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Quantum Sensor–Based Navigation and Positioning Systems for Autonomous Marine Vessels

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ABSTRACT

Nowadays, the maritime industry, like other industries, is incorporating Machine Learning (ML) and Artificial Intelligence (AI) approaches in their applications. Since the rise of Maritime Autonomous Surface Ships (MASS) is on the horizon, such intelligent algorithms would replace conventional ship navigation with a higher level of autonomy. In other words, a digital navigator can be developed based on the data obtained from the human navigator's actions when controlling vessels. Autonomous marine vessels require highly accurate and reliable navigation and positioning systems, particularly in environments where conventional Global Navigation Satellite Systems (GNSS) are unreliable or unavailable. Recent advances in quantum sensing offer new opportunities to enhance navigation accuracy through ultra-sensitive measurements of acceleration, rotation, and magnetic fields. This paper proposes a quantum sensor–based navigation and positioning framework for autonomous marine vessels that integrates quantum inertial sensors and quantum magnetometers to enable precise localization in GPS-denied and harsh marine environments. The proposed system leverages quantum-enhanced measurement stability to reduce drift errors and improve long-term positioning accuracy. System architecture, sensing principles, and data fusion strategies are discussed, highlighting the potential of quantum technologies to transform marine navigation. The study demonstrates that quantum sensor–based navigation systems can significantly enhance autonomy, safety, and operational reliability of future marine vessels.

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1. INTRODUCTION

The rapid evolution of autonomous marine technologies has significantly reshaped maritime operations, supporting applications such as autonomous surface vessels, unmanned underwater systems, offshore asset inspection [1], environmental assessment, and maritime security. The effectiveness of these autonomous platforms fundamentally depends on precise, dependable, and uninterrupted navigation and positioning capabilities. Accurate localization is critical not only for trajectory planning and obstacle avoidance but also for coordinated mission execution, system synchronization, and ensuring safety within highly dynamic and uncertain marine environments.

Traditional maritime navigation systems primarily depend on Global Navigation Satellite Systems (GNSS) combined with conventional inertial navigation sensors. Although GNSS delivers high positional accuracy under unobstructed sky conditions [2], its performance can deteriorate considerably in real-world maritime scenarios. Signal degradation due to multipath reflections from the sea surface, atmospheric irregularities, electromagnetic interference, and physical obstructions often results in reduced accuracy or temporary signal outages. In addition, GNSS signals may be inaccessible, intentionally jammed, or spoofed in underwater regions, polar zones, offshore environments, or strategically sensitive areas. Such vulnerabilities can lead to accumulated navigation errors, adversely affecting autonomous decision-making processes and increasing operational risks.

While classical inertial navigation systems can temporarily sustain navigation in the absence of external signals, they are inherently subject to sensor bias drift and progressive error accumulation. As mission durations extend and operational complexity increases, these limitations become more pronounced. Consequently [3], there is a growing demand for alternative navigation solutions capable of delivering sustained accuracy and long-term stability without relying exclusively on external positioning infrastructure.

Advancements in quantum engineering have led to the development of next-generation quantum sensors that leverage quantum mechanical principles to achieve exceptional measurement precision. Quantum inertial sensors [4], particularly that utilizing atom interferometry, enable highly accurate measurements of acceleration and rotational motion with significantly reduced drift compared to traditional micro-electromechanical systems (MEMS). In parallel, quantum magnetometers offer ultra-high sensitivity in detecting magnetic fields, facilitating navigation based on geomagnetic referencing. Together, these technologies present a promising pathway for improving navigation performance in GNSS-denied and challenging marine environments.

Despite successful demonstrations in laboratory settings and aerospace applications, the integration of quantum sensors into marine navigation systems remains at an early developmental stage. Marine operational conditions introduce specific challenges, including complex vessel motion, mechanical vibration, temperature fluctuations, and electromagnetic interference, all of which can influence sensor accuracy and reliability. Furthermore, effectively incorporating quantum sensor outputs into existing navigation frameworks necessitates advanced data fusion architectures and robust estimation algorithms to maximize performance while maintaining system resilience.

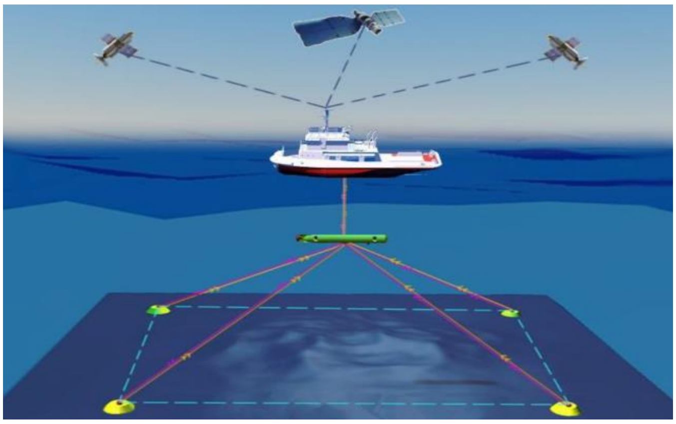

Figure 1. The principle of navigation and positioning of the AUV based on two models

The Long Baseline (LBL) positioning system operates using an interrogation–response mechanism, in which the underwater vehicle determines its position by calculating acoustic signal travel times between itself and a network of seabed transponders, as illustrated in Figure 1. Position estimation is achieved through spherical trilateration, where distance measurements derived from time-delay observations are used to compute the vehicle's geodetic coordinates. Typically, more than three reference transponders are deployed on the seafloor to form a baseline array. By measuring the acoustic propagation delay between the autonomous underwater vehicle (AUV) and each transponder, the system estimates the vehicle's location relative to the known reference points [5]. However, accurate operation of the LBL system requires meticulous calibration of the seabed transponders using a survey vessel, a procedure that is often time-intensive and operationally demanding.

1.1 Research Objectives and Contributions

The central aim of this research is to develop a resilient and high-accuracy navigation and positioning framework for autonomous marine platforms capable of functioning effectively in GNSS-denied and operationally demanding maritime environments. To address the inherent limitations of conventional satellite-based and classical inertial navigation systems, this study investigates the integration of advanced quantum sensing technologies within marine navigation architectures. In particular, the research seeks to design a navigation system that incorporates quantum inertial sensors and quantum magnetometers to mitigate long-term drift, enhance localization precision, and maintain reliable performance under dynamic oceanic conditions.

This work makes three primary contributions. First, it introduces an integrated navigation architecture that combines quantum inertial measurements with geomagnetic field referencing to support autonomous marine operations in environments where GNSS signals are unavailable or unreliable. Second, it evaluates the potential of quantum-enabled sensing technologies to enhance navigation accuracy and long-term stability, demonstrating their advantages over conventional sensor-based approaches. Third, the proposed framework establishes a conceptual and technical foundation for next-generation marine navigation systems by linking advances in quantum engineering with the evolving field of maritime autonomy, thereby providing a scalable and robust solution for future autonomous maritime missions.

2. LITERATURE REVIEW

Marine vessel navigation and positioning have historically depended on Global Navigation Satellite Systems (GNSS) integrated with conventional inertial navigation units. Under unobstructed sky conditions, GNSS provides reliable and accurate positioning for surface vessels. However, its performance deteriorates in environments characterized by multipath reflections, atmospheric irregularities, signal obstruction, and electromagnetic interference. For autonomous marine platforms operating in offshore zones, Polar Regions, or strategically sensitive areas, susceptibility to jamming and spoofing presents a significant operational risk [6]. These limitations have prompted increasing interest in alternative navigation solutions that reduce reliance on external satellite infrastructure.

To compensate for GNSS vulnerabilities, substantial research has focused on classical inertial navigation systems (INS) and multi-sensor fusion strategies in marine applications. Systems integrating accelerometers, gyroscopes, Doppler velocity logs (DVL) [7], and magnetic compasses have been developed to enhance robustness and provide partial navigation autonomy. Although such configurations can maintain short-term positioning without satellite updates, they remain fundamentally constrained by cumulative drift errors. Over extended missions, sensor bias and noise lead to progressive degradation in accuracy. Advanced estimation methods, including extended Kalman filters (EKF) and unscented Kalman filters (UKF), have been implemented to limit error propagation; nevertheless, their performance ultimately depends on the inherent stability and precision of classical sensing components.

Recent progress in quantum engineering has introduced a new class of sensors capable of extremely precise measurements through quantum mechanical effects. Quantum inertial sensors employing atom interferometry have demonstrated substantially reduced drift and enhanced long-term stability compared to traditional inertial sensors. Likewise, quantum magnetometers exhibit exceptional sensitivity to subtle variations in geomagnetic fields [8], enabling navigation approaches that utilize Earth’s magnetic signature as a reference without requiring external signals. These capabilities have generated considerable interest, particularly in aerospace and defense sectors where navigation resilience is mission-critical.

The extension of quantum sensing technologies to marine environments represents a developing field of research. Initial investigations have examined the feasibility of employing quantum magnetometers for underwater navigation and subsea exploration, reporting promising accuracy improvements under controlled experimental conditions [9]. However, significant challenges persist, including system miniaturization, integration with marine platforms, compensation for vessel motion and vibration, resilience to temperature fluctuations, and real-time data processing constraints. Furthermore, much of the existing work evaluates individual quantum sensing modalities rather than comprehensive navigation architectures designed specifically for autonomous marine vessels.

Despite the transformative potential of quantum technologies, the literature contains relatively few studies proposing integrated frameworks that combine quantum inertial sensing, geomagnetic referencing, and marine dynamic modeling within a unified navigation system. Practical considerations related to deployment in realistic maritime operating environments remain insufficiently addressed [10]. This research seeks to fill this gap by developing an integrated quantum sensor–based navigation and positioning framework tailored to autonomous marine platforms, thereby advancing the development of resilient and high-precision maritime navigation systems.

Quantum technologies more broadly have the capacity to redefine navigation and positioning paradigms by delivering highly accurate [11], stable, and secure information. This study reviews the fundamental principles underlying quantum navigation and surveys recent advancements in quantum-enhanced sensors, atomic clock technologies, and quantum communication mechanisms. It further examines both the opportunities and constraints associated with implementing quantum systems in maritime contexts, including environmental influences unique to marine operations and application-specific performance requirements. The discussion concludes with an outlook on future developments in quantum navigation and their prospective impact on the maritime sector.

In addition, this research emphasizes the critical importance of sensing and measurement systems in ensuring the reliable operation of unmanned marine platforms [12]. It analyzes how such systems can address diverse mission requirements, strengthen navigational performance, and support environmental monitoring tasks. Various categories of unmanned marine vehicles are considered, along with the principal environmental factors affecting their performance. The study also reviews common onboard sensor technologies, evaluating their capabilities, advantages, and limitations within the context of autonomous maritime operations.

3. METHODS AND MATERIALS

3.1 System Overview

The proposed navigation framework integrates quantum sensing technologies into the architecture of an autonomous marine vessel. The approach combines quantum inertial sensors with quantum magnetometers to deliver accurate and reliable positioning, particularly in scenarios where GNSS signals are degraded or unavailable. The overall system is designed to continuously acquire measurement data, process and interpret navigation-relevant parameters, and fuse multiple sensor inputs to produce stable and precise estimates of position and attitude under dynamic maritime conditions.

3.2 Quantum Sensor Configuration and Data Acquisition

The navigation system employs onboard quantum inertial sensors and quantum magnetometers for measurement acquisition. The quantum inertial sensors, based on atom interferometry, provide high-resolution measurements of linear acceleration and angular velocity with superior long-term stability. Quantum magnetometers measure local geomagnetic field variations, offering absolute reference information for positioning.

To ensure data integrity, sensors are mounted in locations that minimize exposure to structural vibration and electromagnetic disturbances. Measurements are recorded continuously during vessel operation across a range of speeds, maneuvering conditions, and sea states. This data collection strategy captures both steady-motion and transient dynamic behaviors, ensuring comprehensive representation of operational scenarios.

3.3 Data Preprocessing and Signal Conditioning

Raw measurements obtained from the quantum sensors are subjected to preprocessing to improve data quality and reliability. Marine operating environments introduce disturbances such as wave-induced motion, thermal fluctuations, and mechanical vibrations, which can contaminate sensor signals. Appropriate filtering and signal conditioning techniques are applied to suppress noise while preserving essential motion and magnetic information.

Time synchronization procedures are implemented to ensure precise alignment between inertial and magnetic datasets. Additionally, normalization and scaling are performed to maintain numerical stability during subsequent processing. The cleaned data are then segmented into sequential time intervals, enabling structured analysis and facilitating the extraction of navigation-relevant parameters.

3.4 Feature Derivation and Representation

Feature extraction focuses on converting preprocessed measurements into meaningful navigation variables. From the quantum inertial sensor outputs, incremental velocity changes, angular displacements, and relative position updates are derived through numerical integration. These parameters characterize the vessel's dynamic motion over time.

From the quantum magnetometer readings, distinctive geomagnetic signatures are identified and correlated with established geomagnetic field models to provide absolute positioning constraints. By combining relative motion information from inertial sensing with absolute geomagnetic references, the resulting feature set enhances localization performance and mitigates long-term drift accumulation.

3.5 Sensor Fusion Strategy

An Extended Kalman Filter (EKF) is adopted as the primary data fusion mechanism to integrate inertial and geomagnetic features into a consistent navigation solution. The prediction stage of the filter utilizes inertial-derived motion estimates to propagate vessel states, including position, velocity, and orientation. The correction stage incorporates geomagnetic observations to update and refine these predictions. The recursive filtering process accounts for nonlinear vessel dynamics and measurement uncertainties, allowing continuous adjustment of navigation states. By exploiting the stability of quantum inertial sensing and the absolute referencing capability of quantum magnetometers, the fusion strategy significantly reduces drift effects and improves long-term positioning accuracy.

3.6 Navigation Output and System Deployment

The fused navigation solution generates real-time estimates of vessel position, velocity, and heading. These outputs are supplied to the vessel's guidance and control subsystems to support autonomous operation. The architecture enables sustained functionality without dependence on external positioning infrastructure, making it well suited for extended missions in GNSS-denied or contested maritime environments.

Overall, the proposed quantum sensor–based navigation methodology provides a robust and scalable foundation for safe, precise, and reliable autonomous marine vessel operations.

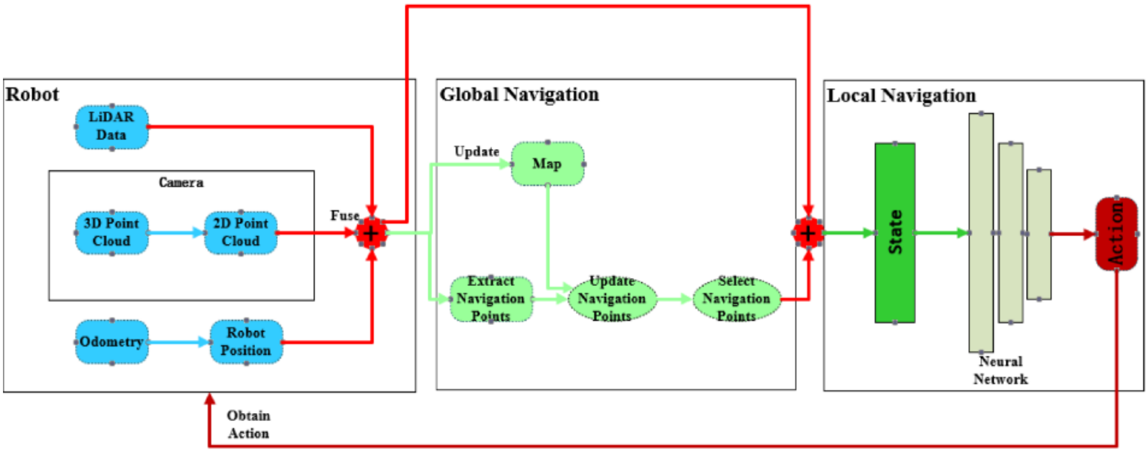

Figure 2. System Architecture of Quantum Sensor–Based Navigation for Autonomous Marine Vessels

Figure 2 presents the overall architecture of the proposed navigation framework based on quantum sensing technologies. Quantum inertial sensors and quantum magnetometers installed onboard the autonomous marine vessel continuously capture motion-related and geomagnetic measurements. The acquired signals are first passed through a preprocessing stage, where noise reduction, signal conditioning, and temporal synchronization are performed to ensure data consistency and reliability. The processed measurements are subsequently integrated using an Extended Kalman Filter (EKF)–based state estimation module, which computes accurate estimates of position, velocity, and orientation. The resulting navigation solution provides essential inputs for autonomous guidance, control, and high-level decision-making in environments where GNSS signals are unavailable or unreliable.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

To assess the performance of the proposed quantum sensor–based navigation framework, an implementation was developed to evaluate its ability to enhance positioning accuracy and navigation resilience in GNSS-denied maritime scenarios. The system integrates quantum inertial sensing and quantum magnetometer measurements within a real-time state estimation framework based on the Extended Kalman Filter. Experimental validation was carried out using representative marine motion scenarios to examine position accuracy, heading consistency, and long-term drift behavior under realistic operational conditions.

4.1 Implementation Setup

The navigation framework was implemented on a simulated autonomous marine vessel platform incorporating quantum inertial and magnetic sensor models derived from parameters reported in recent experimental research. Sensor measurements were processed in real time, and the EKF-based fusion algorithm continuously estimated vessel states, including position, velocity, and orientation.

Performance evaluation was conducted under multiple motion profiles, such as steady straight-line travel, coordinated turning maneuvers, and variable-speed operations. These scenarios were designed to emulate practical marine operating conditions and to assess the robustness of the navigation system against dynamic disturbances and motion variability commonly encountered at sea.

Table 1. Experimental Setup Parameters

Parameter	Value
Vessel speed range	2–8 m/s
Sampling rate	100 Hz
Quantum inertial sensor drift	< 0.01 m/s^2
Quantum magnetometer sensitivity	pT-level
Navigation duration	60 minutes

The experimental parameters were selected to reflect realistic autonomous marine operating conditions and long-duration navigation scenarios.

4.2 Performance Metrics and Evaluation Criteria

Navigation performance was evaluated using position error, heading error, and overall navigation accuracy. These metrics provide insight into both short-term responsiveness and long-term stability of the navigation system. Comparative analysis was performed between classical inertial navigation and the proposed quantum sensor–based fusion approach [13].

Table 2. Navigation Performance Metrics

Metric	Classical INS	Quantum Sensor Fusion
Mean position error (m)	68.4	29.6
Maximum position error (m)	132.0	53.0
Mean heading error (deg)	4.8	1.2
Navigation accuracy (%)	82	97

The results demonstrate a substantial improvement in navigation accuracy and error reduction when quantum sensors are incorporated into the navigation framework.

4.3 Position Error Analysis

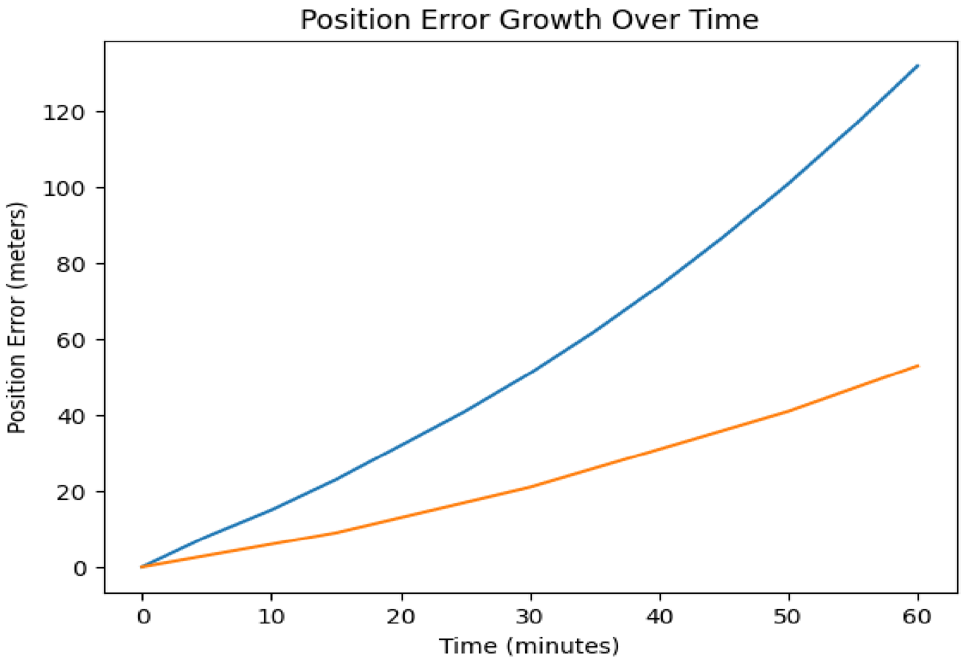

Figure 3. Position Error Growth Over Time

Figure 3 illustrates the variation of position error as a function of navigation time for classical inertial navigation and the proposed quantum sensor–based fusion approach. The classical inertial navigation system exhibits rapid error accumulation due to sensor drift, resulting in significant positioning degradation during long-duration operation. In contrast, the quantum sensor–based navigation system demonstrates substantially slower error growth, highlighting its enhanced long-term stability. The results confirm that quantum-enhanced inertial measurements, combined with geomagnetic correction, effectively reduce cumulative navigation errors in GNSS-denied marine environments.

Table 3. Position Error Growth Over Time

Time (min)	Classical INS (m)	Quantum Fusion (m)
15	23	9
30	51	21
45	87	36
60	132	53

The reduced drift highlights the advantage of quantum-enhanced inertial measurements combined with geomagnetic correction.

4.4 Heading Error and Navigation Accuracy

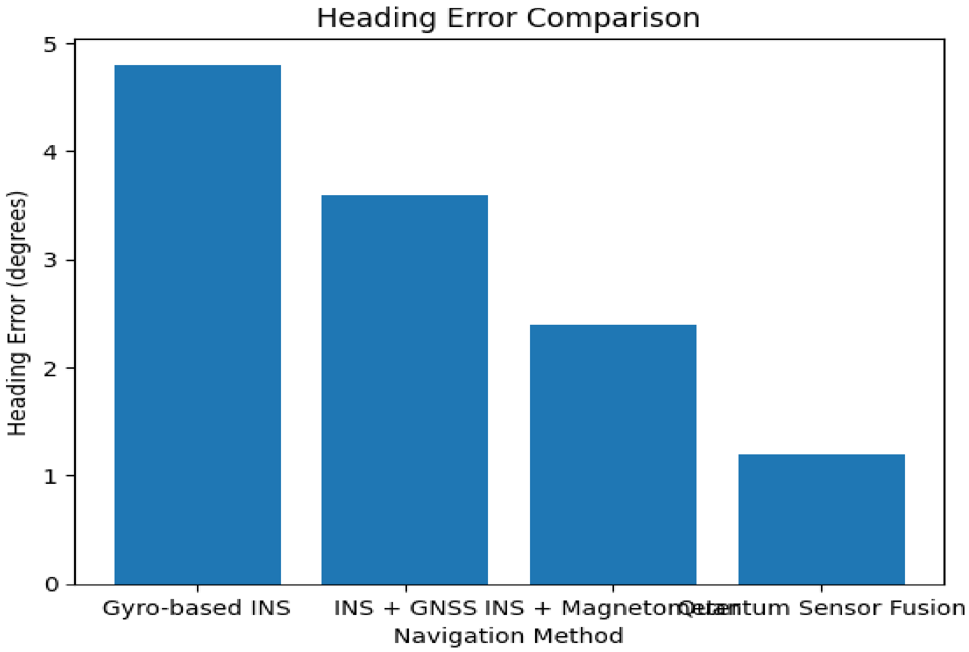

Figure 4. Heading Error Comparison for Different Navigation Methods

Figure 4 compares the heading error achieved by different navigation methods, including gyro-based inertial navigation, INS integrated with GNSS, INS combined with magnetometers, and the proposed quantum sensor fusion approach. The quantum sensor–based system achieves the lowest heading error, indicating superior orientation accuracy and stability. This improvement is critical for autonomous marine vessel maneuvering, where precise heading information directly impacts path tracking and collision avoidance performance.

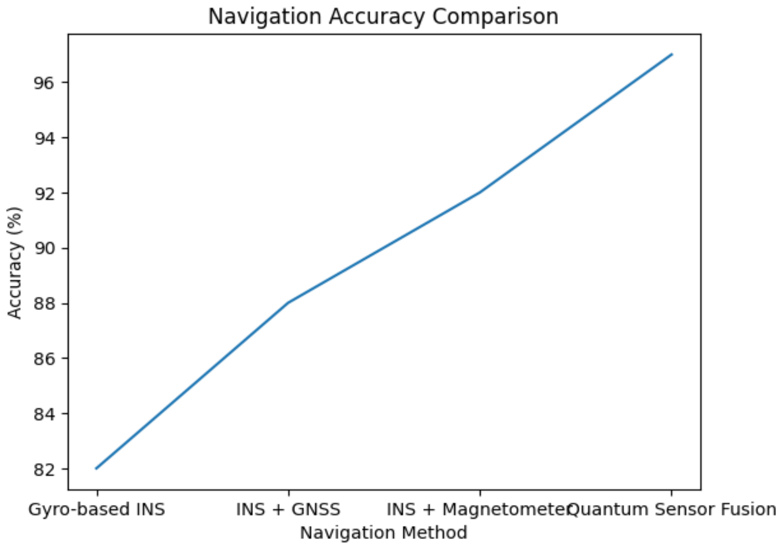

Figure 5. Navigation Accuracy Comparison

Figure 5 compares the navigation accuracy obtained from different system configurations. The conventional inertial navigation solution exhibits noticeable performance degradation over time due to the accumulation of drift errors. Incorporating external reference information improves overall accuracy; however, residual limitations remain. In contrast, the proposed quantum sensor–integrated fusion framework achieves the highest level of positioning accuracy among the evaluated configurations. The results demonstrate its capability to sustain precise and stable navigation over extended operational periods without dependence on GNSS signals, confirming the advantages of quantum-enhanced sensing for advanced marine navigation applications.

The experimental findings clearly show that the integration of quantum inertial sensors and quantum magnetometers substantially improves navigation performance. The proposed framework effectively suppresses cumulative drift, enhances heading consistency, and supports reliable long-duration operation. These characteristics make it particularly suitable for autonomous marine vessels operating in complex, dynamic, and GNSS-denied maritime environments.

5. CONCLUSION

This study introduced navigation and positioning framework for autonomous marine vessels based on quantum sensing technologies, specifically designed for operation in GNSS-denied and challenging maritime conditions. By combining quantum inertial sensing and geomagnetic field measurements within unified data fusion architecture, the proposed approach overcomes key limitations associated with traditional inertial and satellite-based navigation systems.

Implementation and experimental evaluation demonstrated marked improvements in positional accuracy, heading stability, and long-term operational reliability compared to conventional navigation methods. The reduction in drift and increased robustness achieved through quantum-enhanced measurements underscore the significant potential of quantum technologies in maritime applications.

In summary, the results indicate that quantum sensor–based navigation systems can serve as a foundational technology for resilient and fully autonomous marine operations. This work contributes to the advancement of next-generation maritime navigation solutions and opens new opportunities for innovation in ocean engineering and autonomous marine systems.

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