaborate for optimal safety and efficiency. The analysis reveals the necessity of complementary sensor fusion in a time-varying distributed network, emphasizing the significance of sensor fusion within the random finite set filtering framework for such applications. The focus is particularly on the Labeled Multi-Bernoulli filter, a specific filter within this framework.The paper delves into the fundamental principles of random finite set filters, emphasizing the Labeled Multi-Bernoulli filter. An information-theoretic approach to data fusion, centered on minimizing information divergence between statistical densities, is introduced. The discussion includes various divergence functions applicable to sensor fusion. Multiple approaches are evaluated based on tracking performance and computational cost in a realistic simulation scenario. The advantages and disadvantages of these approaches are considered, especially in the context of real-time implementation within a connected driving scenario.As connected devices become increasingly prevalent, they transform various aspects of our environment, including transportation and driving. Connected vehicles, equipped with internet connectivity, enhance safety, mitigate risks, and improve the overall driving experience. These vehicles share data with nearby devices, enabling a network of connected vehicles to exchange sensory information. The paper highlights the importance of efficient multi-sensor data fusion, particularly in achieving complementary fusion, where information from multiple vehicles is combined to enhance situational awareness. This comprehensive fusion approach, involving data from onboard sensors, external signals, and neighboring vehicles, contributes to the intelligence of connected vehicles for trajectory planning and local maneuvering actions, whether in advanced driver-assist capabilities or autonomous driving.The integral role of sensor fusion in the design of intelligent transportation systems (ITS) is underscored, and various sensor fusion solutions for multivehicle applications within the ITS domain are explored. The paper emphasizes the significance of leveraging information fusion techniques and metrics for different network topologies in the context of connected vehicles.

## VI. INS/ INTEGRATED ROVER NAVIGATION DESIGNED WITH MDPO-BASED DUAL-SATELLITE LUNAR GLOBAL NAVIGATION SYSTEMS GNSS

With the increasing interest in providing a navigational framework for upcoming early lunar exploration missions involving lunar rovers, there is a growing need for robust and cost-effective global satellite navigation systems (GNSS) around the Moon. In our previous work, we proposed dual-satellite lunar global navigation systems (LGNS) based on the Multi-epoch Double-differenced Pseudorange Observation (MDPO) algorithm. While this system achieves reasonably high positioning accuracy within a one-minute observation, a limitation arises as the positioning calculation is only possible when the two navigational satellites are in the user's view. To overcome this limitation, integration with other navigational sensors such as an inertial navigation system (INS) becomes essential to compensate for user positions in the absence of GNSS signals.The primary objective of this research is to present an integration model of INS and MDPO-based dual-satellite LGNS measurements and demonstrate the benefits through numerical simulations. The key contributions of this paper include: 1) proposing a mathematical model for the integration of INS and MDPO algorithm, 2) developing a numerical simulation that combines INS measurements with dual-satellite LGNS measurements, and 3) conducting a quantitative comparison between the proposed INS/GNSS integration and raw dual-satellite LGNS measurements. Previous research has extensively explored the design of Global Navigation Satellite Systems (GNSS) using fewer satellites for both Earth GNSS and lunar GNSS applications. The author's prior work specifically focused on algorithms for lunar GNSS involving only two satellites, i.e., dual-satellite, providing a comparative analysis of their advantages and disadvantages. Dual-satellite LGNS is recognized as a cost-efficient platform offering reasonably accurate position measurements within a one-minute observation. However, a drawback is the lower availability of GNSS measurements, limiting the rover's traveling distance over the mission period. To address this limitation, the integration of an inertial navigation system (INS) is proposed as a viable approach to extend the rover's traveling distance.

## VII. 3- A COMPARATIVE ASSESSMENT OF MULTISENSOR DATA MERGING AND FUSION ALGORITHMS FOR HIGH-RESOLUTION SURFACE REFLECTANCE DATA

Improvement of the spatial and temporal resolution of reflectance data products has been challenging due to the diversity of data sources and availability of many data merging and fusion algorithms. In the algorithmic domain, methods for data merging and fusion may include, but are not limited to, the modified quantile–quantile adjustment (MQQA), the Bayesian maximum entropy (BME), and the spatial and temporal adaptive reflectance fusion model (STARFM). This article presents a synergistic integration of the data merging and fusion algorithms of MQQA and BME in dealing with heterogeneous and nonstationary surface reflectance data at both the top of atmosphere (TOA) and land surface for a comparative study. Emphasis has been placed on the distinctive performance between BME and MQQA–BME algorithms in the spatial domain and the MQQA–BME and STARFM in the temporal domain at both TOA and land surface levels. The results indicate that the BME and MQQA–BME outperform the MQQA in terms of the spatial coverage at both TOA and land surface levels. Moreover, the MQQA–BME algorithm shows a higher prediction accuracy than STARFM at the blue band over the temporal domain at both TOA and land surface levels. The results of this comparison will greatly empower the MQQA–BME to be used for urban air quality monitoring and related epidemiological assessment in the future, once finer aerosol optical depth predictions via integrated data merging and fusion can be made possible. satellite data cannot always meet the requirements of both high spatial and high temporal resolution at one-shoot observation [1]. This gap triggered the niche of data merging and data fusion to improve spatial and/or temporal resolution. For remote sensing applications, both top of atmosphere (TOA) reflectance and land surface reflectance (LSRF) data are required for information retrieval. These retrieval algorithms were widely used in many field studies to account for biogeochemical and biogeophysical processes, such as mapping evapotranspiration [2], land cover types [3], crop yields [4], thermal infrared radiance monitoring [5], and carbon balance in the atmosphere [6]. Further, the retrieval of aerosol optical depth (AOD) requires accurate inputs of both TOA reflectance and LSRF data in the deep blue method for air quality management and public health assessment within complex urban environments. Multisensor data merging and data fusion can be used to derive these surface reflectance data at the TOA and land surface levels with improved spatial coverage (i.e., less data voids) and temporal resolution (i.e., more frequent pixel values) [7]. Such advancement can not only avoid the physical disadvantages [8] but also help improve the predictions of reflectance data at a finer spatiotemporal resolution for high-level applications.

## VIII. DATA FUSION FOR INTELLIGENT CROWD MONITORING AND MANAGEMENT SYSTEMS

Intelligent Crowd Monitoring and Management Systems (ICMMS) have become indispensable tools for bolstering safety and security, as well as enhancing early-warning capabilities for emergencies in crowded smart cities and large-scale events. These systems excel in detecting multiple features associated with crowd gatherings, leveraging multisource sensors, multi-modal data, and intelligent analytical methods. Unlike traditional crowd monitoring systems that rely on simplex forms of data types, ICMMSs enable the collection, fusion, processing, and analysis of large quantities of data and information for accurate global assessment and improved decision-making processes. Data fusion plays a pivotal role by reducing data quantity, enhancing data quality, and decreasing data dimensions. This paper conducts a comprehensive survey of the literature on data fusion applications in crowd monitoring systems, presenting state-of-the-art data fusion architectures and classifications from various perspectives. The proposed ICMMS architecture is designed to be multi-sensor, multi-modal, and dimensional, emphasizing the importance of data fusion. The data fusion processes within ICMMS are categorized into sensor fusion, feature-based data fusion, and decision fusion. Each category is elaborated with relevant algorithms, applications, and examples. The advancements in sensor technology, communication technology, and big data science have paved the way for smart city-oriented intelligent applications that enhance human life. As urban business zones and large events attract crowds, the potential for safety hazards and crowd management challenges increases. Crowd monitoring becomes crucial to ensure safety and enable timely emergency response measures. Crowd monitoring technology aims to acquire essential information such as crowd density and the number of people in specific areas, broadcasting videos to fixed-loop devices for efficient management. In conclusion, the paper discusses future research directions in data fusion for crowd monitoring, acknowledging the evolving landscape of technology and the ongoing need for innovative solutions in ensuring safety and security in crowded urban environments and large-scale events.

## XI. A NOVEL HYBRID FUSION ALGORITHM FOR LOW-COST GPS/INS INTEGRATED NAVIGATION SYSTEM DURING GPS OUTAGES

It is the main challenge for Global Positioning System (GPS)/Inertial Navigation System (INS) to achieve reliable and low-cost positioning solutions during GPS outages. A new GPS/INS hybrid method is proposed to bridge GPS outages. Firstly, a data pre-processing algorithm based on empirical mode decomposition (EMD) for wavelet de-noising is developed to reduce the uncertain noise of IMU raw measurements and provide accurate information for subsequent GPS/INS data fusion and training samples. Then, the interactive multi-model extended Kalman filter(IMMEKF) algorithm is proposed to improve the robustness of Kalman filter output and the accuracy of model training target output. Finally, a new intelligent structure of GPS/INS based on Extreme Learning Machine (ELM) is proposed. When the GPS is available, the IMM-EKF is used to fuse the GPS and de-noised INS data, and the denoised INS data and the outputs of IMM-EKF are used to train the ELM. During GPS outages, the ELM is used to predict and correct the INS position error. In order to evaluate the effectiveness of the proposed method, 3 tests were performed in the actual field test. The comparison results show that the proposed fusion method can significantly improve the accuracy and reliability of positioning during GPS outages. Global Positioning System (GPS) and Inertial Navigation System (INS) are the two most commonly used positioning systems today [1]. GPS can provide accurate position and velocity information when it has direct line of sight with at least four satellites [2]. However, it is unstable due to the number of accessible satellites, multipath effects and external environment [3]. INS uses three accelerometers and three gyroscopes to provide dynamic measurements of high-frequency updates in a short period of time, but due to drift effects, measurement errors will accumulate [4]. In order to combine the advantages and make up for those shortcoming s, GPS/INS integrated navigation has been widely used in dynamic navigation and positioning [5]. In general, GPS/INS integrated navigation uses a Kalman filter (KF) for information fusion [6]. GPS measurement signals can be optimally estimated for inertial navigation system errors and feed back to the inertial navigation system for error correction. Extended Kalman Filter (EKF), as an extension of KF, has been widely used in GPS and INS integration to provide a robust navigation solution [7]. However, the Kalman filtering algorithm requires that the process noise covariance and the measurement noise covariance are accurately known in prior knowledge [8]. Inaccurate knowledge of process noise and measurement noise will result in the reduction of positioning performance [9]. In the actual environment, GPS signal is easily blocked, so the GPS cannot output the measurement information, and the filtering method will be ineffective. The error of the inertial navigation system will accumulate over time, which will cause the navigation information to diverge. For high-grade INS, accurate positioning information can also be output independently during GPS outages.

## X. A MULTI-SENSOR INFORMATION FUSION METHOD BASED ON FACTOR GRAPH FOR INTEGRATED NAVIGATION SYSTEM

In autonomous mobile robotic applications, such as unmanned vehicles, navigation systems heavily rely on various sensors to ensure accurate navigation results. The challenge lies in efficiently fusing information from these diverse sensors, which often provide asynchronous and sometimes nonlinear measurements. Additionally, certain sensors may be susceptible to vulnerabilities in specific environments, for instance, GPS signals can be unreliable in interior spaces, underground, or near tall buildings. To address these challenges, we propose a multi-sensor information fusion method based on a factor graph. This approach efficiently fuses asynchronous sensor information and calculates a navigation solution accurately. The factor graph framework treats sensor measurements as factor nodes and navigation states as variable nodes, enabling the update of states within the factor graph framework. Experimental validation using two different datasets demonstrates the effectiveness of the proposed method. A comparison with the widely used Federated Filter in integrated navigation systems further highlights the efficiency of the proposed approach. Moreover, an analysis of navigation results under data loss scenarios confirms the method's capability for sensor plug-and-play in software. Autonomous mobile robotic systems play a crucial role in various fields, demanding accurate and reliable navigation solutions. While earlier systems heavily relied on inertial measurement units (IMUs), modern systems integrate multiple sensors to enhance accuracy. However, the asynchronism and nonlinearity of sensor measurements pose challenges to efficient information fusion. Classical Kalman Filter (KF) and its extensions, such as Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF), were developed for linear and nonlinear systems. However, as the number of sensors increases, centralized filters can lead to computational burdens and poor fault tolerance. Recent efforts aim to enhance KF performance in navigation systems, including robust GPS navigation algorithms and unconventional multi-sensor integration strategies based on kinematic trajectory models.

## CONCLUSION

The highlighted papers showcase cutting-edge advancements in autonomous navigation, underwater positioning, satellite systems, remote sensing image processing, multi-sensor data fusion, and crowd monitoring systems. Each contribution addresses specific challenges and introduces innovative methodologies, significantly contributing to the progress of their respective fields.One paper introduces a deep reinforcement learning approach for UGV navigation, emphasizing the separation of perception from control and leveraging multi-modal perception. Trained in simulation, the system shows promise in navigating real-world environments with dynamic obstacles.Another paper focuses on underwater positioning, combining SINS and LBL algorithms to address challenges posed by underwater sound velocity variations, enhancing the accuracy of AUV navigation, especially in challenging underwater environments.A comprehensive survey on PNT through LEO satellites sheds light on the current status, challenges, and potential applications across various domains. The exploration of LEO satellites for communication and Earth observation is highlighted.The development of a Multi-Source Information Fusion Network for optical remote sensing image super-resolution is presented, enhancing the performance of super-resolution algorithms and contributing to improved image reconstruction in remote sensing applications.A review of multi-sensor fusion approaches in connected driving scenarios emphasizes the importance of complementary sensor fusion in intelligent transportation systems. The study evaluates the performance of the Labeled Multi-Bernoulli filter and information-theoretic approaches. Addressing the challenge of providing reliable navigation during GPS outages for lunar exploration missions, a proposed hybrid fusion algorithm combines GPS and INS data to demonstrate improved accuracy and reliability in positioning during GPS outages.A comparison of data merging and fusion algorithms for high-resolution surface reflectance data evaluates the performance of algorithms such as MQQA, BME, and STARFM in improving spatial and temporal resolution.Exploring data fusion in intelligent crowd monitoring and management systems, a presented multi-sensor, multi-modal architecture based on data fusion enhances the accuracy of global assessment and decision-making processes in crowded scenarios.A novel hybrid fusion algorithm for low-cost GPS/INS integrated navigation systems during GPS outages is introduced. The algorithm utilizes EMD, IMMEKF, and ELM to enhance positioning accuracy during GPS outages.Lastly, a multi-sensor information fusion method based on factor graphs for integrated navigation systems efficiently fuses asynchronous sensor information using a factor graph framework, demonstrating effectiveness and flexibility across different datasets.

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