Development of a Low Cost Unmanned Surface Vessel for Autonomous Navigation in Shallow Water

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Synopsis

Unmanned Surface Vessels (USVs) are commonly autonomous or remotely controlled, serving diverse maritime purposes such as oceanographic research, surveillance, environmental monitoring, and maritime security. These vessels exhibit variability in size, shape, and functionality, ranging from nimble crafts to specialized, larger platforms. This paper introduces the development and validation of a low-cost, agile USV tailored for autonomous navigation in shallow waters. In shallow water, the foremost challenge for USVs is maneuverability, underscoring the crucial need for cost-effective platforms as efficient monitoring systems for maritime applications. The 3D-printed twin-hull catamaran-style platform is equipped with an Inertial Measurement Unit (IMU) and a Global Navigation Satellite System (GNSS) utilizing a Raspberry Pi 4 for high-level control and Arduino MEGA for low-level control. The hovercraft-style propulsion system is designed with a differential drive configuration powered by two DC motors. The design utilizes the Robot Operating System (ROS) to develop the control framework and incorporates Extended Kalman Filter (EKF)-based sensor fusion techniques. The paper evaluates the USV's autonomy through open water captive model experiments, employing remote control methods to assess the vessel's maneuverability and overall performance characteristics in shallow water conditions.

Keywords: Unmanned Surface Vessels, Robot Operating System, Extended Kalman Filter, Autonomous Navigation, Maneuvering

1 Introduction

In recent years, unmanned vehicles have garnered significant attention from both researchers and companies. Ground, aerial, and aquatic unmanned vehicles have become the focal points of research and development efforts (Mancini et al., 2015). There is a growing interest in developing low-cost platforms for complex environmental missions involving various types of vehicles. Consequently, many researchers are exploring frameworks designed for complex scenarios in which unmanned aerial, ground, and aquatic vehicles operate collaboratively (Sotelo-Torres et al., 2023; Mendonça et al., 2013; Prats et al., 2012; Benini et al., 2012; Lewicka et al., 2022).

A particularly encouraging avenue of research focuses on employing USVs for comprehensive environmental monitoring in smaller aquatic environments. This approach facilitates the swift and secure collection of environmental data compared to methods involving human fieldwork and enables surveillance of remote and challenging-to-access areas, while also spanning a broad spectrum of spatial and temporal scales (Liu et al., 2016; Bibuli et al., 2023). Furthermore, USVs offer a precise and lightweight solution for such applications. They require lower operational investment, enhance personnel safety, extend operational range, increase autonomy, and provide greater flexibility, particularly in challenging environments such as muddy, harsh, and dangerous missions (Zappalà et al., 2017). Nevertheless, USVs encounter certain challenges in this research avenue, such as the development of fully autonomous vehicles capable of operating effectively in shallow water environments (Kum et al., 2020; Seto and Crawford, 2015; Shetty et al., 2022). Significant advances have been made in the past decade in the development of USVs, aimed at enhancing the operational efficiency of vessels in shallow water environments with a strong emphasis on design, navigation and collision avoidance capabilities (Pasculli et al., 2020; Han et al., 2020; Kebkal et al., 2014; Aissi et al., 2020; Odetti et al., 2020, 2019). However, despite the progress in these areas, there has been a noticeable dearth of research focusing specifically on comprehensively understanding the maneuvering capabilities of USVs within such environments (Li et al., 2019). This aspect remains relatively underexplored, warranting further investigation to fully grasp the maneuvering dynamics of USVs in shallow water conditions.

There are several methods available to assess the maneuvering performance and controllability of a marine vessel such as Computational Fluid Dynamics (CFD), Planar Motion Mechanism (PMM) experiment and free-running test in open water. This paper presents the design, development, and deployment of a USV, along with an assessment of its controllability performance via a series of maneuvring experiments through the free-running

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test in open water. These experiments utilize a remote control approach to evaluate the vessel's maneuverability and overall performance within shallow water environments. Additionally, the USV is engineered to serve as a test platform for validating autonomous navigation techniques and integrating sensors, further enhancing its utility in advancing autonomous maritime technologies. The paper is organised as follows. In Section 2, the paper outlines the specifications of the developed USV, while Section 3 elaborates on the experimental approach to the USV along with the results obtained from field tests conducted on the developed system. Furthermore, in Section 4, a discussion is presented on the results and potential future developments for the USV platform.

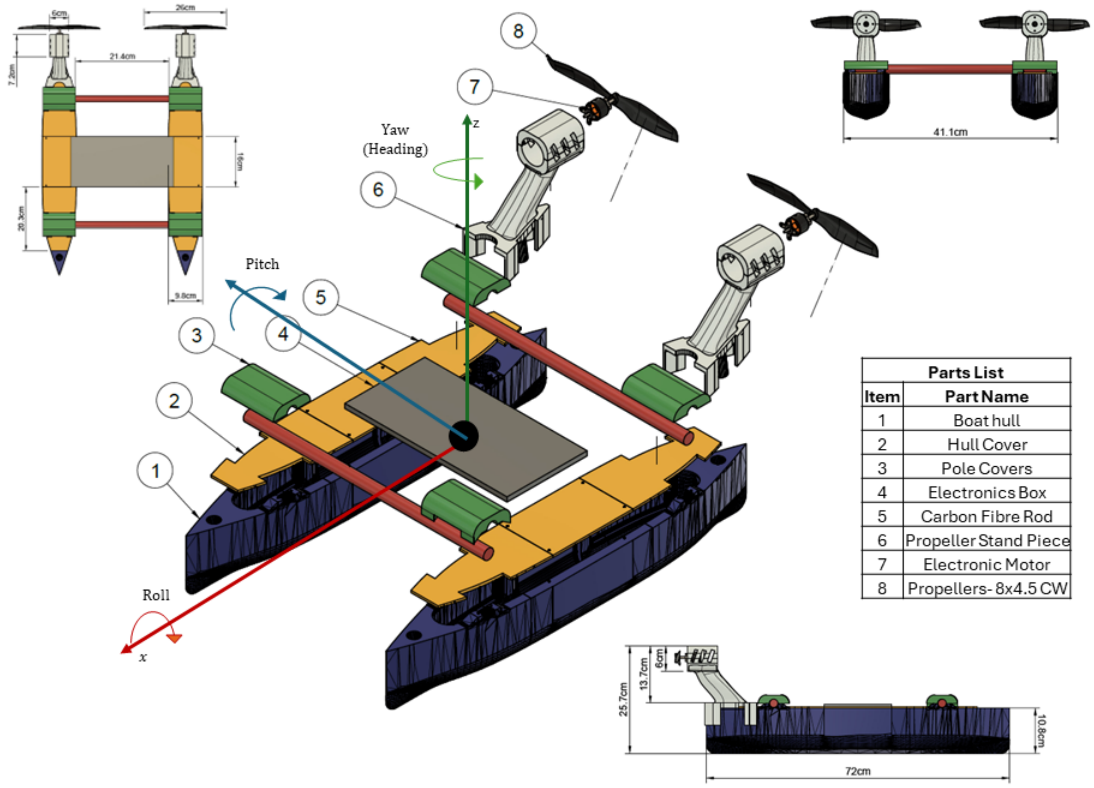
2 Design and Development of USV Platform

2.1 Hardware Design and Control System

The USV features a twin-hull catamaran design, 0.72m in length, and 0.41m in width. Each hull consists of three parts, 3D printed using Polylactic acid (PLA) filaments, spray-painted for waterproofing, and then joined together using Epoxy Resin to form a single unit. Carbon fibre rods are used to connect the two hulls. This lightweight construction allows for easy assembly of the boat. Figure 1 illustrates the fully assembled CAD design along with a list of individual components. Table 1 shows the particulars of the designed USV.

Items	**Value**
Mass	4.88 Kg
Draft	0.045 m
Maximum Speed	4.79 m/s
Centre of Gravity	0.253 m
Length	0.720 m
Breadth	0.508 m

Table 1: Particulars of the USV



Parts List	
Item	**Part Name**
1	Boat hull
2	Hull Cover
3	Pole Covers
4	Electronics Box
5	Carbon Fibre Rod
6	Propeller Stand Piece
7	Electronic Motor
8	Propellers- 8x4.5 CW

Figure 1: Assembled CAD model of the USV Platform.

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The assembled design is fitted with a power system, a sensors system and a propulsion system as shown in Figure 2 with the developed prototype. Electric power is supplied to the USV via 2 channels. The first channel is a power bank that provides the 5V required by the electronic system and sensors connected via USB to the Raspberry Pi and the Arduino Mega. The second channel is the power for the propulsion system which is supplied by a Li-Po battery connected to outboard thrusters via a power distribution board and two electronic speed controllers (ESCs).

The thrusting mechanism, inspired by hovercraft technology and depicted in Figure 2, is powered by two 850Kv 2830 high-efficiency motors connected to 3D-printed propellers. This design enables the vessel to be maneuvered with precision, independent of the fixed propellers' reliance on rudders. Moreover, at very low speeds, rudders are inefficient for turning the vessel. The system employs a counter-rotating setup, with motors rotating in opposite directions, to balance forces, improve stability, and enhance maneuverability. This configuration enables the vessel to move straight, turn, or rotate in place by adjusting the relative speeds of the wheels.

The control system of the USV utilizes both high-level and low-level control mechanisms, achieved through the integration of a Raspberry Pi (RPi) 4 and an Arduino MEGA 2560, respectively. This dual-system approach allows for a comprehensive control over the USV's operations, encompassing both complex computational tasks and direct hardware interfacing. The low-level control system consists of an Arduino MEGA 2560 board as the main controller driving the ESCs, IMU and communication module. The propellers are connected with calibrated ESCs and controlled using pulse-width modulation on the Arduino MEGA. The ESCs are linked to a power distribution board (PDB), which in turn is connected to the Li-Po battery supplying power to the entire system. Figure 3 illustrates the schematic of the hardware design for the USV platform.

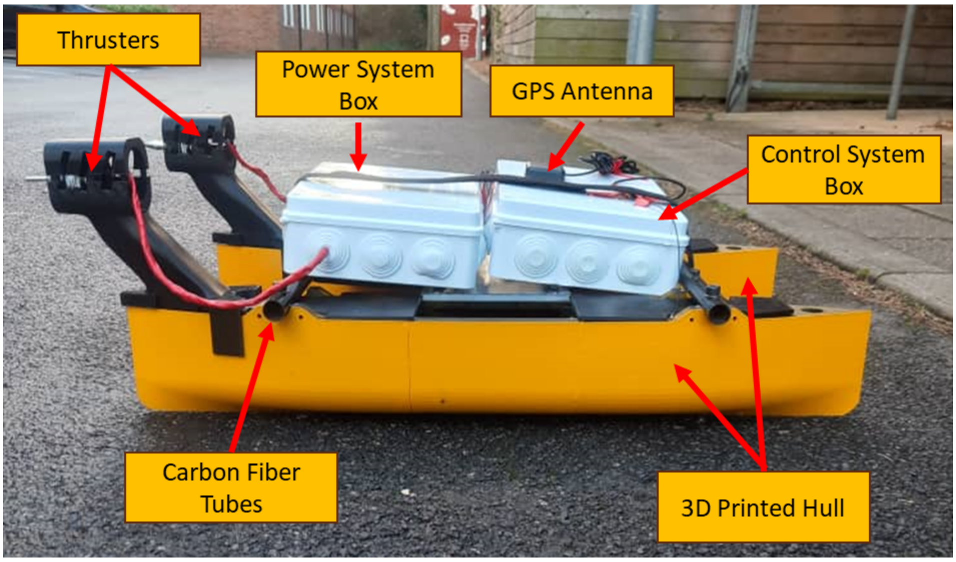

Figure 2: Developed prototype of the USV Platform

The high-level control system consists of an RPi operating the Robot Operating System (ROS) Noetic distribution within the Linux Ubuntu 20.02 environment. Through a serial connection, the GNSS module interfaces with the Arduino Uno board, while in conjunction with the IMU sensor, it establishes an *ekf_localisation* node within ROS. This node facilitates the localization of the boat within three-dimensional space.

2.2 Software Design

The software stack for the USV platform is built, utilizing a dual-layer approach that combines the strengths of both C++ and Python, in conjunction with the Robot Operating System (ROS) as shown in Figure 4. This structure ensures a robust and efficient software framework, catering to the distinct needs of both the low-level and high-level control systems of the USV.

The setup in ROS is built using nodes and launch files. Nodes are implemented to manage Arduino communication using ROSSERIAL and GNSS communication via the serial driver. In addition, we have *vel_con* and *GNSSimu2odom* nodes that take data from the GNSS and IMU publishers and transform that into odometry information. The RPi serves as the onboard computer and is responsible for running the ROS, and interfacing sensors. This setup is crucial for managing the autonomous control aspects of the USV. In ROS, the sensors connected are controlled using launch files to start them up while a subscriber is initiated to subscribe to the IMU data from the low-level controller. All this data is fed into the *robot_localization* package in the ROS which eventually contains the *ekf_localization* node to help the vessel better localize itself and perform state estimation. A detailed

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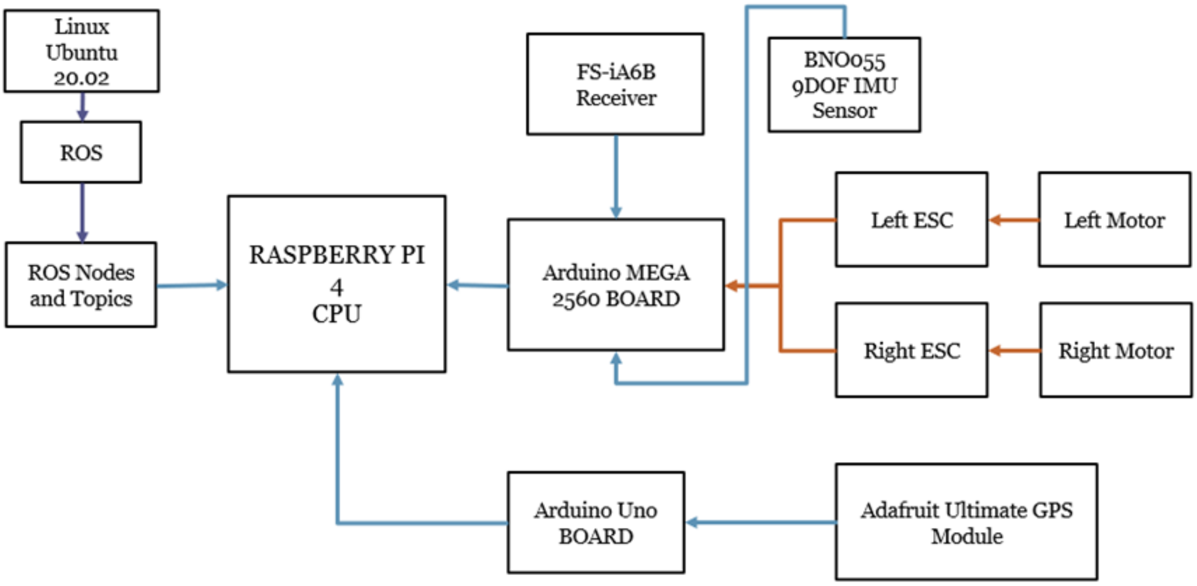

Figure 3: Schematic of the hardware design for the USV Platform

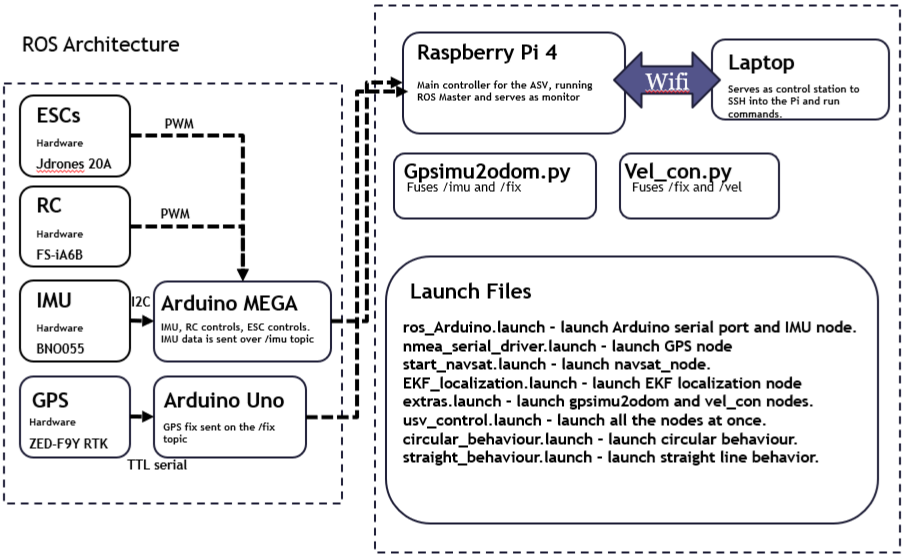

Figure 4: USV software stack

explanation of sensor fusion is explained in section 2.3.

2.3 Extended Kalman Filter based Sensor Fusion

In this study, we utilize the data fusion approach of Moore and Stouch (2016) 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 GNSS. This configuration is chosen to effectively manage the significant interference encountered in the operational environment of the USV.

2.4 Cost Analysis

The design of our USV emphasizes low-cost construction while maintaining high functionality. Key electronic components, including a Raspberry Pi4, RTK GNSS, IMU, Arduino Uno, Arduino MEGA, and RC Controller, collectively cost £310. At the same time, the mechanical parts like propellers, an IP7 electronics box, 3D Printing and Carbon Fibre tubes add £177 to the total. This strategic selection of components results in a comprehensive, budget-friendly USV design with a total cost of £487, making it an accessible option for research and development. The table 2 summarises the cost breakdown for low-cost USV design.

Category	**Items**	**Cost (£)**
Electronics	Brushless DC Motors (x2)	35
	ESCs (x2)	20
	RTK GNSS	24
	IMU	28
	Arduino Uno	18
	RC Controller	60
	11.1V LiPo Battery	24
	Power Board	8
	Raspberry Pi4	50
	Arduino MEGA	50
Mechanical	Propellers (x2)	10
	IP7 Electronics Box	28
	Carbon Fibre Tubes	32
	3D Printing	100
	Total	487

Table 2: Cost breakdown for low-cost USV design

2.5 Communication System

The communication system of the USV is designed with two distinct parts namely, the Control Communications Part (CCP) and the Telemetry Communications Part (TCP) with both segments designed to employ radio communications to enhance the range and reliability of the data transmission. The CCP is primarily responsible for the remote-control operations of the USV. This system comprises two main elements: a transmitter and a receiver, both critical for the effective remote operation of the vehicle. The receiver in the CCP is intricately connected to the Arduino MEGA 2560, the core of the USV's control system and is mounted on the USV's electronics shelf. The placement of the receiver is crucial for optimal signal reception and processing, allowing for seamless communication between the remote operator and the USV. The transmitter utilized in the CCP is the FS-i6 Flysky digital proportional radio control system. The choice of the FS-i6 Flysky transmitter is based on its efficiency, reliability, and compatibility with the overall design and operational requirements of the USV.

The TCP of the USV is strategically designed around the ROS communication between two computers, one on the robot and the local base station via a local wireless network, operating at 2.4GHZ ISM (Industrial, Scientific and Medical) band. This is to ensure minimal interference and efficient telemetry data transmission for both real-time analysis on the local base station and offline analysis through recorded sensor/ROS topics information saved on the robot using ROSBAGS. With this setup, data transmitted via TCP between the two computers ensures reliable communication for the USV. The stable wireless connection between the two computers supports low-latency data exchange, which is crucial for real-time control and monitoring. Additionally, the recorded ROSBAGS enable detailed post-mission analysis, aiding in evaluating performance and diagnosing issues. This integrated system allows for precise and dependable operation of the USV, while also generating valuable data for ongoing improvements and system optimization.

3 Experimental Approach to USV

3.1 Testing Arena

The USV platform was tested locally at Millhouse Park in Sheffield, United Kingdom, chosen for its realistic shallow water environment as shown in Figure 5 with support from the local boating community to ensure the safety of the USV trials. Initially, a float test was conducted to test the stability and robustness of the designed platform with the vessel orientation data being recorded for the duration of the float test. Figure 6 shows the pitch, roll and heading data for the float test showing no deviation from the initial values thereby confirming the stability of the USV platform.

Figure 5: Marked testing arena for the USV Platform

3.2 Autonomy Protocol

The vessel's autonomy was evaluated through a series of remote-control (RC) tests, utilizing radio communication to govern its motion as described in section 2.5. Sensor data recordings were made using ROSBAGs and analyzed using the *MATLAB ROSBAG Viewer Tool* and *Foxglove Studio*. The RC setup, illustrated in Figure 7, enables the propulsion of the USV using a differential drive system. This system allows for precise movements, making the USV ideal for navigation in diverse aquatic environments. The tests were conducted using a laptop as a ground station with an Intel i7 1.90 GHz quad-core CPU and Ubuntu 20.04 as OS.

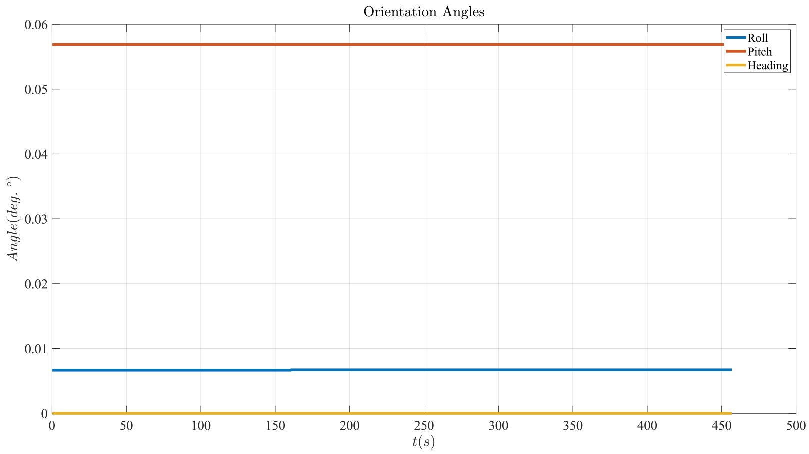

Figure 6: Orientation of the USV platform during float test

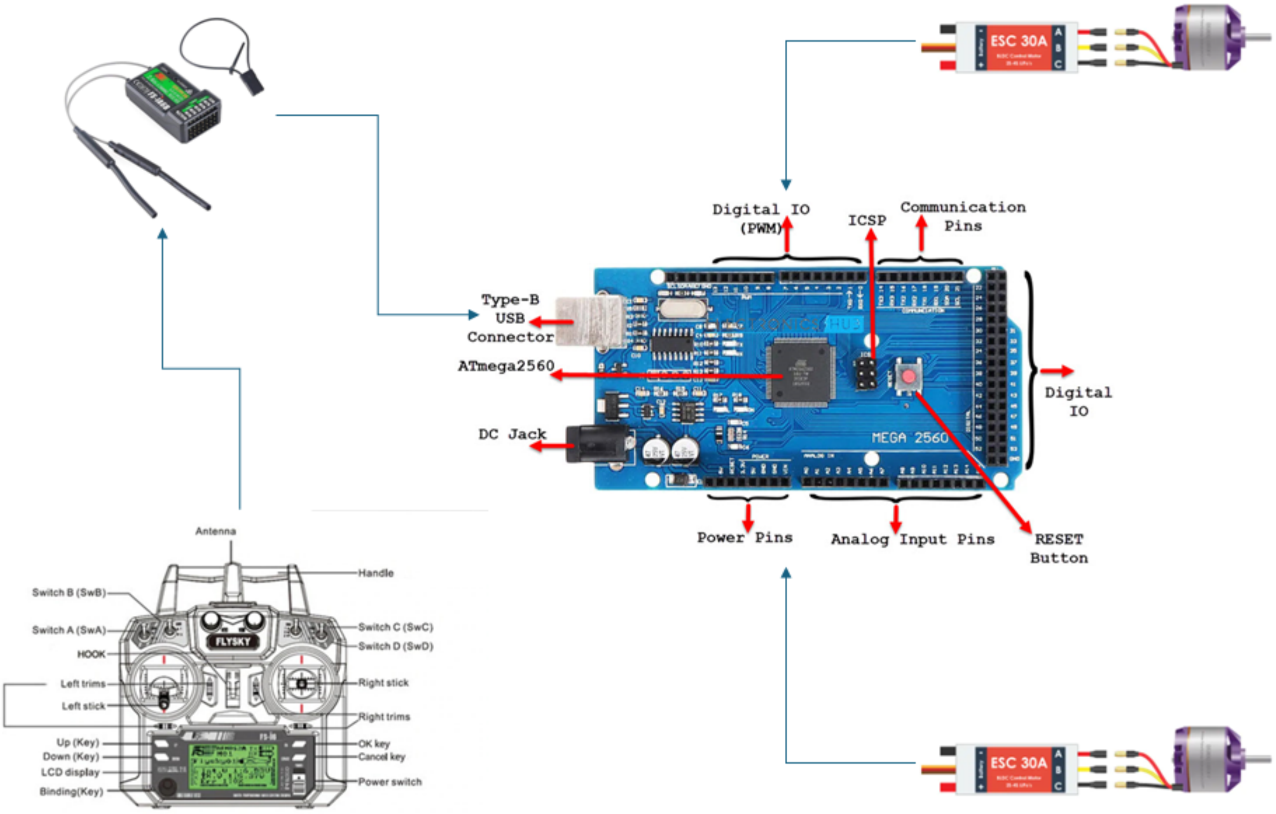

Figure 7: RC setup for the USV platform

3.3 Maneuvering Experiments and Results

The maneuvering performance of the vessel was evaluated in open water using a widely recognized captive model turning circle test. In the test, the vessel was made to do a turning circle of 540° to determine following parameters as shown in Figure 8:

- Tactical diameter
- Advance
- Transfer
- Loss of speed on a steady turn

- Time to change heading 90°
- Time to change heading 180°

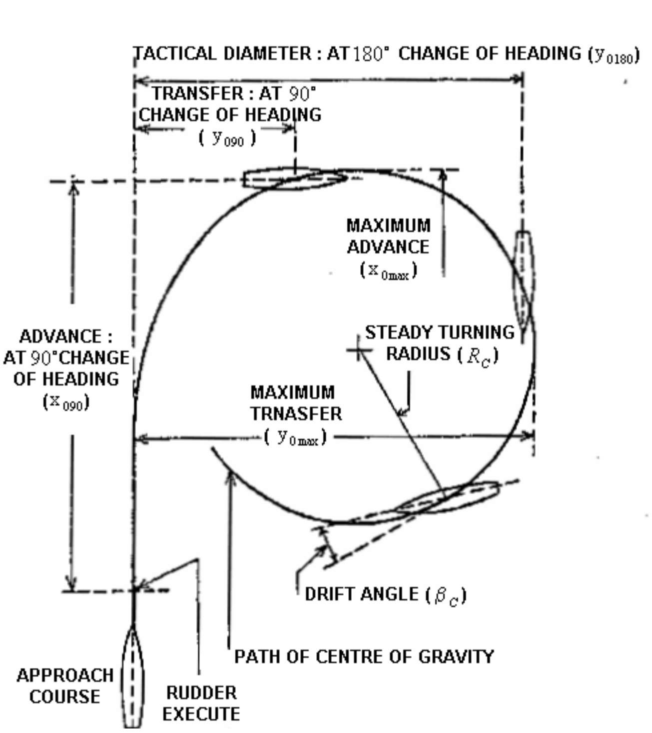

Figure 8: Turning Circle definitions

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

To perform the free-running maneuvering experiments in open water, International Maritime Organisation (IMO) Resolution A.751 stating interim standards for ship maneuverability(Kim et al., 1996; BAKAR, 2015) were adopted with suggested modifications for differential drive propulsion vessels as follows:

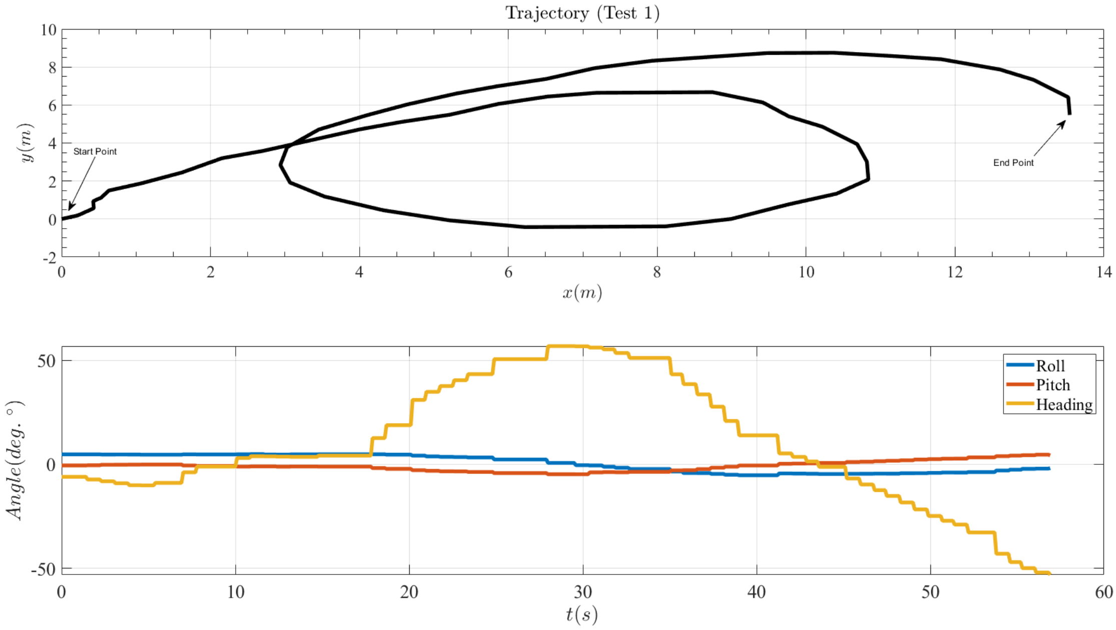

Figure 9: Turning Circle results from Test 1 (Starboard side)

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

Table 3: IMO evaluation criteria for maneuverability

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

Three different tests from three different start and goal points within the testing arena were performed to determine the USV maneuverability in terms of turning circle parameters and were compared against the IMO-enforced minimum maneuverability criteria listed in Table 3 (BAKAR, 2015). The turning circle test data is summarised in the Table 4.

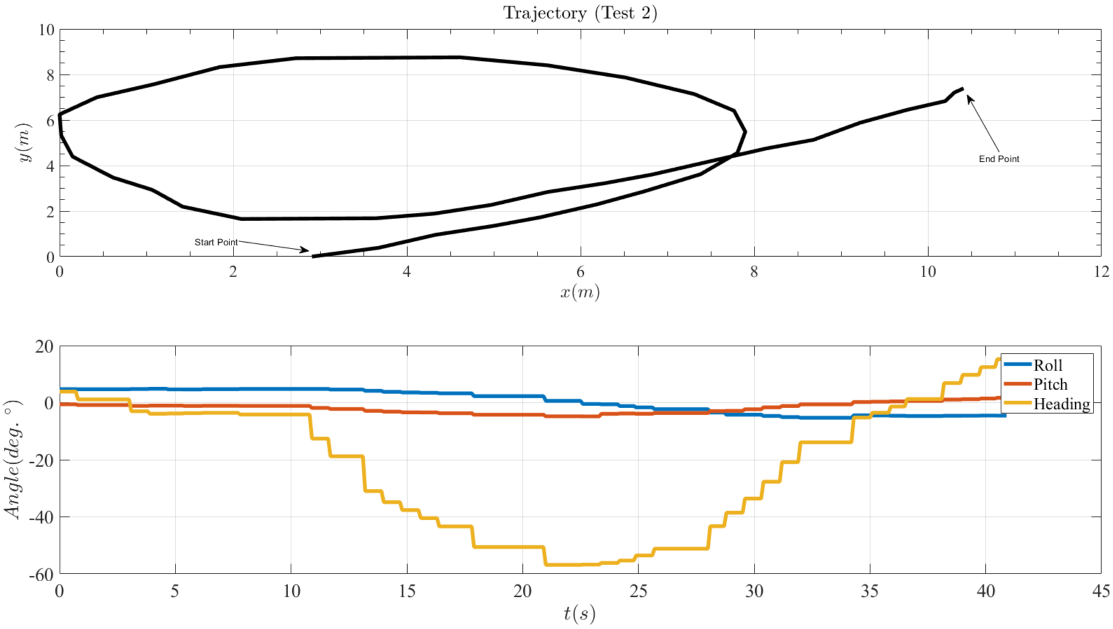

Figure 10: Turning Circle results from Test 2 (Port side)

Figure 9 and Figure 11 presents the data collected from the turning circle tests for the Starboard side while Figure 10 presents the data collected on the Port side of the USV.

Parameters	**Test 1 (Starboard)**	**Test 2 (Port)**	**Test 3 (Starboard)**
Advance (m)	8.4202	9.0802	5.7385
Transfer (m)	3.803	4.9336	4.4181
Tactical Diameter (m)	7.0774	7.184	6.8264
Loss of speed-steady turn (%)	7.24	5.75	8.01
Time to change heading 90°(s)	23.12	17.24	11.12
Time to change heading 180°(s)	31.86	24.29	18.11

Table 4: Turning Circle test results

The IMO compliance for Tactical Diameter and Advance for the three tests is detailed in Table 5. The trial data shows that the recorded values significantly exceed the specified criteria for meeting IMO standards regarding turning ability, particularly Tactical Diameter and Advance. This considerable deviation is attributed not only

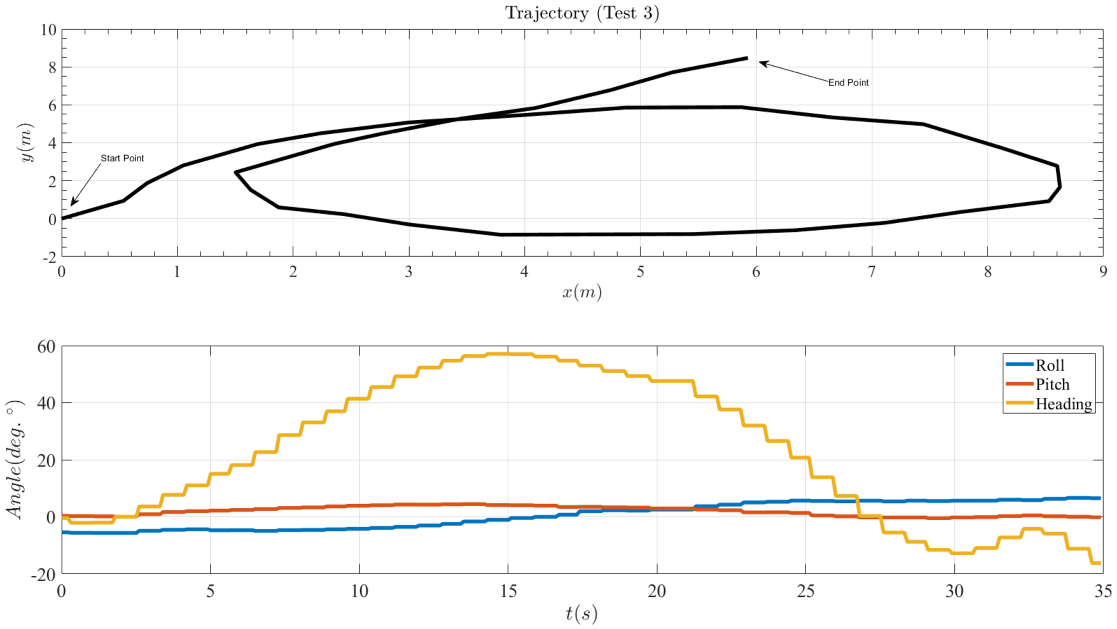

Figure 11: Turning Circle results from Test 3 (Starboard side)

Test	**Parameters**	**Measured**	**Criteria**	**IMO Compliance (Yes or No)**
1 (Starboard)	Tactical Diameter, Advance	7.0774, 8.4202	3.6, 3.24	No, No
2 (Port)	Tactical Diameter, Advance	7.184, 9.0802	3.6, 3.24	No, No
3 (Starboard)	Tactical Diameter, Advance	6.8264, 5.7385	3.6, 3.24	No, No

Table 5: IMO compliance for Turning Circle test

to the lower-cost sensor readings affecting measurement accuracy but also to external factors such as wind and surface currents in the testing area. Importantly, the measurements on the Starboard side display less variability compared to those on the Port side. The roll and pitch results from all three tests demonstrate minimal deviation, highlighting the stability and reliability of the USV, particularly in shallow waters and amidst challenging surface currents generated by wind. The recorded trials can be found at https://youtu.be/UrtKRdADDVc and the project repository can be found at https://github.com/YogangSingh/catamaranshu.

4 Lessons Learned

The dual-system approach using a Raspberry Pi and Arduino MEGA proved effective in managing both high-level computational tasks and low-level hardware interfacing. The 3D-printed hulls made from PLA filaments, reinforced with carbon fibre rods, demonstrated durability and stability in various water conditions, validating the feasibility of using cost-effective materials without compromising structural integrity. The turning circle tests highlighted significant deviations from the IMO criteria, indicating areas for improvement in sensor accuracy and propulsion control. The results showed that while the USV maintained good stability and minimal roll and pitch deviations, the tactical diameter and advance did not meet the required standards. The total cost of £487 for the USV, including electronics and mechanical parts, demonstrates that a functional USV can be developed on a low budget. Using widely available and affordable components like the Raspberry Pi, Arduino boards, and 3D-printed parts was pivotal in keeping the costs low while achieving the desired functionality. The USV achieved its aim of functional performance through successfully integrating navigation and control systems, even though the maneuverability metrics did not fully comply with IMO standards.

5 Conclusions and Future Work

The assessment of the performance and maneuverability of the designed USV was conducted through an open-water free-running turning circle test. The trial outcomes demonstrate a notable deviation from the specified IMO criteria, underscoring the imperative for further refinement in both hardware and software design for the USV.

This necessitates the incorporation of more advanced sensors and exploration of innovative design avenues. The iterative process seeks to elevate the USV's capabilities, ensuring compliance with regulatory standards while enhancing its efficiency and reliability across diverse maritime operations. Despite this, the ongoing focus on integrating CAD-designed components, 3D printed parts, and a basic sensor suite, alongside limited testing, lays a foundational framework for future enhancements.

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