

Inertial Sensor Self-Calibration Module Using Attitude Heading and Reference System for Autonomous Underwater Vehicle Navigation

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(Received: 19 March 2025; Accepted: 17 November 2025; Published online: 12 January 2026)

ABSTRACT: This research addresses the complex task of enhancing navigation accuracy in Autonomous Underwater Vehicles (AUVs), a self-propelled robotic system used for ocean exploration, environmental monitoring, and underwater interventions. A core component of AUV navigation is an Inertial Measurement Unit (IMU), a sensor suite that tracks orientation and motion by measuring accelerations and angular rates. However, the IMU is highly susceptible to noise interference, which degrades accuracy and reliability. To address these challenges, this study introduces an innovative Inertial Sensor Self-Calibration Module that dynamically adjusts calibration parameters in real time, thereby compensating for sensor drift and inaccuracies. The research further conducts a comparative analysis of several calibration and filtering techniques integrated into the AUV's Inertial Navigation System (INS), including Magnetic Calibration, the Extended Kalman Filter (EKF), the EKF with Measurement Noise, the EKF with Process Noise, and the Attitude and Heading Reference System (AHRS) Filter. Among these, the AHRS filter demonstrated superior precision, achieving the lowest average error of 1.06 degrees with a standard deviation of 0.345 degrees in angle measurements, an improvement of up to 97.81% compared to raw data. These findings highlight the effectiveness of the AHRS filter in improving navigation accuracy in complex underwater environments. The insights gained from this research not only deepen the understanding of noise impact and sensor calibration in AUV systems but also pave the way for future innovations in oceanic exploration, environmental monitoring, and underwater interventions.

ABSTRAK: Kajian ini adalah berkenaan menangani tugas kompleks meningkatkan ketepatan navigasi Kenderaan Bawah Air Autonomi (AUV), iaitu sistem robotik berkuasa sendiri digunakan bagi penerokaan lautan, pemantauan alam sekitar, dan intervensi bawah air. Komponen utama navigasi AUV bergantung pada Unit Pengukuran Inersia (IMU), iaitu rangkaian pengesan orientasi dan pergerakan dengan mengukur pecutan dan kadar sudut. Namun, IMU sangat terdedah kepada gangguan bunyi, di mana ianya mengurangkan ketepatan dan kebolehpercayaan. Oleh itu, kajian ini memperkenalkan Modul Kalibrasi Diri Pengesan Inersia yang inovatif, iaitu secara dinamik menyesuaikan parameter kalibrasi pada masa nyata, secara efektif mengimbangi hanyutan sensor dan ketidaktepatan. Kajian ini juga membuat analisis perbandingan beberapa teknik kalibrasi dan penapisan yang diintegrasikan pada Sistem Navigasi Inersia (INS) AUV, termasuk Kalibrasi Magnetik, Penapis Kalman Lanjutan (EKF), EKF dengan Bunyi Pengukuran, EKF dengan Bunyi Proses, dan Penapis Sistem Rujukan Sikap dan Haluan (AHRS). Antara teknik-teknik ini, penapis AHRS menunjukkan ketepatan terbaik, dengan ralat purata terendah iaitu 1.06 darjah dan sisihan piawai pengukuran sudut 0.345 darjah dan peningkatan sehingga 97.81% berbanding data mentah. Penemuan ini menunjukkan keberkesanan penapis AHRS dalam meningkatkan ketepatan navigasi pada persekitaran bawah air yang kompleks. Dapatkan kajian ini bukan sahaja memperdalam pemahaman tentang kesan bunyi dan kalibrasi pengesan dalam sistem

AUV, tetapi turut membuka ruang terhadap inovasi masa depan dalam penerokaan lautan, pemantauan alam sekitar, dan intervensi bawah air.

KEY WORDS: *Autonomous Underwater Vehicle (AUV), Inertial Navigation System (INS), Inertial Measurement Unit (IMU), Attitude Heading and Reference System (AHRS), Extended Kalman Filter (EKF)*

1. INTRODUCTION

The robotics era has reached a point at which the Autonomous Underwater Vehicle (AUV) industry is well established, with thousands of AUVs created and deployed since its inception [1]. Today, the robotics and AUV industries are growing steadily, driven by advances in functionality and reliability [2]. The primary objective of underwater robotics is to develop autonomous, intelligent AUVs capable of decision-making under diverse conditions. To accomplish these goals, several studies have been conducted worldwide, with an emphasis on design, navigation, energy sources, and information systems.

A core component of AUV navigation is an Inertial Measurement Unit (IMU), a sensor suite that tracks orientation and motion by measuring accelerations and angular rates. However, the IMU is highly susceptible to noise interference, which degrades accuracy and reliability. To address these challenges, this study introduces an innovative Inertial Sensor Self-Calibration Module that dynamically adjusts calibration parameters in real time, thereby compensating for sensor drift and inaccuracies. The primary obstacle to the successful operation of the AUV navigation module is maintaining the AUV's position accuracy over extended periods [3-5]. During long missions, strong, prolonged currents and other underwater resistances affect the AUV's motion, thereby decreasing accuracy [6,7]. If the position of the AUV is not analyzed correctly, the accuracy of the AUV's position will degrade over time, and a lack of observation and references from external sources makes AUV navigation impossible.

Most AUV navigation systems use inertial navigation because the Global Positioning System (GPS) cannot function underwater. Some AUVs require acoustic guidance from a mother ship or use underwater acoustic transponders to increase the vehicle's autonomy [8]. To avoid the costly deployment of underwater transponders, the Inertial Sensor Self-Calibration Module is a favorable alternative, and the key sensors typically required are accelerometers, gyroscopes, pressure sensors, and Doppler Velocity Logs (DVLs) [3,9-10].

Persistent sensor drift can undermine the reliability and performance of AUVs, limiting their effectiveness in dynamic underwater environments [11]. In practice, due to their considerable drift and interference with the magnetic field, the sensor readings are prone to error and instability [12]. One of the primary challenges arises from noise in IMU data, which can stem from electronic interference, vibrations, and environmental conditions [13].

Advances in inertial platform technology have reduced their cost to a level that small researchers can now afford. Inertial navigation systems were also available, but not all could afford them. Advances in inertial platform technology have reduced their cost to a level that small researchers can now afford [14].

AUV navigation systems have continued to improve in accuracy over time. In recent years, many researchers have sought to apply GPS technology to their AUVs. GPS technology has contributed significantly to AUV navigation systems due to its precise positioning and navigation capabilities; however, it also has a significant disadvantage: GPS signals cannot reach underwater. The researchers have developed a method to address this drawback [15].

2. METHODOLOGY

2.1. AUV Design Process

The design process for an AUV involves several key phases. The initial phase emphasizes establishing the AUV's foundational framework, encompassing both its electrical and mechanical design elements. This foundational stage serves as the cornerstone of subsequent phases, providing a robust foundation for overall AUV development.

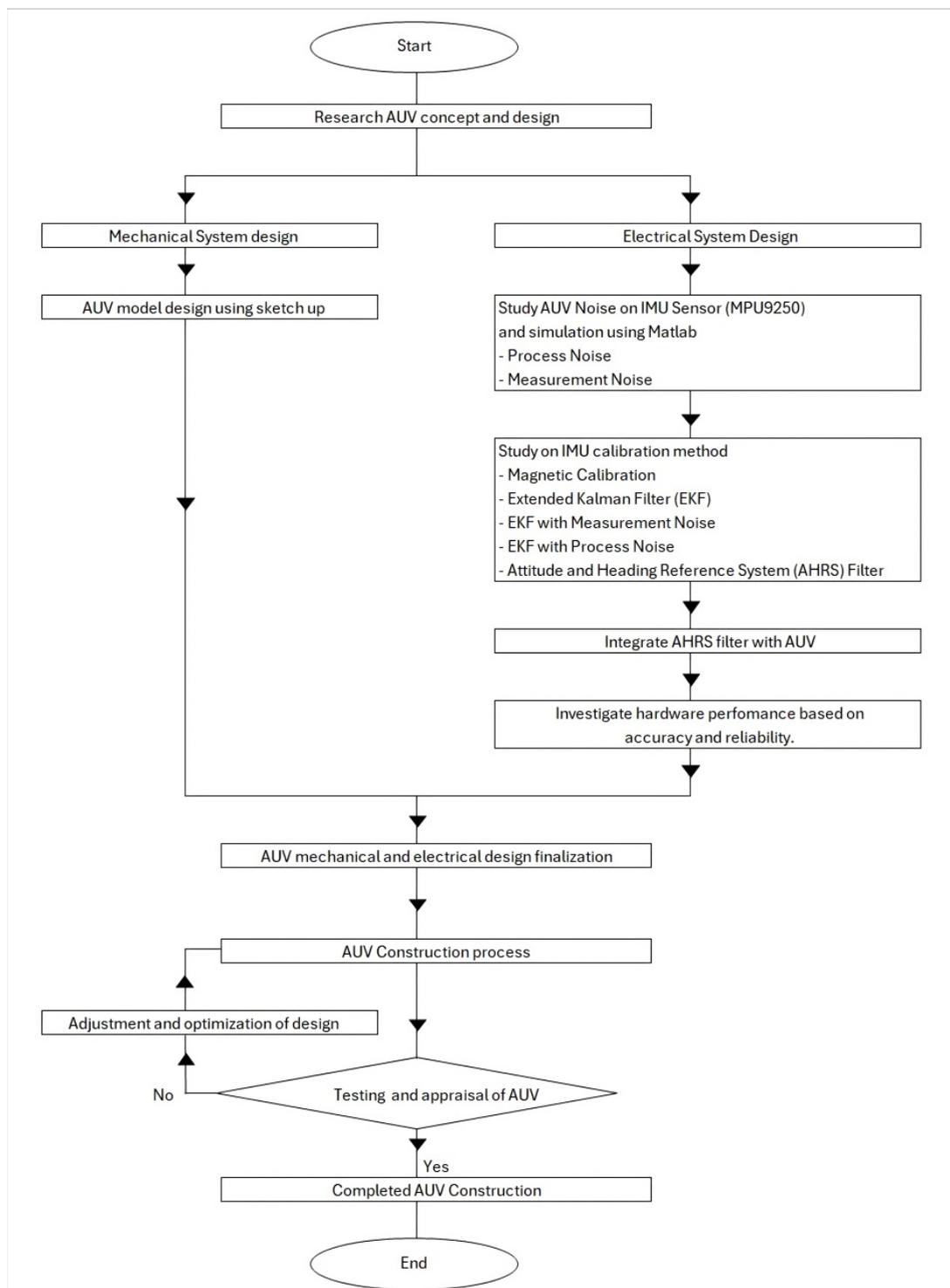


Figure 1. Overall project flowchart.

The subsequent stages can be broadly categorized into two sections, each addressing distinct aspects of the AUV's design. The first section delves into the mechanical design of the AUV. During this phase, Computer-Aided Design (CAD) software is employed to model and animate the AUV's mechanical structure in detail. This software facilitates a detailed visualization of the AUV's physical components, thereby aiding in the refinement and optimization of its structural design.

Simultaneously, the second section of the design process focuses on the electrical and electronic aspects of the AUV. This involves not only the design of electronic components but also the meticulous planning of the wiring layout. Special attention is given to preventing magnetic interference between components to mitigate the risk of sensor errors. This comprehensive approach ensures that the AUV's electrical systems are efficiently integrated and function cohesively.

The final phase of the AUV design process centers on rigorous testing. Once both mechanical and electrical components are installed, the AUV undergoes thorough testing to identify any potential issues or errors. This testing phase is crucial for validating the AUV's overall functionality. Any discrepancies or inefficiencies that arise during testing prompt adjustments, whether major or minor, to correct and refine the AUV's performance.

In summary, the AUV design process follows a systematic approach, beginning with the foundational electrical, electronic, and mechanical design and progressing through detailed modelling, wiring design, and rigorous testing. This methodical process, as illustrated in Figure 1, ensures a comprehensive and well-optimized AUV design that meets the project's objectives, scope, and requirements.

2.2. AUV Design Structure

The AUV design structure will comprise several key design aspects, implemented in SketchUp, a CAD software. These figures provide detailed insight into the overall structure and composition of the AUV, meticulously capturing the designed dimensions, materials used, and the arrangement of various components.

The utilization of SketchUp facilitates a comprehensive representation of the AUV's mechanical design. The software enables modelling and visualization of the AUV's physical structure, providing a detailed depiction of how components and materials interact to form the AUV framework. This visual representation serves as a crucial reference for understanding the spatial organization of mechanical parts within the AUV.

By visually presenting the AUV design through these figures, the CAD software not only aids in conveying the physical structure but also serves as a valuable tool for design evaluation and refinement. Engineers and stakeholders can use these visual representations to assess the feasibility, efficiency, and overall effectiveness of the AUV design before proceeding with construction and assembly.

Notably, Figures 2-4 depict the placement of mechanical components, including the primary and secondary compartments. The main compartment houses critical AUV components, with the mechanical elements arranged to optimize functionality. Simultaneously, the secondary compartment is designed to accommodate various electrical components, thereby illustrating the integration of mechanical and electrical systems within the AUV. Figure 5 shows the completed AUV design structure, based on the initial CAD sketch, with adjustments and optimizations made during AUV construction.

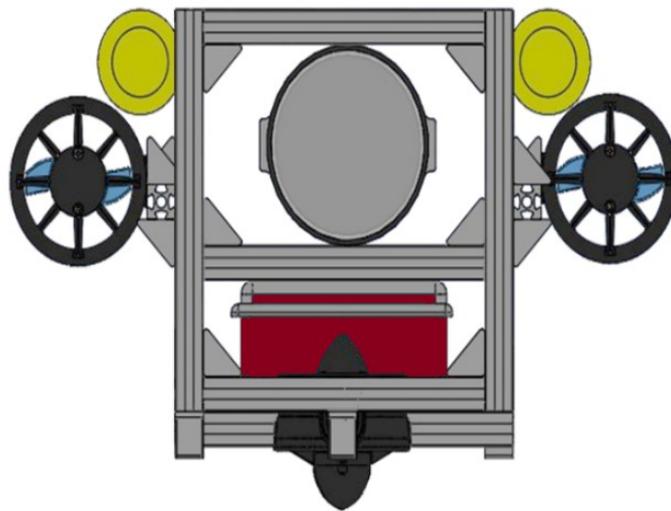


Figure 2. AUV Design Front View

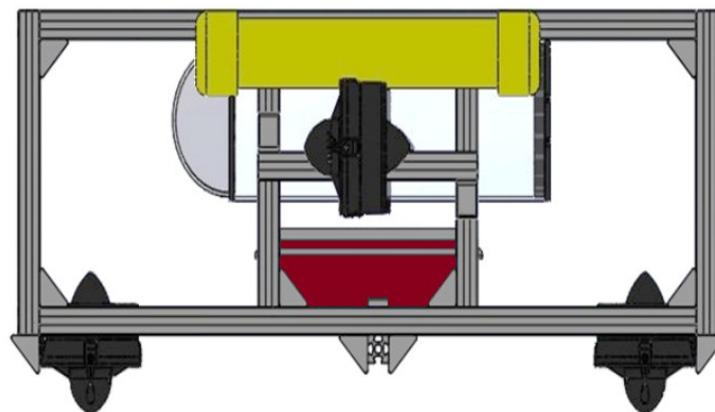


Figure 3. AUV Design Side View

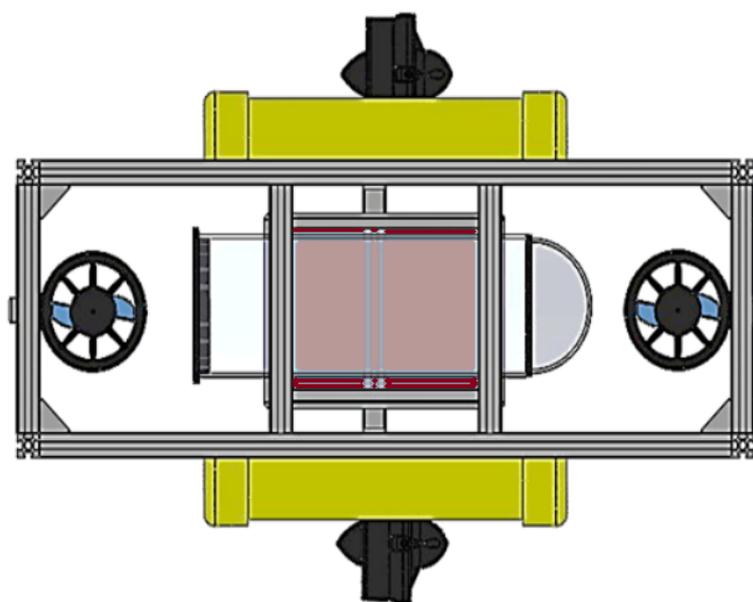


Figure 4. AUV Design Top View

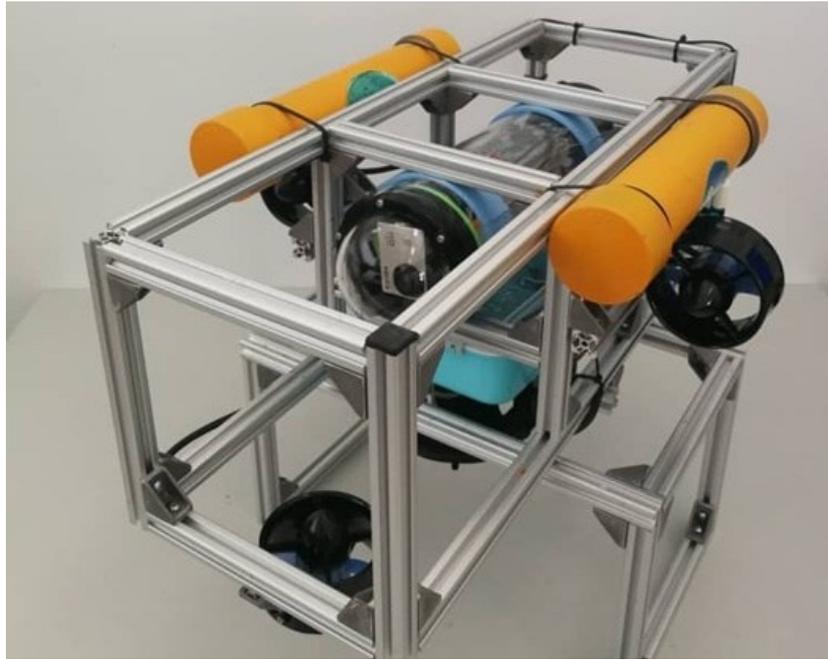


Figure 5. Completed AUV Design

Next, an essential component is to provide detailed insight into the AUV's main electronic system architecture. This serves as a key reference point for understanding the configuration and interconnection of electronic components crucial to the AUV's navigation system.

The core of the AUV's navigation system is prominently integrated into the electronic system architecture, underscoring the IMU's central role. The IMU is a critical component that corrects potential errors in other sensors within the AUV. This correction mechanism is pivotal for ensuring the accuracy and reliability of the AUV's navigation system, particularly in the dynamic and challenging underwater environment.

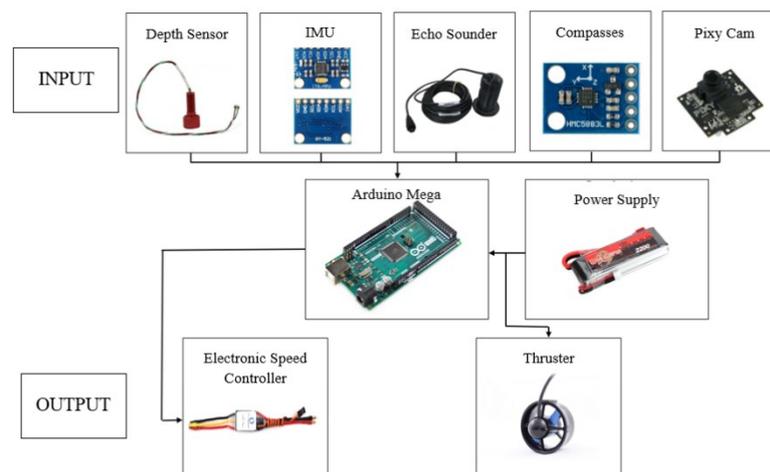


Figure 6. Electrical and Electronic System

By visually representing the electronic system structure, the design provides insight into how electronic components, including sensors and the IMU, are integrated into the overall AUV framework. The explicit depiction of these connections aids engineers and designers in assessing the effectiveness of the electronic system, identifying potential areas for improvement, and ensuring the seamless coordination of electronic components for precise

navigation. Figure 6 serves as a valuable visual reference for understanding the electrical and electronic architecture of the AUV, highlighting the IMU's pivotal role in enhancing the accuracy and reliability of the navigation system.

3. RESULTS AND DISCUSSION

3.1. AUV IMU Filters Performance Analysis Simulation using Matlab

This simulation assessment will focus on the AUV's orientation readings to analyze and ensure the stability of the AUV's performance during navigation. Filter performance was evaluated through a thorough MATLAB simulation over 140 seconds, yielding 28 data samples at 5-second intervals. The yaw, pitch, and roll parameters represent the AUV's rotational motion. Yaw signifies horizontal rotation, pitch indicates vertical inclination, and roll denotes lateral rotation. The samples are selected to ensure stable sampling, as the accelerometer, gyroscope, and magnetometer in the MPU9250 have distinct sampling periods. This meticulous assessment was conducted at angles of 0° , 90° , 180° , and -90° , as shown in Figures 7-10, in a controlled testing environment to evaluate the effectiveness of a range of filter and calibration techniques.

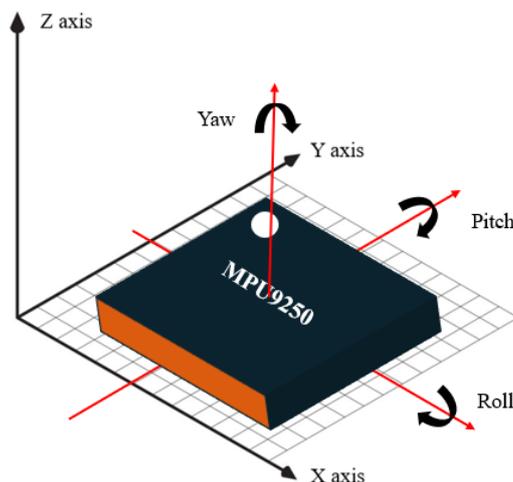


Figure 7. Example IMU orientation at 0° Pitch angles

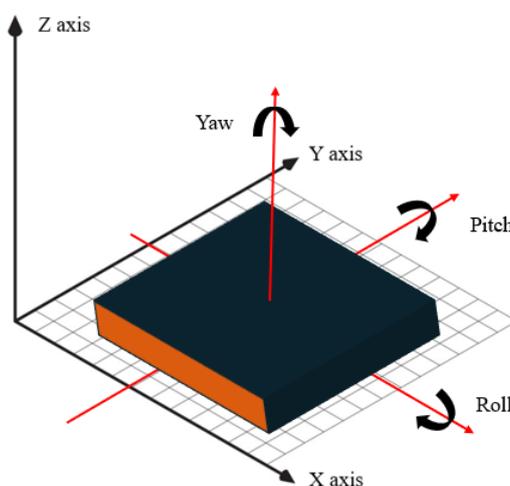


Figure 8. Example IMU orientation at 180° Pitch angles

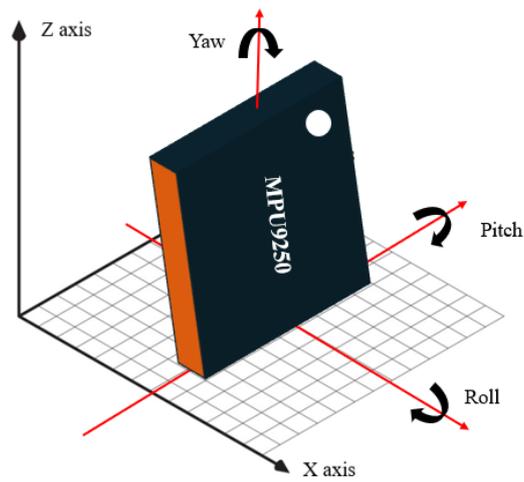


Figure 9. Example IMU orientation at 90° Pitch angles

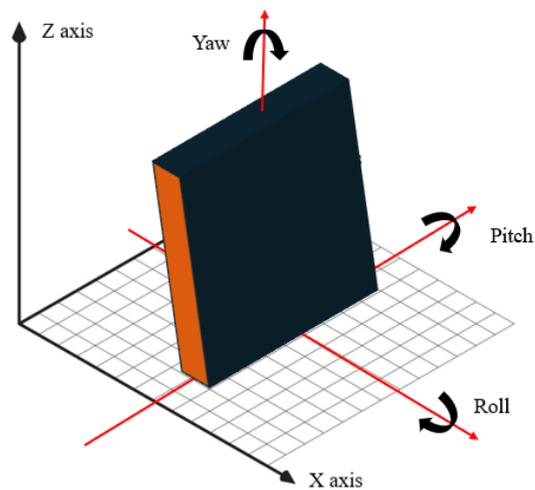


Figure 10. Example IMU orientation at -90° Pitch angles

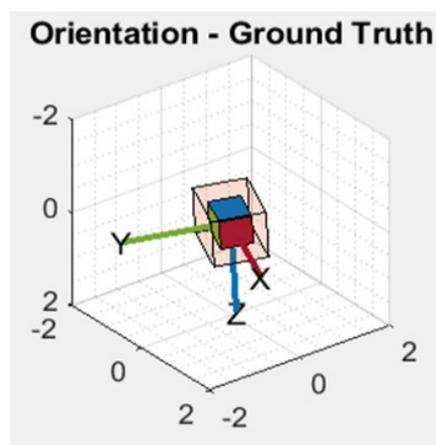


Figure 11. AUV Matlab orientation simulation

Figure 11 illustrates the AUV MATLAB simulation orientation obtained from the orientation assessment, yielding yaw, pitch, and roll readings for the selected angle

orientations, serving as a reference for the accurate depiction of the actual angle measurements. This figure illustrates the orientation under investigation.

3.2. IMU Filters Performance Analysis Simulation at 0° angle

Figures 12 - 17 illustrate yaw, pitch, and roll rotations for 28 data samples. This graph visually portrays orientation dynamics across filter techniques: Raw Data, Magnetic Calibration, EKF, EKF with Measurement Noise, EKF with Process Noise, and AHRS Filter on 0° angle orientation to verify each filter's efficiency. Notably, the visual representation indicates that the AHRS Filter yields the most favorable outcomes, enhancing orientation accuracy. These graphs are further analyzed using tabular methods to determine the maximum, minimum, mean, and standard deviation for each filter.

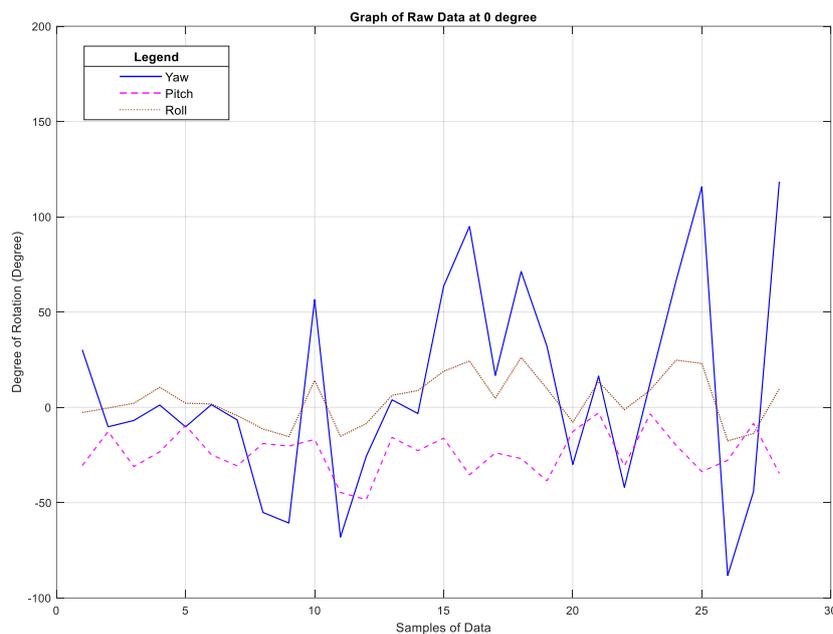


Figure 12. Graph of raw data at 0° angle.

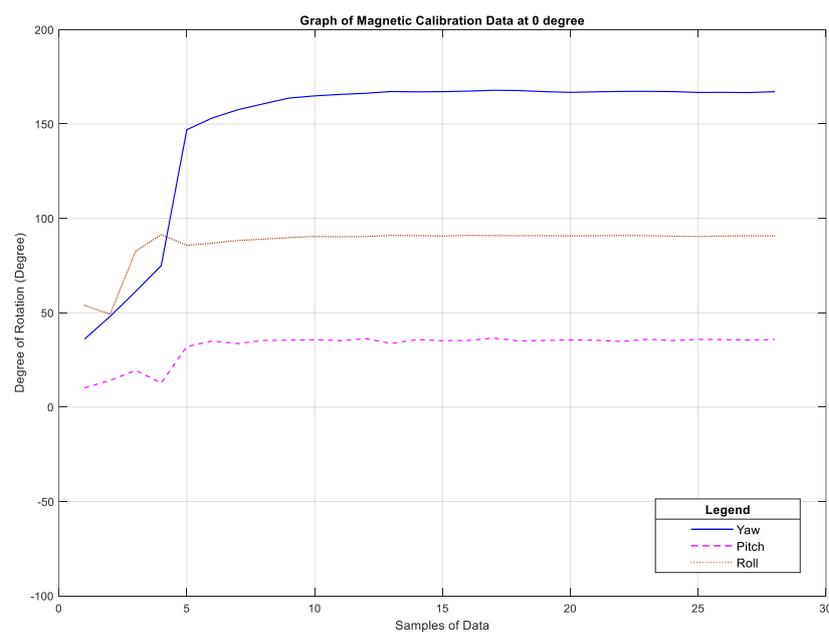


Figure 13. Graph of magnetic calibration data at 0° angle.

Figure 13 shows a graph of magnetic calibration data at 0° , which yields reduced fluctuations relative to the raw data but still exhibits visible noise. This approach improves orientation accuracy by correcting magnetic field distortions. However, it remains limited in dynamic situations characterized by noise and drift, necessitating advanced filtering techniques to further improve performance.

Figure 14 shows EKF filter data at 0° , which outperforms magnetic calibration in terms of stability and accuracy. Anticipating and correcting sensor data using a mathematical model successfully lowers noise and drift. However, occasional departures indicate difficulties in managing complex underwater dynamics without additional noise compensation.

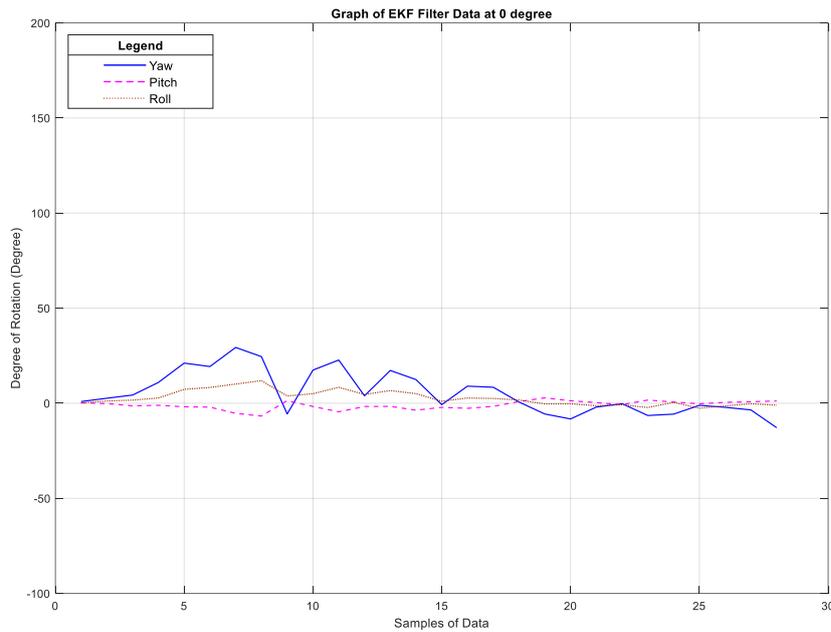


Figure 14. Graph of EKF filter data at 0° angle.

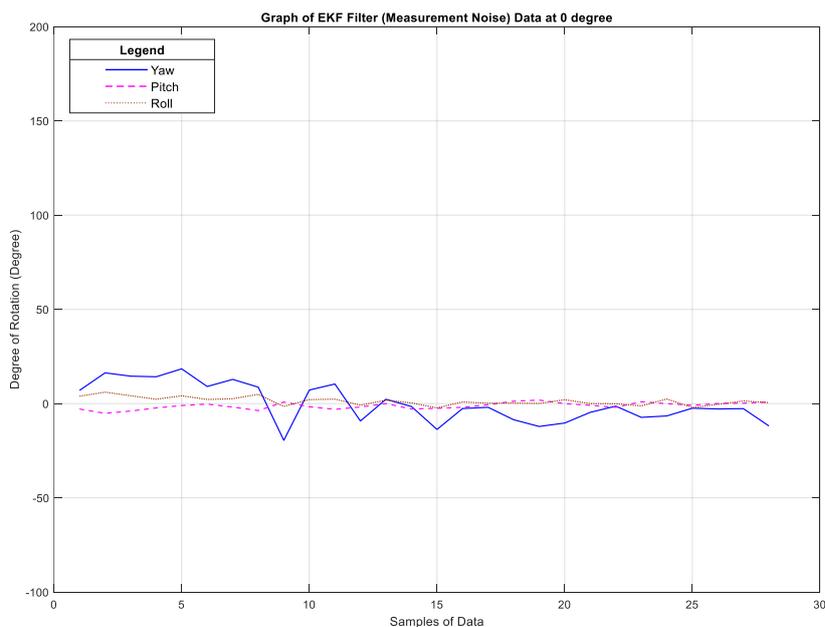


Figure 15. Graph of EKF filter with measurement noise data at 0° angle.

Figure 15 shows a graph of the EKF filter with measurement noise at an angle of 0° , which is more refined than the standard EKF. By explicitly accounting for measurement noise, orientation calculations become more consistent and accurate. While successful, it nevertheless shows significant variability, particularly in demanding situations, indicating limitations in noise adaptation.

Figure 16 shows a graph of the EKF filter with process noise data at 0 degrees, demonstrating improved performance by resolving uncertainties in the AUV's motion model. This approach produces smoother orientation estimations than the EKF with measurement noise, but slight inconsistencies indicate an opportunity for improvement in highly dynamic or noisy situations.

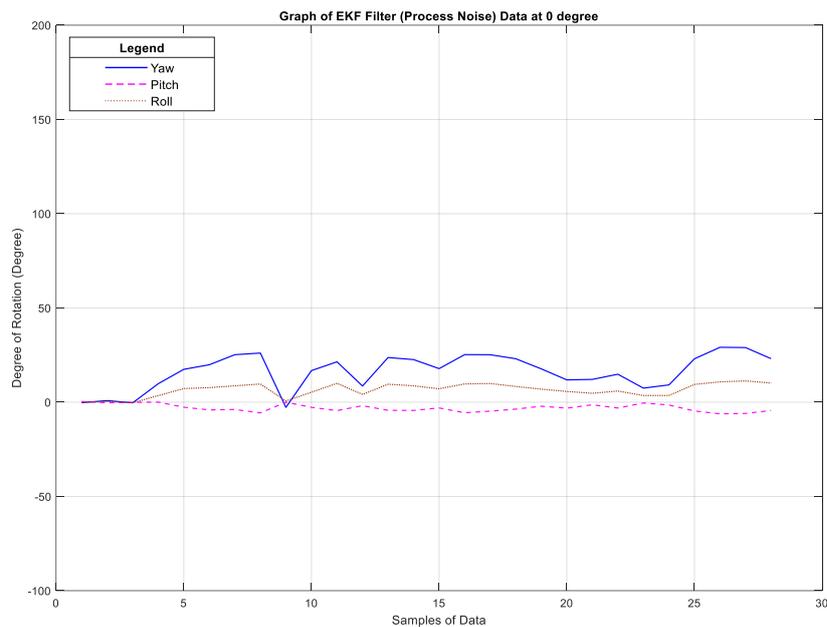


Figure 16. Graph of EKF Filter with Process Noise Data at 0 Degrees.

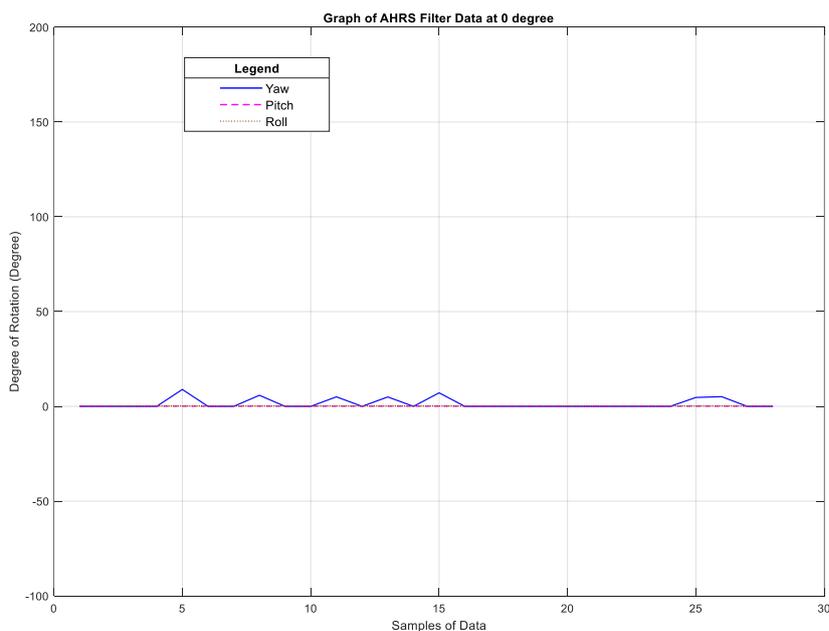


Figure 17. Graph of AHRS Filter data at 0° angle.

Figure 17 shows an AHRS filter data plot at 0 degrees, exhibiting excellent stability and precision with minimal variation. This filter integrates multiple sensor inputs and dynamically adapts to changes, thereby mitigating noise and drift. Its high performance makes it well-suited for accurate orientation tracking in challenging underwater conditions.

Based on Table 1, the comprehensive evaluation of orientation data at 0 degrees using various filters and calibration techniques has provided valuable insights into their respective performance. The results indicate distinct characteristics for each method, which can significantly impact orientation accuracy and stability.

Table 1. Comparison of the analyzed filter performance at 0 Degrees.

	Raw Data	Magnetic Calibration	EKF Filter	EKF Filter (Measure. Noise)	EKF Filter (Process Noise)	AHRS Filter
Max	118.45	167.85	29.33	18.44	29.13	8.92
Min	-88.30	10.20	-12.85	-19.48	-6.17	0.00
Mean	-3.62	89.47	2.35	0.07	6.61	0.60
Std. Deviation	35.37	53.59	7.42	6.13	9.84	1.68

The Raw Data approach exhibits a wide range of values, with a substantial standard deviation of 35.37 degrees. This underscores the inherent noise and variability present in unfiltered measurements.

The Magnetic Calibration demonstrates notable deterioration, with a larger standard deviation of 53.59° and a less concentrated distribution of values. The EKF demonstrates further refinement, with a significantly lower standard deviation of 7.42° in the angle. The filtering process reduces noise and bias, thereby improving orientation estimates.

The application of the EKF with both measurement and process noise highlights the importance of noise modelling. The former achieves a minimal standard deviation of 6.13° in angle, whereas the latter exhibits a larger standard deviation of 9.84 °.

Remarkably, the AHRS Filter demonstrates exceptional precision, with a standard deviation of only 1.68 degrees. This technique significantly reduces noise, bias, and other sources of error, providing the most reliable orientation estimates.

4. CONCLUSION

The study on the impact of noise on the IMU sensor module revealed that environmental and operational noise significantly affect the accuracy and stability of sensor data. This underscores the need to incorporate effective noise-mitigation strategies to enhance the reliability of IMU data in underwater environments. Next, the development of a self-calibrated module for orientation estimation was a pivotal advancement.

This module was designed to continuously adjust its calibration parameters based on real-time data, effectively compensating for drift and sensor inaccuracies. The implementation of this self-calibration capability resulted in substantial improvements in orientation accuracy, thereby contributing to more stable and reliable AUV navigation. Comparison of various filtering techniques integrated into the INS demonstrated distinct differences in their ability to manage sensor noise and improve navigation accuracy.

To enhance AUV navigation, this study explored the crucial module of Inertial Sensor Self-Calibration. By meticulously investigating angle measurements, particularly those derived

from raw data and an AHRS filter, significant insights were gained into the potential of self-calibration techniques for AUV navigation.

The analysis began by establishing a baseline through the examination of raw data, thereby revealing the initial state of the measurements before calibration. Subsequently, the AHRS filter emerged as a standout performer, exhibiting the lowest standard deviation and variance. This finding underscored the AHRS filter's capacity to enhance the accuracy of angle measurements, a pivotal factor for ensuring dependable navigation for AUVs operating in complex underwater environments.

The AHRS filter's exceptional performance supports its utility in addressing the inherent challenges of underwater navigation, where precision is paramount. As AUVs continue to evolve and diversify in their applications, the insights gained from this study can serve as a cornerstone for further advancements. By harnessing the potential of self-calibration modules such as the AHRS filter, new avenues for oceanic exploration, environmental monitoring, and underwater interventions are enabled.

ACKNOWLEDGEMENT

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through MDR (vot Q693) and GPPS (vot Q647).

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