

Design and Analysis of a Double-hulled Water Sampling Vessel

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Abstract:

This paper presents the design and analysis of a double-hulled water sampling vessel capable of operating in both autonomous and manual modes for environmental water sampling applications. The vessel integrates structural, propulsion, sampling, and control subsystems to ensure stable performance in near-shore and inland water environments. A dual-mode control strategy is implemented, supporting manual teleoperation via PPM signals and autonomous navigation using GPS-IMU sensor fusion with PID-based heading control. Field tests validate the system's capability for accurate waypoint tracking and safe manual override.

Keywords:

Double-hulled Vessel, Water Sampling, GPS-IMU Fusion, PID Control, PPM, PWM, Unmanned Surface Vehicle (USV)

1. Introduction

Environmental water sampling is essential for monitoring water quality, tracking pollutant dispersion, and assessing the health of aquatic ecosystems. Traditional sampling methods often rely on manual collection, which is labor-intensive, time-consuming, and may expose personnel to hazardous conditions. Unmanned Surface Vehicles (USVs) offer a promising alternative by enabling automated sampling with reduced human intervention and enhanced spatiotemporal coverage.

This study focuses on the design, control integration, and experimental validation of a low-cost double-hulled water sampling vessel that supports both manual and autonomous navigation modes to accommodate diverse mission requirements [1], [3].

2. Theoretical Basis

2.1. Hull Form and Hydrodynamics

The vessel employs a catamaran-style twin-hull configuration to improve transverse stability and reduce hydrodynamic resistance at moderate speeds. This design has two core advantages:

- (1) Increases available deck area for payload (e.g., sampling equipment, sensors);

(2) Facilitates the placement of propulsion units in each hull, enabling differential thrust steering.

Key hydrodynamic considerations include buoyancy distribution, center of gravity placement, and minimizing added resistance when carrying sampling equipment [5].

2.2. Sensors and Navigation

Accurate navigation is achieved through sensor fusion of a GPS module and an IMU (MPU-9250). A Kalman filter combines two types of data to generate stable estimates of heading and position (critical for closed-loop control):

- Low-frequency absolute positioning data from GPS;
- High-frequency inertial measurements from the IMU.

To ensure reliable IMU performance, sensor placement and magnetic interference mitigation are carefully optimized [6], [7].

2.3. Control Principles

Vessel motion is controlled through differential thrust generated by two independent propellers. A PID controller computes heading corrections based on heading error and adjusts motor commands accordingly. The control architecture supports two operation modes:

- Direct teleoperation (via PPM-to-PWM mapping);
- Autonomous closed-loop navigation [8], [11].

3. Vessel Operation Modes and PWM/PPM Control

3.1. Manual Mode (PPM Teleoperation)

In manual mode, a standard RC transmitter sends PPM signals corresponding to three core commands: throttle, steering, and mode selection. The microcontroller decodes these signals and converts them into PWM outputs for Electronic Speed Controller (ESC) operation.

Differential mapping is implemented to ensure intuitive manual control: steering inputs adjust the relative speeds of the two propellers, enabling precise direction changes [11].

3.2. Autonomous Mode (GPS+IMU with PID Control)

When autonomous mode is activated, the vessel switches to closed-loop navigation, following a four-step workflow:

Data Acquisition: GPS provides target-relative positioning, while the IMU supplies high-frequency heading data;

Sensor Fusion: A Kalman filter fuses GPS and IMU inputs to generate a filtered pose estimate;

PID Control: A PID controller adjusts motor speeds to minimize heading error and guide the vessel toward the target waypoint;

Safety Fallback: Built-in safety mechanisms ensure automatic fallback to manual control in case of sensor failure [6], [8].

4. Vessel Design and System Integration

4.1. Mechanical Layout

The twin hulls are constructed from lightweight composite materials, with sealed compartments housing electronics and batteries to prevent water damage. Key design features include:

Central Deck: Supports the sampling system (e.g., pumps, tubing);

Propulsion System: Two brushless DC motors with ESCs, optimized for thrust within the vessel's operational speed range;

Stability Optimization: Ballast and battery placement are designed to maintain a low center of gravity and proper longitudinal trim [5].

4.2. Sampling System

A peristaltic pump (located in the central compartment) enables controlled water sample collection. Critical design details for accuracy include:

Intake lines positioned below the hulls to minimize surface contamination;

Sample containers and valves arranged for easy retrieval;

Compatibility with future upgrades (e.g., automated multi-sample sequencing) [8].

4.3. Electronics and Communication

The control unit is based on an ESP32-WROOM microcontroller, with standardized interfaces for all subsystems. The table below details key components, their interfaces, and functions:

Component	Interface	Function
GPS Module	UART	Positioning data transmission
IMU (MPU-9250)	I ² C	Inertial measurement (heading, acceleration)
ESCs	Hardware PWM	Motor speed control
Telemetry/Debugging	Serial/Wireless	Real-time monitoring

The power distribution system includes voltage regulation for sensors and logic circuits to ensure stable operation [4], [6].

4.4. Rotary Sampling Module

To improve sampling efficiency, a rotary wheel sampling system was designed for the vessel. The module consists of a circular wheel equipped with eight evenly distributed sample bottles, allowing the vessel to collect up to eight water samples during a single mission. The rotary mechanism is driven by two motors: one motor controls the rotation of the lower disc to position each bottle beneath the intake nozzle, and the other motor drives a threaded cover that opens and closes each bottle. Both the wheel threads and the bottle neck threads are manufactured to identical specifications to ensure proper alignment and tight sealing. This threaded coupling design minimizes leakage, enhances durability, and ensures mechanical precision during repeated operations. By enabling fully automated, multi-bottle sampling, the

rotary module significantly reduces manual intervention and improves sampling reliability in field conditions.

5. Integrated Control System and Implementation

A dual-mode intelligent control system was developed to ensure stable navigation and operational flexibility, integrating manual teleoperation and autonomous navigation within a unified framework.

5.1. Control Architecture

The table below compares the core workflow of manual and autonomous modes [6], [8]:

Mode	Core Workflow
Manual Mode	ESP32 decodes PPM signals from RC transmitter → Maps signals to PWM outputs for ESCs → Differential steering enables real-time control
Autonomous Mode	Activated by transmitter switch → Fuses GPS/IMU data via Kalman filter → PID controller adjusts motor speeds to track waypoints

5.2. Hardware Integration

All sensors and actuators are modularly housed in waterproof compartments to withstand near-shore/inland water conditions. Key integration details:

Power Supply: ESCs are powered by a lithium-ion battery pack positioned low in the hull to enhance stability;

Sensor Placement: GPS antenna and IMU are mounted on the upper deck to minimize magnetic interference and ensure clear signal reception;

Low-Latency Control: Motor control signals are delivered via hardware PWM to reduce response delay [4].

5.3. Software and Algorithm

The control software is written in Arduino-based C++ and runs on the ESP32. The main loop executes a continuous navigation routine, with adaptive PID gains to reduce overshoot and oscillation. The control loop follows these steps:

- (1) Read GPS and IMU data;
- (2) Estimate current pose using a Kalman filter;
- (3) Compute desired heading to the target waypoint;
- (4) Calculate heading error and apply PID correction;
- (5) Update motor outputs via differential thrust;
- (6) Monitor mode switch for manual takeover [6], [8].

5.4. Safety and Mode Switching

Mode switching is designed to be seamless and fail-safe, with three critical safeguards:

Immediate Manual Takeover: Toggling the manual switch immediately restores PPM-based control;

Fault Shutdown: Invalid GPS data or IMU failure triggers motor shutdown to prevent uncontrolled motion;

Startup Calibration: A startup delay allows for ESC calibration and GPS signal acquisition [9].

5.5. Performance and Validation

Field tests confirmed the system's effectiveness, with key results:

- Reliable mode switching and responsive manual control;
- Autonomous navigation achieved an average heading error of $<5^\circ$ and maintained position within acceptable sampling tolerances;
- Energy consumption and battery life were assessed to ensure mission feasibility [3], [9].

6. Conclusions

This study developed a double-hulled unmanned water sampling vessel with hybrid manual and autonomous control capabilities. By integrating GPS–IMU sensor fusion (with Kalman filtering) and PID-based differential thrust control, the platform achieves robust heading regulation and waypoint tracking—critical for environmental sampling missions.

The twin-hull design enhances lateral stability and payload capacity, while the modular electronics support maintainability and future upgrades. Field tests validated the system's operational effectiveness in near-shore and inland waters.

- Future work will focus on three directions:
- Enhanced autonomy features;
- Real-time telemetry;
- Energy optimization for extended missions [12].

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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References

- [1] G. Katsouras et al. Use of Unmanned Surface Vehicles (USVs) in Water Quality Monitoring. *Sensors*, 2024, 24(9), 2809.

- [2] Unmanned Surface Vehicle for Intelligent Water Quality Monitoring. *Water/Environmental Journal*, 2024.
- [3] J.H. Ryu et al. Prototyping a Low-Cost Open-Source Autonomous Unmanned Surface Vehicle (iDroneboat). *J. Field Robotics*, 2022.
- [4] F. Sotelo-Torres et al. An Unmanned Surface Vehicle (USV): Development and Applications for Bathymetric Surveying. *Sensors*, 2023.
- [5] J. Zhu et al. Tuna robotics: A high-frequency experimental platform exploring the performance space of swimming fishes. *Science Robotics*, 2019, 4(34), eaax4615.
- [6] G. Welch.; G. Bishop. An Introduction to the Kalman Filter. Univ. of North Carolina, TR 95-041, 1995.
- [7] GPS-IMU Sensor Fusion for Reliable Autonomous Vehicle Navigation. arXiv preprint, 2024.
- [8] M. I. H. Z. Farouk et al. Towards online surface water quality monitoring technology. *Science of the Total Environment*, 2023.
- [9] S. Kocaman. GPS-INS integration with Kalman filtering for direct navigation. Technical Report, 2003.
- [10] J. Kim. A vehicular positioning with GPS/IMU using adaptive algorithms. *Sensors Conference*, 2016.
- [11] O. Liang. PWM and PPM Difference and Conversion. Technical Note, 2022.
- [12] H. Zheng et al. An overview of Unmanned Surface Vehicles: Methods, hardware and applications. *Ocean Engineering Review*, 2025.



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