EVALUATION OF AUTONOMOUS NAVIGATION AND PATH ACCURACY FOR UNMANNED SURFACE VEHICLES USING IMU SENSOR AND GPS DATA

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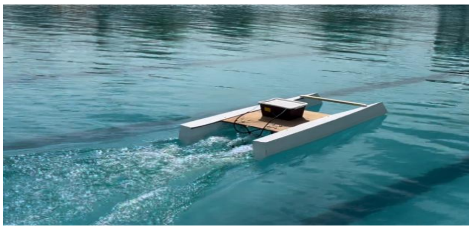
Graphical Abstract



Abstract

The development of autonomous systems for environmental monitoring is becoming increasingly important. This project focuses on creating a robotic marine vessel, Aqua Sense, for efficient water quality monitoring. Existing methods are often labour-intensive, time-consuming, and lack real-time data capability. The objective is to develop a robotic vessel with autonomous navigation for water quality applications. A comprehensive design approach, including a literature review and careful component selection, was employed. Key components include the Arduino Mega, Blue Robotics T200 thruster, GlobalSat BU-353N5 GPS sensor, BNO055 Inertial Measurement Unit (IMU), and a Li-po 11.1v battery. In this paper, several field trials data collection is presented to evaluate the navigation algorithm. These findings validate the feasibility of Aqua Sense for real-world applications. The varying distance errors at points B and C demonstrate an error range, with a maximum error of approximately 1.130m at point B (about 0.11% of the target location) and a significant variation at point C, reaching up to 1.660m (approximately 0.15%).

Keywords

Robotic marine vessel, water quality monitoring, autonomous navigation, environmental monitoring, Aqua Sense, unmanned surface vehicle

Introduction

Ensuring the cleanliness of our water environments is crucial, yet traditional water quality monitoring methods have significant limitations. Static systems struggle to adapt to dynamic aquatic environments, and manual methods pose risks to personnel and are time-consuming. Therefore, there is a critical need for an innovative solution that transcends these limitations. Unmanned surface vehicles (USVs), among other surface vehicles, play an important role in improving marine security [1], search and rescue operations [2], environmental monitoring [3], and disaster response [4]. Unmanned surface vehicles have a complex design since, to perform their assigned jobs, their mechanical parts, sensors, actuators, and navigation algorithms must all work together in unison. A USV has the same mechanical layout as a normal vessel, although it is smaller in size [5]. There are many different kinds of vessel designs; the two most popular ones are the catamaran (dual hull) and monohull designs [6]. When developing testing platforms for research, the catamaran design is a common choice since it offers better stability and cargo capacity than monohull designs [7-8]. In these regions, the usage of USVs reduces the risk to human life while increasing efficiency. Using a mobile water monitoring boat fitted with GPS technology, this system analyses data in real-time, allowing for navigation across different sites and thorough assessments in both essential and non-critical areas. The research community has developed many USVs recently. These systems are made with the specific task at hand in mind during the design process. For example, Seqwater's Autonomous Motorised Monitoring Instrument (SAMMI) is an autonomous device that can monitor water quality without the need for human involvement. This is made possible by sophisticated navigation and control algorithms that let SAMMI navigate across difficult water pathways [9]. Enhancing responsiveness in addressing issues related to water quality, reducing the dangers associated with manual procedures, and making a substantial contribution to the sustainable maintenance of clean water settings are the main goals. By introducing this state-of-the-art technology, the project aims to revolutionize conventional water quality monitoring methods, fostering a more efficient and proactive approach to safeguarding aquatic ecosystems. This work makes significant contributions in the following aspects:

- Development of a prototype robotic marine vessel
- Material selection for prototype development
- Utilization of an embedded system to wirelessly operate and navigate the robotic marine vessel
- Inclusion of GPS functionality for location information

METHODOLOGY

The general parameters of the USV model are detailed in Table 1, providing a clear overview of the vessel's specifications. These specifications confirmed that the vessel met the necessary criteria for military use, ensuring it was suitable for our project's rigorous demands. The overall length of 1.52 meters and a beam of 0.61 meters provided a compact yet stable platform, while the design draft of 0.07 meters and a maximum design speed of 1.50 meters per second highlighted its agility and performance capabilities.

Table 1: General Parameters of the USV Model

Description	Specification
Length overall *	1.52 m
Beam *	0.61 m
Design draft	0.07 m
Maximum design speed	1.50 m/s

To enhance the vessel, we began with surface preparation. Using a sanding machine, we smoothed the hull to remove surface irregularities, old paint, and contaminants. Manual sanding with finer grit sandpaper followed, ensuring an even smoother finish. Masking tape and protective coverings were applied to areas not requiring paint, preventing unwanted coverage. We chose AIKKA pearl white paint for its durability and high-quality finish. Four layers were applied, each with adequate drying time to prevent drips and ensure even coverage as in Figure 1. This meticulous approach to surface preparation and painting was essential in enhancing the vessel's performance and aesthetic appeal.

Figure 1: Process in preparing vessel's surface

Next, we designed and fabricated a motor mount using SolidWorks CAD software, which can be seen in Figure 2. The motor mount consisted of a base plate, support column, and top plate. Detailed technical drawings were created, and a 3D prototype was produced using PLA+ material. This prototype allowed us to inspect and test the motor mount before final fabrication.

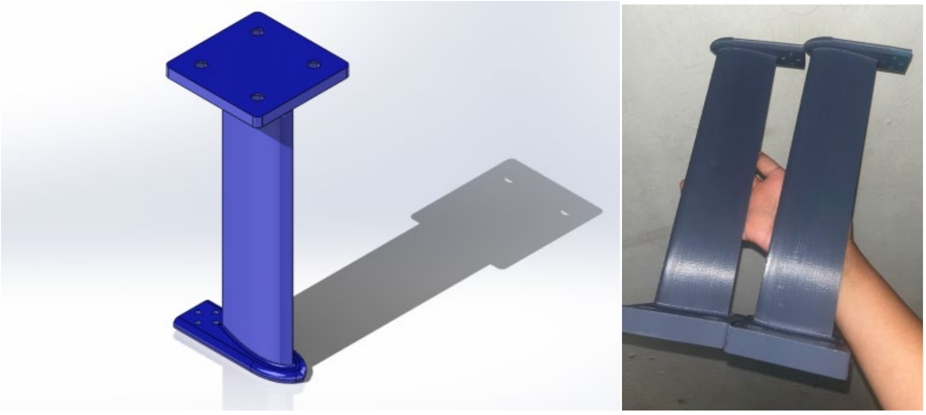


Figure 2: Design of Motor Mount

NAVIGATION CONTROL SYSTEM DESIGN

The USV navigation control system design incorporated various electronic components, including a microcontroller (Arduino Mega), GPS sensor (BU-353N5), IMU sensor (BNO 055), T200 thrusters from Blue Robotics, Speed Controller for thruster (ESC), servos, and a power supply. The system's main components in Figure 3 demonstrate the control system of the robotic marine vessel. The Arduino Mega acted as the central hub, managing data inputs from the GPS and IMU sensor as well as controlling the servos and thrusters.

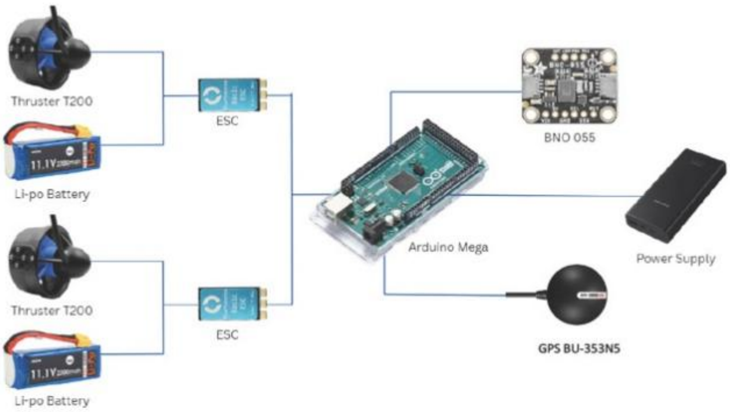


Figure 3: Inputs and outputs of the USV control system

The USV is equipped with a GPS receiver from GlobalSat BU-353N5 as the primary sensor that provides essential geographical location data for navigation along with a BNO-055 inertial measurement unit (IMU). The IMU is responsible for measuring orientation, acceleration, and angular velocity, ensuring the USV stability and proper orientation. It connects to the Arduino with its SDA pin linked to the SDA pin (Pin 20) and the SCL pin to the SCL pin (Pin 21). The IMU's VCC pin connects to the 5V output, and its GND pin to the common ground. Servos, which control the direction and thrust of the T200 thrusters, have their signal wires connected to Digital Pins 6 and 5 on the Arduino for the left and right servos, respectively. These servos draw power from an external 5V source to ensure sufficient current supply, with their ground wires connected to the common ground.

The T200 thrusters are controlled via the Electronic Speed Controller (ESC). The ESC signal wire for the left thruster connects to Digital Pin 6, while the right thruster's ESC signal wire connects to Digital Pin 5. Both ESCs receive power directly from the positive terminal of the battery, with their ground wires connected to the battery's negative terminal, which also links to the Arduino's common ground. This configuration allows the ESCs to effectively control the thrusters based on commands from the Arduino.

GPS calibration is a crucial process that ensures accurate positioning data by aligning the sensor's readings with known reference points. This process involves capturing multiple readings from the GPS sensor at predefined locations and comparing them with accurate coordinates obtained from reliable sources, such as Google Earth. Any discrepancies between the recorded data and the reference coordinates are analysed and used to adjust the sensor settings, compensating for factors such as environmental interference or sensor drift. Effective calibration improves the overall reliability of the GPS, making it suitable for precise navigation and location-based applications. Figure 4 shows the errors in latitude readings are relatively small, ranging from 0.00006% to 0.0212%. Meanwhile, Figure 5 highlights the errors in longitude readings are even smaller, with the maximum error being 0.000193%.

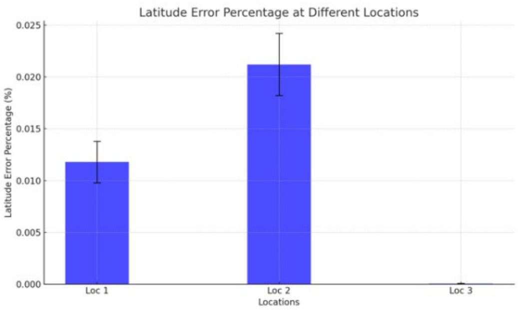


Figure 4: Percentage of error for latitude readings

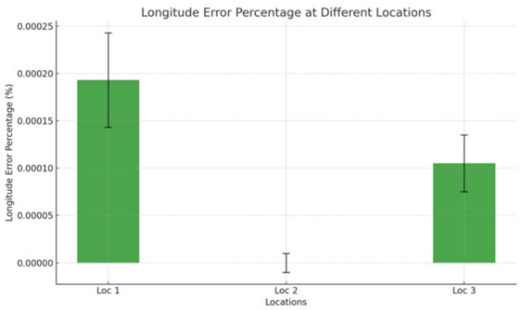


Figure 5: Percentage of error for longitude readings

For accurate navigation and control, we calibrated the Inertial Measurement Unit (IMU) sensor three times. The calibration of the IMU sensor was performed through a series of tests, where the actual angles were compared against the measured angles obtained from the sensor. The tests were conducted at multiple reference points: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. For each reference point, three tests were performed to ensure the reliability and repeatability of the sensor's measurements. The data from the calibration tests were plotted on graphs to visualize the relationship between the test angles (angles measured by the IMU) and the actual angles. Linear regression analysis was applied to determine the calibration equations, which describe how the measured angles relate to the actual angles. Figure 6 illustrates the calibration graph of the IMU sensor.

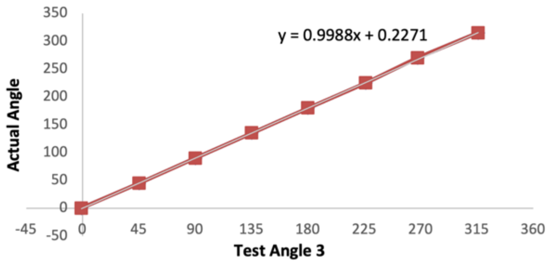


Figure 6: Relationship between the actual angle and the test angle of the IMU sensor

The control system of Aqua Sense integrated an orientation sensor, GPS module, and servo motors. The hardware components were initialized, and sensor data were processed to calculate navigation angles. Based on this data, the vehicle adjusted its heading to stay on course toward predefined GPS coordinates. The navigation logic, outlined in the flowchart in Figure 7, determined the vehicle's movements based on the difference between the current and desired headings, ensuring the vehicle stopped within a target radius.

Results and Discussions

The Aqua Sense prototype is an advanced autonomous marine vessel designed for precise navigation. Extensive testing was done at UTM Swimming Pool as in Figure 8 and Figure 9 to ensure it could accurately reach specific coordinates. In three separate tests, Aqua Sense consistently reached its target points B and C from the starting point A based on Figure 10, demonstrating high navigational accuracy within a 1-meter radius. The tests highlighted Aqua Sense's ability to make course corrections and maintain stability, even when initial paths were irregular.

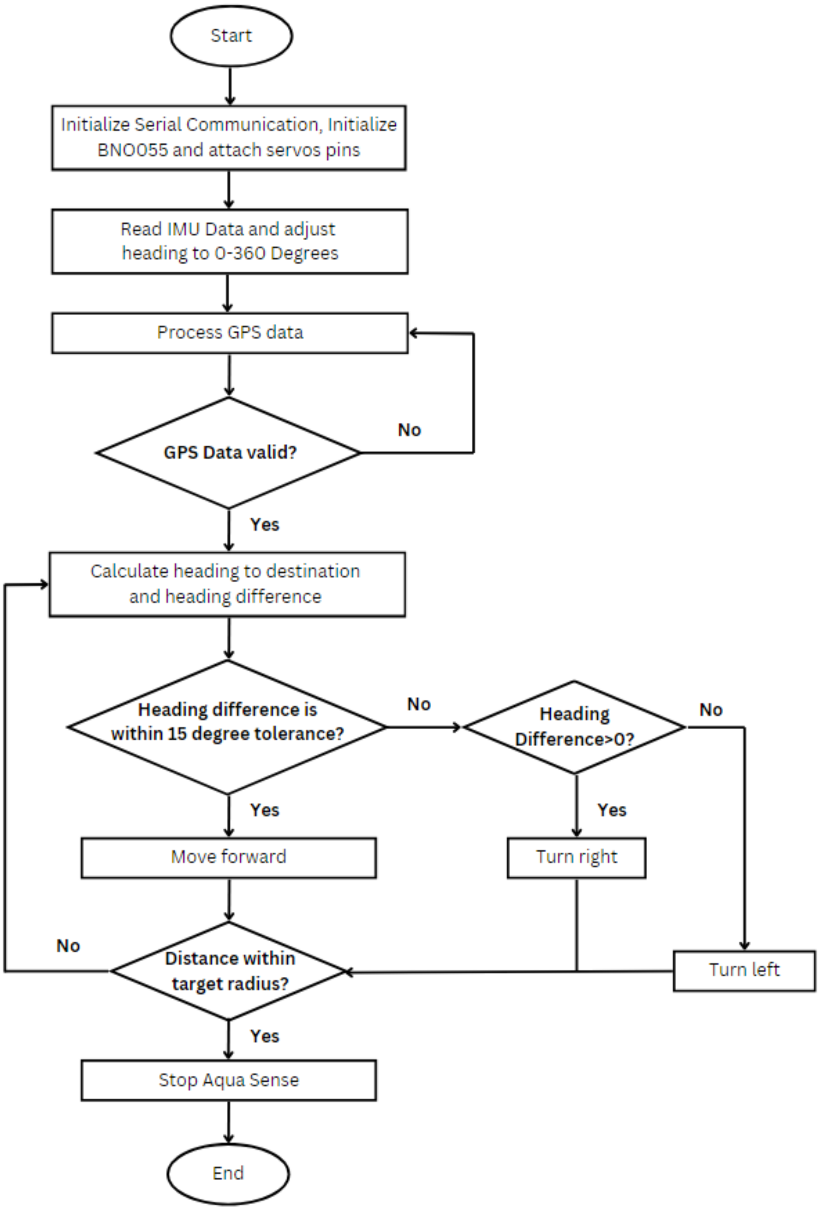


Figure 7: Threshold-based autonomous navigation algorithm

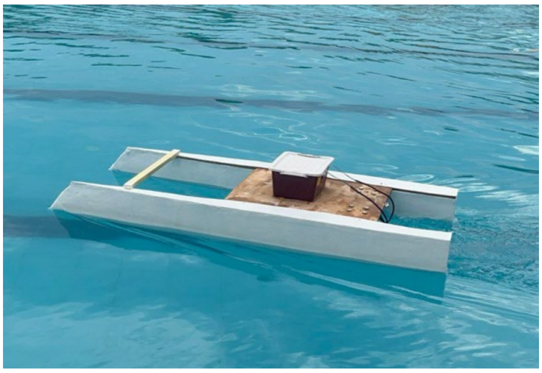


Figure 8: The prototype of Aqua Sense with autonomous navigation control system

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Table 2: Performance of different localization approaches

	Actual location		Real location			Distance Error (m)
Loc.	Latitude	Longitude		Latitude	Longitude	
B	1.55701862 28578300	103.655148 235684	Test 1	1.557001113891600	103.6551055908200	1.124
			Test 2	1.557001113891600	103.6551055908200	1.100
			Test 3	1.557042503356930	103.6551437377920	1.130
			Test 4	1.557001113891600	103.6551055908200	1.120
C	1.55686311 21711800	103.655108 002549	Test 1	1.556858634948730	103.6550903320310	1.030
			Test 2	1.556863784790030	103.6550750732420	1.660
			Test 3	1.556858634948750	103.6550903320340	1.023
			Test 4	1.556858634948730	103.6550903320300	1.010

Figure 9: Aqua Sense testing at UTM Swimming Pool

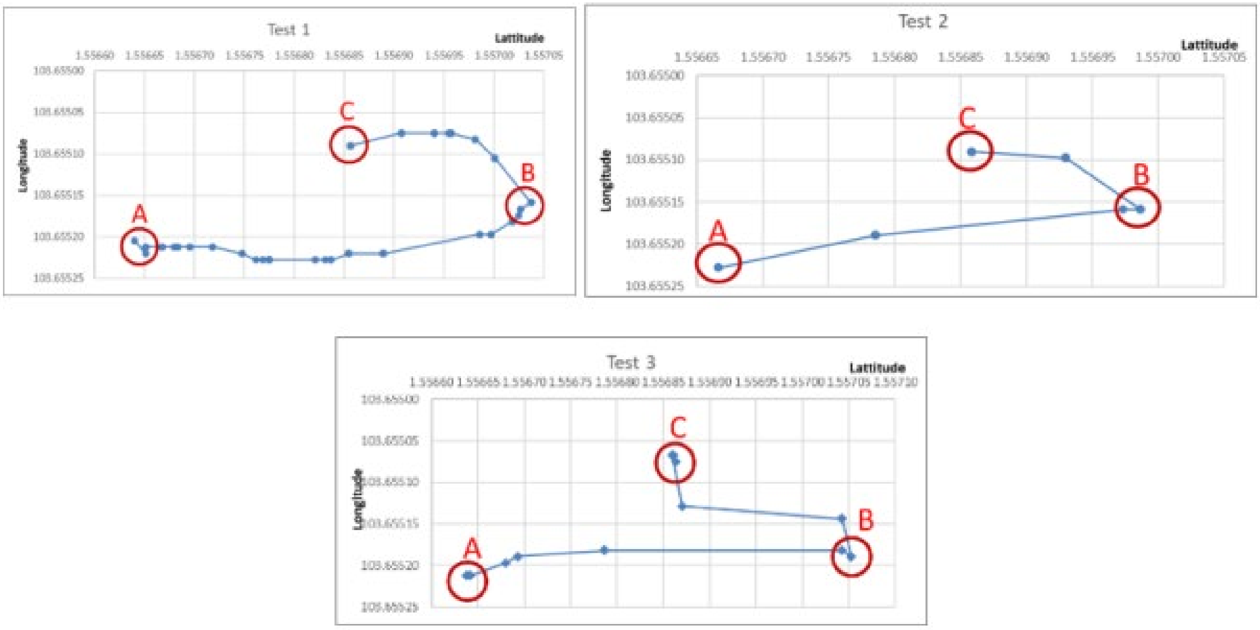

Figure 10: Three results of the navigation test

Overall, the tests confirmed Aqua Sense's high navigational accuracy, consistently reaching designated waypoints from the starting point. Differences in test paths provided insights into its navigational dynamics, with improved control and precision over time.

For location accuracy, Table 2 shows the real locations for points B and C, along with distance errors from four tests. Errors for point B were around one meter, while those for point C varied more. These consistent errors suggest the navigation system is generally reliable but could benefit from further refinement in initial positioning and improved GPS and sensor integration.

The analysis of travel time from point A to B revealed a relationship between Pulse Width Modulation (PWM) settings and travel time. Based on the graph in Figure 11, as PWM values increased from 1100 to 1400, travel time also increased. The shortest mean travel time was at PWM 1100, indicating the highest propulsion efficiency. As PWM values approached the neutral point (1500), travel times increased, reflecting reduced propulsion efficiency.

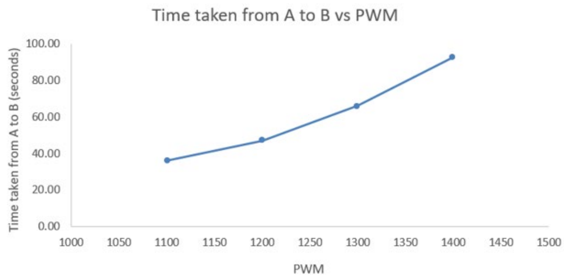

Figure 11: Three results of the navigation test

Conclusion

The Aqua Sense project has successfully demonstrated the potential of an unmanned surface vessel (USV) for precise autonomous navigation. By integrating GPS, orientation sensors, and advanced control algorithms, the Aqua Sense was able to navigate predefined routes accurately and efficiently. Rigorous testing showed the vessel could reliably reach its target destinations, effectively correcting its course as needed. The navigation analysis confirmed Aqua Sense's capability to achieve precise navigation, with minimal positioning errors which around 1m attributed to GPS signal quality, sensor calibration, and environmental factors. Additionally, the propulsion system's performance analysis revealed that the vessel operated most efficiently at high-speed settings, optimizing travel times. In summary, the Aqua Sense project achieved its objectives, showcasing the USV's ability to navigate autonomously with high accuracy. The integration of sophisticated navigation algorithms, precise control systems, and thorough vessel preparation resulted in a reliable and effective autonomous maritime platform. For further improvements, it is recommended to integrate advanced obstacle avoidance systems like LiDAR for safer navigation and develop a more user-friendly map-based navigation interface. These enhancements will ensure more precise positioning, safer operation, and a better user experience, solidifying Aqua Sense as a robust autonomous maritime solution.

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