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This document is the Published Version [VoR]

Citation:

SINGH, Yogang and TEMILOLORUN, Aiyelari (2026). Design and Development of a Cost-Effective Unmanned Surface Vehicle for Water Quality Monitoring in Shallow Aquaculture Environments. In: SINGH, Yogang, (ed.) AIR '25: Proceedings of the 2025 7th International Conference on Advances in Robotics. ACM. [Book Section]

Design and Development of a Cost-Effective Unmanned Surface Vehicle for Water Quality Monitoring in Shallow Aquaculture Environments

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Abstract

Unmanned Surface Vessels (USVs) are typically autonomous or remotely operated systems designed for environmental monitoring across various aquatic environments. In aquaculture, continuous water quality monitoring is essential for maintaining system health and productivity, as poor water conditions can lead to disease outbreaks, reduced growth rates, and even mass mortality of cultured species. Many small-scale aquaculture operations, especially in developing regions, face financial constraints and operate in shallow water environments such as inland ponds, coastal lagoons, estuaries, and shallow rivers. These conditions present significant maneuverability challenges, highlighting the need for agile, cost-effective USVs for efficient monitoring.

This paper presents the design and development of a low-cost, 3D-printed, twin-hull catamaran USV equipped with an Inertial Measurement Unit (IMU) and a Global Navigation Satellite System (GNSS). The platform features a two-layered control framework and a differential drive configuration powered by two high-efficiency T-200 thrusters. The system is built using the Robot Operating System (ROS) to implement the control framework and integrates Extended Kalman Filter (EKF)-based sensor fusion techniques for localization. The USV's autonomy is evaluated through open-water captive model experiments, employing remote control methods to assess its manoeuvrability and overall performance in shallow water conditions.

CCS Concepts

• **General and reference → Performance**.

Keywords

Environmental Monitoring, Unmanned Surface Vessel, Aquaculture, Low-Cost, Manoeuvrability

ACM Reference Format:
Yogang Singh and Aiyelari Temilolorun. 2025. Design and Development of a Cost-Effective Unmanned Surface Vehicle for Water Quality Monitoring in Shallow Aquaculture Environments. In *Advances in Robotics 2025 (AIR 2025), July 02–05, 2025, Jodhpur, India.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3787370.3787414

1 Introduction

The global aquaculture industry has become a key driver of food security, with its rapid expansion significantly influencing the marine sector. In 2022, global aquaculture production reached 185 million tons, generating an estimated 452 billion USD. [3]. Developing regions in Asia, Africa, and South America have been the primary drivers of this growth, contributing 89% of the 80 million metric tons produced globally in 2016 [11]. This expansion is primarily fueled by the rise of small-scale aquaculture operations, which play an increasingly crucial role in satisfying local demand [4]. However, these operations frequently struggle with outdated practices, an aging workforce, and labor shortages, all of which contribute to declining aquaculture water quality [10]. Small-scale aquaculture in developing regions encounters unique challenges, especially in shallow water environments. These areas experience fluctuating temperatures, low oxygen levels, and increased vulnerability to contamination, making water quality management more complex [5]. Conventional monitoring and intervention methods are often impractical in these environments, highlighting the need for innovative solutions. Additionally, high operational costs further intensify the challenges faced by small-scale aquaculture in these regions [9]. Overcoming these challenges necessitates the creation of cost-effective and adaptable robotic solutions. This manuscript presents the design and development of a low-cost Unmanned Surface Vehicle (USV) specifically engineered for water quality monitoring in shallow waters. These USVs play a vital role in delivering real-time data and management capabilities, safeguarding aquatic species' health and productivity while remaining affordable and accessible for small-scale operations in developing regions. Their mobility is particularly crucial in confined shallow water environments, where larger vessels face limitations, making this an innovative and practical solution for the aquaculture industry.

The current manuscript explores an experimental investigation of proposed low-cost USV mobility using standard free-running manoeuvring tests in shallow water, specifically focusing on the Turning Circle test [2]. This test is crucial for assessing a USV's manoeuvrability in shallow water environments, as it measures the vehicle's ability to perform tight turns in restricted spaces. This is particularly important in areas where draft and clearance are limited. By analyzing the turning circle's size and the precision of the turns, the test provides valuable insights into how well the USV

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AIR 2025, Jodhpur, India

ACM ISBN 979-8-4007-1383-5/25/07
https://doi.org/10.1145/3787370.3787414

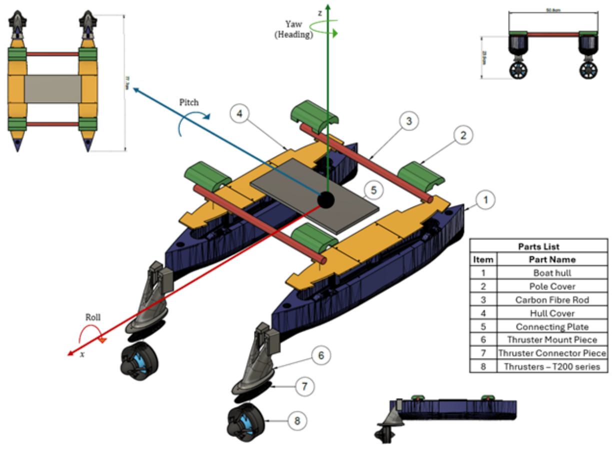
can navigate confined or shallow areas where larger vessels may face difficulties.

The remainder of the paper is structured as follows: Section 2 covers the design and development of the USV platform, including hardware and control system design, cost analysis, software development, and an explanation of the EKF-based sensor fusion technique adopted in the current study. Section 3 presents the experimental results for the designed USV platform, detailing the testing procedures, analysis from the free-running Turning Circle test, and key lessons learned. Finally, Section 4 presents conclusions and future work.

2 Design and Development of USV

2.1 Hardware Design and Control System

The USV is built as a twin-hull catamaran measuring 0.72m in length and 0.41m in width. Each hull consists of three 3D-printed PLA sections, waterproofed with spray paint and bonded with epoxy resin. Carbon fiber rods link the hulls, resulting in a lightweight, modular, and easy-to-assemble frame. Its shallow draft allows safe navigation in shallow waters, while the streamlined design minimizes underwater protrusions, reducing the risk of snagging on obstacles. With sensors and propulsion components mounted above the keel line, the USV remains effective in debris-filled and low-depth environments, making it well-suited for inland monitoring tasks. Figure 1 presents the fully assembled computer-aided design (CAD) model along with a breakdown of its individual components.



Parts List	
Item	Part Name
1	Boat hull
2	Pole Cover
3	Carbon Fibre Rod
4	Hull Cover
5	Connecting Plate
6	Thruster Mount Piece
7	Thruster Connector Piece
8	Thrusters – T200 series

Figure 1: Assembled CAD model of the USV platform

The assembled design incorporates a power system, a sensor system, and a propulsion system, as shown in Figure 2 alongside the developed prototype. The USV is powered through two separate channels. The first channel consists of a power bank that supplies 5V to the electronic system and sensors, which are connected via USB to the Raspberry Pi (RPi) and the Arduino Mega. The second channel powers the propulsion system using a Li-Po battery, which is connected to the outboard thrusters through a power distribution board and two electronic speed controllers (ESCs).

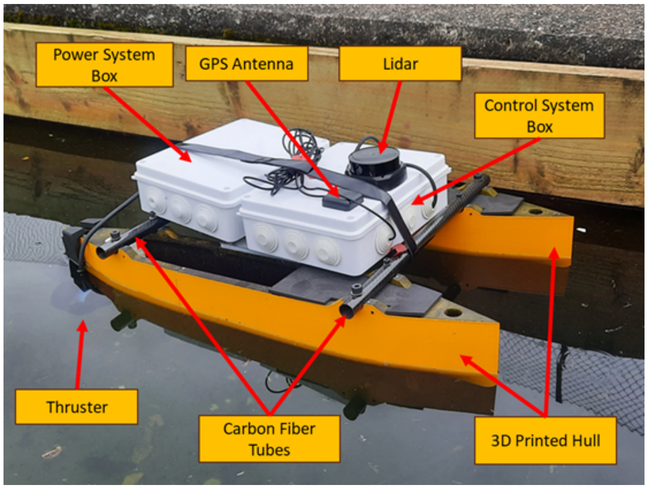


Figure 2: Developed prototype of the USV platform

The propulsion system, shown in Figure 2, is powered by two high-efficiency T-200 thrusters, allowing precise maneuverability without relying on rudders, which are ineffective at very low speeds. To enhance stability and control, the system employs a counter-rotating setup, with motors spinning in opposite directions to balance forces and improve maneuverability. This configuration enables the vessel to move straight, turn, or rotate in place by adjusting the relative speeds of the thrusters.

The USV's control system integrates both high-level and low-level control mechanisms, utilizing a Raspberry Pi (RPi) 4 for complex computational tasks and an Arduino MEGA 2560 for direct hardware interfacing. The low-level control system, managed by the Arduino MEGA 2560, controls the ESCs, IMU, and communication module. The thrusters are connected to specialized ESCs and regulated using pulse-width modulation (PWM) on the Arduino MEGA. These ESCs are linked to a power distribution board (PDB), which is connected to a Li-Po battery that supplies power to the entire system. Figure 3 provides a schematic representation of the USV's hardware design.

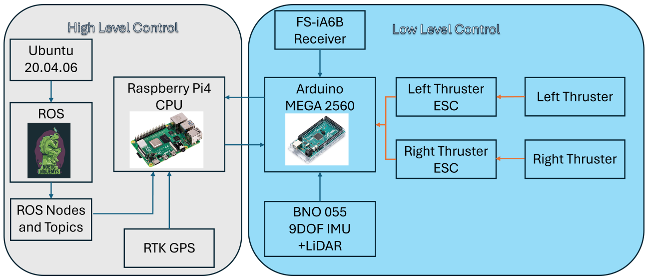


Figure 3: Schematic of the hardware design for the USV platform

The high-level control system utilizes a Raspberry Pi running the ROS Noetic distribution on a Linux Ubuntu 20.04 environment. The GPS module communicates directly with the Raspberry Pi via a serial connection, while the IMU sensor interfaces with an Arduino MEGA. Together, these components establish the *ekf_ localisation* node within ROS, enabling the boat's localization in three-dimensional space.

2.2 Cost Analysis

The design of our USV emphasizes a relatively low-cost construction while maintaining high functionality. Key electronic components, including a Raspberry Pi4, RTK GPS, IMU, Arduino Uno, Arduino MEGA, Lidar and RC Controller, collectively cost $950 with the Lidar and RTK GPS costing more than half of the total amount. At the same time, the mechanical parts like IP7 electronics box, 3D Printing and Carbon Fibre tubes add $160 to the total. This strategic selection of components results in a comprehensive, budget-friendly USV design with a cost of $1118, making it an accessible option for research and development. The Table 1 summarises the cost breakdown for low-cost USV design.

Table 1: Cost breakdown for USV design

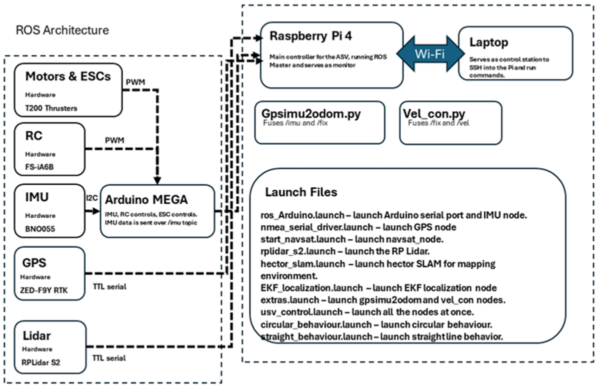
Category	Items	Cost ($)
Electronics	T- 200 Thrusters (x2)	200
	ESCs (x2)	20
	RTK GPS	350
	IMU	28
	Arduino Uno	18
	RC Controller	60
	11.1V LiPo Battery	24
	Power Board	8
	Raspberry Pi4	50
	Arduino MEGA	50
	Lidar	150
Mechanical	IP7 Electronics Box	28
	Carbon Fibre Tubes	32
	3D Printing	100
	Total	1118

2.3 Software Design

The USV platform's software stack is developed using a dual-layer approach that leverages the strengths of both C++ and Python, integrated with ROS, as illustrated in Figure 4. This architecture provides a robust and efficient framework, effectively addressing the distinct requirements of both the low-level and high-level control systems.

The ROS setup is structured using nodes and launch files. Nodes are implemented to handle Arduino communication via ROSSERIAL and GPS communication through a serial driver. Additionally, the *vel_ con* and *gpsimu2odom* nodes process data from the GPS and IMU publishers, converting it into odometry information. The Raspberry Pi functions as the onboard computer, running ROS and interfacing with various sensors, essential for managing the USV's autonomous control.

In ROS, sensors are managed using launch files that initialize them, while a subscriber is set up to receive IMU data from the low-level controller. All collected data is processed through the *robot_ localization* package, which includes the *ekf_ localization* node, enhancing the vessel's localization and state estimation. A detailed explanation of sensor fusion is provided in Section 2.4.



ros_Arduino.launch – launch Arduino serial port and IMU node.
nmea_serial_driver.launch – launch GPS node
start_navsat.launch – launch navsat_node.
rplidar_s2.launch – launch the RP Lidar.
hector_slam.launch – launch hector SLAM for mapping environment.
EKF_localization.launch – launch EKF localization node
extras.launch – launch gpsimu2odom and vel_con nodes.
usv_control.launch – launch all the nodes at once.
circular_behaviour.launch – launch circular behaviour.
straight_behaviour.launch – launch straight line behavior.

Figure 4: ROS architecture for the USV

2.4 EKF based Sensor Fusion

In this study, we utilize the data fusion approach of [8] to integrate data from an array of sensors on a USV. A *robot_ localization* package developed as a part of the work has been used in the current study for the implementation of an EKF for sensor fusion. Although the original work was tested with mobile robots, this study extends its application to marine robots, adapting the methodology for use in the maritime domain. The current section details the implementation of the developed *ekf_ localization* node as the component of the *robot_ localization* package. The goal of the EKF is to estimate the full 3D pose and velocity of the USV over time. The non-linear dynamical system of the USV can be described with

$$x_k = f(x_{k-1}) + w_{k-1} \tag{1}$$

where x_k is the USV system state at a time k, f is a non-linear state transition function and w_{k-1} is the normally distributed noise. The USV state vector x consists of the USV's 3D pose, orientation and their respective velocities. The received measurements are expressed as

$$z_k = h(x_k) + v_k \tag{2}$$

where z_k is the measurement at time k, h is a mapped non-linear sensor model and v_k is the normally distributed measurement noise. In the initial stage, EKF performs a prediction step, advancing the current state estimate and error covariance forward in time using equations (3) and (4) as follows:

$$\hat{x}_k = f(x_{k-1}) \tag{3}$$

$$\hat{P}_k = FP_{k-1}F^T + Q \tag{4}$$

In this study, f is the standard 3D kinematic model of the USV with P being the estimated error covariance, projected via F, the Jacobian of f and perturbed by Q, the process noise covariance. The correction step is then carried out using the equations (5) till

(7) to calculate the Kalman gain using observation matrix H and measurement covariance R and $\hat{P}_k$ as follows:

$$K = \hat{P}_k H^T (H \hat{P}_k H^T + R)^{-1} \tag{5}$$

$$x_k = \hat{x}_k + K(z - H\hat{x}_k) \tag{6}$$

$$P_k = (I - KH)\hat{P}_k (I - KH)^T + KRK^T \tag{7}$$

leading to the use of gain to update the state vector and covariance matrix. The fundamental aspect of the adopted approach is its capability for a partial update of the state vector, enabling the omission of certain variables in the state vector during the sensor data capture process. This capability is crucial for USVs, as data loss during operations is a common occurrence. In the present study, we consider the sensor configuration of fused odometry, incorporating a single IMU and a single GPS. This configuration is chosen to effectively manage the significant interference encountered in the operational environment of the USV.

2.5 Communication System

The USV's communication system is structured into two key components: the Control Communications Part (CCP) and the Telemetry Communications Part (TCP). Both segments utilize radio communication to enhance data transmission range and reliability.

The CCP is dedicated to remote-control operations, consisting of a transmitter and a receiver—both essential for effective vehicle operation. The receiver, integrated with the Arduino MEGA 2560 at the core of the USV's control system, is securely mounted on the electronics shelf to ensure optimal signal reception and processing. This setup enables seamless communication between the remote operator and the USV. The FS-i6 Flysky digital proportional radio control system is used as the transmitter, chosen for its efficiency, reliability, and compatibility with the USV's design and operational needs.

The TCP is designed around ROS-based communication between two computers—one onboard the USV and another at the local base station—via a 2.4GHz ISM (Industrial, Scientific, and Medical) band wireless network. This setup minimizes interference and ensures efficient telemetry data transmission for both real-time analysis at the base station and offline evaluation using recorded sensor data and ROS topics saved on the USV via ROSBAGS. The stable wireless connection between the computers supports low-latency data exchange, which is crucial for real-time monitoring and control. Additionally, recorded ROSBAGS facilitate detailed post-mission analysis, aiding in performance assessment and troubleshooting. This integrated communication system ensures reliable USV operation while generating valuable data for continuous system improvements and optimization.

3 Experimental Results

3.1 Testing Arena

The USV platform was tested at Redmires Reservoir in Sheffield, United Kingdom. This site was chosen due to its realistic shallow water conditions and proximity to local aquaculture operations, making it an ideal location for practical evaluation. The designated testing area, marked in red in Figure 5, allowed for assessing the USV's performance in an environment that closely replicates its intended operational setting.

Figure 5: Marked testing arena for the USV platform

3.2 Autonomy Protocol

The vessel's autonomy was assessed through a series of remote-control (RC) tests, utilizing radio communication for motion control, as detailed in Section 2.5. Sensor data was recorded using ROSBAGs and analyzed with the *MATLAB ROSBAG Viewer Tool* and *Foxglove Studio*. The RC setup, depicted in Figure 6, employs a differential drive system for propulsion, enabling precise maneuverability and making the USV well-suited for navigation in various aquatic environments. The tests were conducted using a laptop as the ground station, equipped with an Intel i7 1.90 GHz quad-core CPU running Ubuntu 20.04.

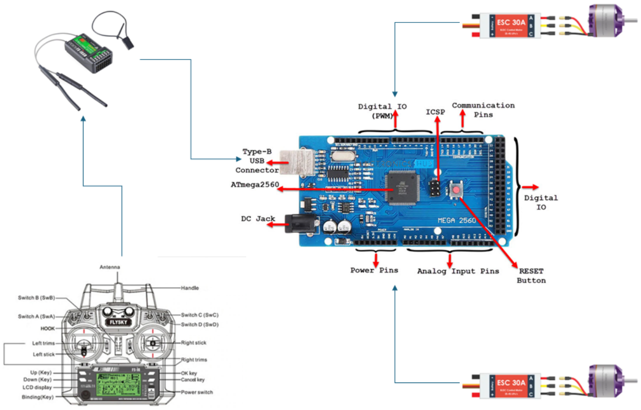


Figure 6: RC setup for the USV platform

3.3 Manoeuvring Experiments and Results

The manoeuvring performance of the vessel was evaluated in open water using a widely recognized captive model Turning Circle Test [6]. In the test, the vessel was made to do a turning circle of 540° to determine the following parameters as shown in Figure 7:

- Tactical diameter
- Advance
- Transfer
- Loss of speed on a steady turn
- Time to change heading 90°
- Time to change heading 180°

This test was conducted on the designed full-scale model of the USV within the testing arena depicted in Figure 5.

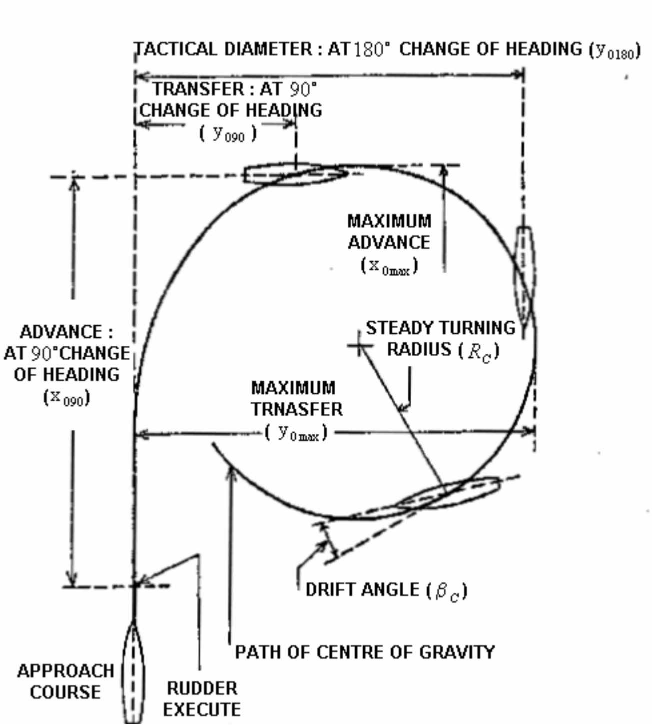


Figure 7: Turning Circle definitions (Port Side)

To conduct free-running manoeuvring experiments in open water, the International Maritime Organization (IMO) Resolution A.751, which outlines interim standards for ship manoeuvrability [1, 7], was adopted with modifications tailored for differential drive propulsion vessels:

1. The approach speed should be 90% of the vessel speed corresponding to 85% of the maximum engine output.
2. Before initiating a maneuver, the vessel must maintain a steady course at a constant setting for at least one minute.

Three tests were conducted using different start and goal points within the testing arena to evaluate the USV's manoeuvrability based on turning circle parameters. The results were compared against the IMO-enforced minimum manoeuvrability criteria outlined in Table 2 [1]. Figure 8 and Figure 9 present the data collected from the Turning Circle tests for the Starboard side, while Figure 10 shows data from the Port side. A summary of the Turning Circle test results is provided in Table 3, and the compliance of Tactical Diameter and Advance with IMO standards across the three tests is detailed in Table 4.

The trial results indicate that the recorded values exceed IMO criteria for turning ability, particularly Tactical Diameter and Advance. This deviation is primarily attributed to lower-cost sensor inaccuracies and external influences such as wind and surface currents at the test site. Notably, the measurements on the Starboard side exhibited less variability compared to the Port side. Additionally, roll and pitch data across all three tests showed minimal deviation, underscoring the USV's stability and reliability, especially in shallow waters and challenging surface conditions caused by wind-generated currents.The recorded trial can be found at https://www.youtube.com/watch?v=iVOl2lOuyIg and the project repository can be found at https://github.com/YogangSingh/catamaran_shu_v2.

Table 2: IMO evaluation criteria for maneuverability (L- Length of the vessel)

Parameters	Test	Criteria
Advance	Turning Circle	< 4.5L
Tactical Diameter	Turning Circle	< 5L

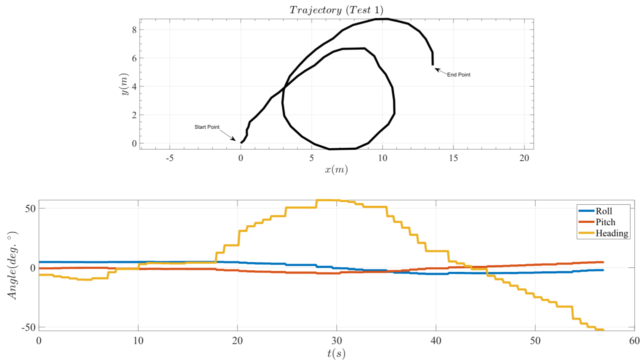


Figure 8: Turning Circle results from Test 1 (Starboard side)

Table 3: Turning Circle test results (P- Port side; S- Starboard side)

Parameters	Test 1 (S)	Test 2 (P)	Test 3 (S)
Advance (m)	7.03	6.10	5.88
Transfer (m)	6.08	6.42	6.70
Tactical Diameter (m)	5.16	4.99	6.67
Loss of speed-steady turn (%)	6.89	6.51	9.34
Time to change heading 90°(s)	11.52	12.27	8.74
Time to change heading 180°(s)	14.31	16.43	15.22

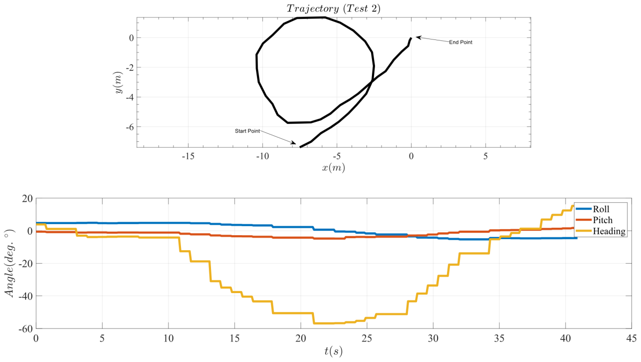


Figure 9: Turning Circle results from Test 2 (Port side)

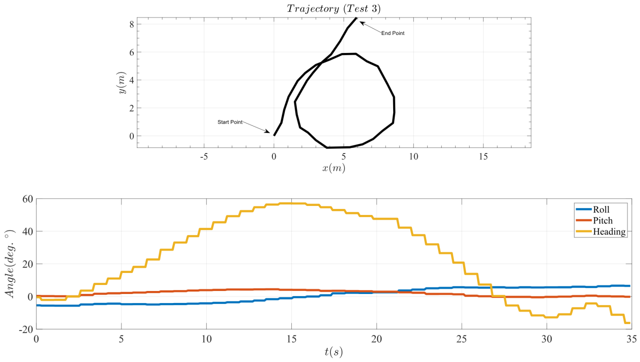


Figure 10: Turning Circle results from Test 3 (Starboard side)

3.4 Lessons Learned

The dual-system setup using a Raspberry Pi and Arduino MEGA effectively managed computation and hardware control. The PLA 3D-printed, carbon fiber-reinforced hulls offered durability and stability, validating the use of low-cost materials. Though Turning Circle tests showed deviations from IMO standards—highlighting the need for improved sensor accuracy and propulsion control—the USV remained stable with minimal roll and pitch. Developed for just $1118, it demonstrates that a functional, budget-friendly USV is achievable with accessible components. Despite manoeuvrability limitations, it successfully integrated navigation and control systems. Future improvements will focus on autonomous features like obstacle avoidance and enhanced decision-making, with expanded validation including straight-line tracking, station-keeping, endurance testing, and sensor accuracy comparisons.

Table 4: IMO compliance for Turning Circle test (P- Port side; S- Starboard side; TD- Tactical Diameter; A- Advance; Y- Yes; N- No)

Test	Parameters	Measured	Criteria	IMO Compliance
1 (S)	TD, A	7.07, 8.42	3.6, 3.24	N, N
2 (P)	TD, A	7.2, 9.08	3.6, 3.24	N, N
3 (S)	TD, A	6.8, 5.74	3.6, 3.24	N, N

4 Conclusions and Future Work

The performance and manoeuvrability of the designed USV were evaluated through an open-water free-running turning circle test. Results revealed significant deviations from IMO standards, highlighting the need for further optimization of both hardware and software. As a next step, water quality sensors—measuring pH, turbidity, temperature, dissolved oxygen, and conductivity—will be integrated via the Arduino and housed in waterproof enclosures beneath the hull to enable real-time data logging and remote monitoring. Using advanced control algorithms (PID, fuzzy logic, adaptive control) can improve accuracy and stability. Enhancing motor drivers, leveraging IMU/GPS feedback, and refining PWM signals boost manoeuvrability. Real-time sensor fusion and open-source tools further optimize performance with minimal cost increase.

Acknowledgments

This research is supported by the Sheffield Hallam Department of Engineering & Mathematics Research & Innovation Funding for the project titled *"Towards Design and Development of an Autonomous Marine Vessel"*. For open access, the author has applied a Creative Commons Attribution (CC BY) licence to any author-accepted manuscript version arising from this submission. This manuscript presents a revised version of a previous workshop paper [12], detailing the design and development of a low-cost Unmanned Surface Vehicle (USV) for water quality monitoring in shallow waters

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