



## Semi-Autonomous Robotic Boat, with Lora Data Acquisition

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### Abstract

Keeping waterways safe can be very challenging, especially in large areas inside countries but also across waterways that borders countries, illegal activities in waterways may be harmful and can damage the aquatic environment. Illegal trading, as well as smuggling tobacco, cannabis, and alcoholic drinks are also problematic. Additionally, armed groups can also use the waterways to smuggle goods and infiltrate into neighbouring countries, leading to violence and insecurity. To address these issues, countries are deploying police and military patrols. Unfortunately, this system uses a lot of personnel that could be deployed in other activities. However, technology can be used to solve those problems efficiently, all the time and in real-time. The primary objective of this project is the development of a scared prototype of a robotic boat that can accurately perform surveillance in real-time. This robot boat is controlled remotely by a radio communication technique that enables long-range data transmissions. It is capable of moving in all directions and is equipped with multiple sensors to facilitate the movement and avoidance of collisions during its autonomous movement. To design and develop a robust and efficient semi-autonomous surveillance boat equipped with advanced features such as a high-resolution camera, ultrasonic sensors, and GPS tracking capabilities for surveillance, on the other hand, the stability of the boat itself while moving on water, and the intercommunication between the transmitter and receiver during the remote control, and the data transmission. LoRa is one of the powerful radio communication techniques that enables Long-Range, low-power wireless data transmission, is a spread spectrum modulation technique that uses license-free radio frequency bands to create long-range communication links. The semi-autonomous robotic boat is expected to perform a real-time surveillance hance enhance security on the waterways effectively and efficiently.

**Keywords:** Robotic boat, LoRa module, semi-autonomous, Surveillance.

### 1. Introduction

A Robotic Boat is an autonomous or semi-autonomous vessel designed to operate on water without a human crew. These boats are used for various purposes such as scientific research, environmental monitoring, defense, mapping, and more. They are multiple types of Robotic Boats among them we have Autonomous Surface Vehicles (ASV) which is fully automated surface boats and Unmanned Surface Vehicles (USV) which defines a broader term that includes remote-controlled and semi-autonomous boats (Li et al., 2019). In this research the author focuses on Unmanned Surface Vehicles (USVs) which is a semi-autonomous robotic boat (Li et al., 2019).

Ghazali et al (2024) noted that the design and implementation of Unmanned Surface Vehicles (USVs) for a remarkably broad spectrum of civil applications have, in recent years, garnered an astonishingly significant amount of attention, reflecting the steadily increasing capabilities and numerous advantages as well as the extraordinary versatility these revolutionary technologies bring to various fields of activity. The continuous evolution and enhancement of USVs is closely

intertwined and aligned with the groundbreaking advancements being made in related unmanned vehicles, which also include Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs). Such impressive progress vividly illustrates how integrated technologies can greatly enhance operational effectiveness in these diverse and rapidly evolving fields, allowing for applications that were once thought to be limited or impractical. As extensively emphasized by Villa et al., the ongoing and relentless development of these vehicles opens up exciting new opportunities for their seamless and strategic integration into crucial sectors like environmental monitoring, maritime security, and oceanographic research. This notable progress is instrumental in expanding the overall scope and potential impact of these innovative and transformative platforms, both on local and global scales, ultimately contributing to enhanced capabilities in managing and protecting our water resources. Moreover, it is absolutely essential to highlight the effective integration of vital cooperative features among these sophisticated unmanned systems, which critically emphasizes the paramount importance of Guidance, Navigation, and Control (GNC) systems. These advanced systems are pivotal for executing complex, multipurpose offshore tasks, which can include effective communication, precise obstacle detection, and meticulous path planning that ensures operational safety and efficiency. The authors further underscore the pressing necessity of establishing highly reliable, high-speed communication channels and the implementation of state-of-the-art sensor technologies which include high-resolution RGB cameras and cutting-edge LiDAR systems to markedly enhance object detection and recognition capabilities in increasingly complex and challenging maritime environments. (Villa et al., 2020)

Building on this solid foundation, Atyabi, MahmoudZadeh, and Nefti-Meziani in 2018 delve deeply into the multitude of advancements in autonomous mission planning and management systems specifically designed for unmanned vehicles. Their insightful work illustrates in detail how emerging hardware technologies have significantly facilitated the development of increasingly sophisticated software solutions that empower these vehicles to engage in highly complex missions with elevated levels of situational awareness. The authors provide an extensive and comprehensive survey of autonomy assessment, meticulously discussing various challenges and potential future directions for enhancing the operational capabilities of Autonomous Underwater Vehicles (AUVs) and Unmanned Aerial Vehicles (UAVs), (Atyabi et al., 2018). This invaluable research not only highlights the growing trend towards reduced human supervision but also underscores the increasing autonomy that is becoming crucial for missions requiring adaptability to dynamic environmental conditions. It paints a picture of a future where unmanned vehicles can operate independently, responding effectively to changing circumstances in real time. (Atyabi et al., 2018)

Simon Watson et al., (2020) contributed to the discourse by addressing the localization challenges faced by Unmanned Underwater Vehicles (UUVs) in complex and confined environments. Simon Watson et al., (2020) further emphasize the limitations of traditional localization systems in such settings, which often result in suboptimal performance and reliance on manual control. Their review advocates for the development of robust localization systems that enable autonomous behavior and accurate mapping, thereby expanding the operational scope of UUVs in hazardous environments.

In the context of enhancing autonomy, Guardeño et al., (2020) present the “Robust Reactive Static Obstacle Avoidance System (RRSOAS)” tailored for USVs. This system is notable for its ability to operate without prior knowledge of the vehicle model, utilizing an estimated closed-loop model to predict trajectories effectively. The authors demonstrate the RRSOAS's robustness in navigating unknown and congested scenarios, underscoring its potential applications in environmental monitoring and surveillance.

Chang et al. (2021) build upon these advancements by focusing on the practical applications of USVs in water quality monitoring and surface cleaning. Their research advocates for the development of cost-effective USVs equipped with advanced sensors for hydrographic measurement and obstacle avoidance. The integration of deep learning algorithms for obstacle detection and segmentation represents a significant leap in enhancing the operational efficiency of USVs. The authors present various examples of USVs designed for specific tasks, such as water

sampling and quality assessment, illustrating the diverse applications of these vehicles in civil contexts.

Through this literature review, it becomes evident that the design and implementation of USVs are rapidly evolving, driven by technological advancements and the need for innovative solutions in civil applications. The articles collectively highlight the critical components of USV systems, including autonomy, localization, obstacle avoidance, and mission planning, setting the stage for future research and innovation in this dynamic field (Alqudsi et al., 2025)

## **2. Methodology and Techniques**

### **2.1 Robotic Boat Design overview**

The design of the advanced robotic boat specifically emphasizes the need to achieve an optimal balance between stability, maneuverability, and durability. This careful balance is essential to ensure effective operation in a wide range of varying civil environments, accommodating different challenges and conditions.

#### **2.1.1. Design Requirements**

The innovative robotic boat is designed and engineered to effectively fulfil essential practical roles within a variety of civil environments and applications. The key design goals include creating a user-friendly platform that incorporates straightforward, widely accessible construction techniques, ensuring that the assembly and maintenance are manageable for users with different skill levels. The boat will be controlled via an intuitive interface that can be operated from familiar devices such as smartphones, tablets, or personal computers, making it easy for users to navigate and manage the vessel remotely. Stability and ease of recovery from disturbances are critical features aimed at enhancing overall operational safety, thereby reducing the risks associated with its use in various settings. Moreover, provisions for rapid charging are meticulously designed to underpin a prolonged, uninterrupted service, ensuring the robotic boat can perform its intended tasks without frequent downtime. The design ambitiously seeks to achieve a minimal aquatic silhouette that is complemented by a strategically low center of gravity. These features work together to promote efficient water displacement while bolstering overall stability in various water conditions. Toward ensuring operational longevity, the platform intends to have a traversing range that exceeds 5 kilometres, along with a maximum cruising velocity that is not less than 3 metres per second, allowing for effective coverage and operation in diverse aquatic environments. This advanced vessel embodies the thoughtful integration of technology and design, set to enhance utility and functionality in civil operational domains.

#### **2.1.2. Hull Design**

The hull design of the robotic boat draws on the autonomy methods described by (Patrick Gigliotti & Edward Wall, 2017) and the hull configuration analyses of (M. Nowak et al., 2008). These studies illustrate the application of physical design aspects for autonomous marine vehicles. The selection of an appropriate hull type is fundamental for accommodating the necessary components and aligning with mission objectives. Hulls must balance hydrodynamic efficiency with capacity for electrical and mechanical installations. The main categories of hull forms include displacement, planing, and semi-planing. Displacement hulls offer steady motion with low power consumption but face speed limitations due to wave resistance. Planing hulls allow for higher speeds at increased power draw, generating substantial hydrodynamic lift and wave creation. Semi-planing hulls represent a compromise between displacement and planing forms and thus were adopted for the current design.

#### **2.1.3. Propulsion System**

The robotic boat incorporates a propulsion system carefully designed to meet operational requirements. Two electric motors, each coupled with a propeller, provide the thrust necessary for movement and maneuvering. The use of electric motors offers advantages in simplicity, reliability, and maintainability, as previously noted in a five-degree-of-freedom robotic submersible developed for gentle-water testing (M. Mbithi, 2014). In that system, four thrusters—two

horizontal and two vertical—enabled independent control of surge, sway, yaw, heave, and pitch to ensure precise positioning during experimental tasks. This arrangement demonstrates how electric motor-driven propulsion can deliver versatile and controlled motion in aquatic vehicles.

#### **2.1.4. Control System**

This section defines the design approach and implementation of the control system for the robotic boat (Alseari et al., 2024). The design objective targets autonomous navigation capability through the transition from remote to fully automated operation.

The control system supervises the functionality of critical components, including the propulsion engine, rudder, and sensor array. It accepts high-level navigation commands from the user interface layer and translates these into motor and rudder control signals.

The control strategy facilitates two operational modes: remote and automatic. In the remote mode, the system acts as an intermediary, relaying commanded motor throttle and rudder angle values directly to the respective actuators. The automatic mode introduces a closed-loop digital control algorithm that converts desired course values into corresponding control commands. In this mode, the system integrates feedback from a global positioning system and a magnetic compass to execute a point-to-point navigation approach, dynamically generating the necessary throttle and rudder adjustments. User commands include modes such as manual control, position hold, command following, and route following, providing a hierarchy of autonomy corresponding to user input.

The coordinated interaction between hardware, firmware, and embedded software realizes the full functional scope of the control system. External commands, communication standards, interface signals, data protocols, and error handling strategies form the interface specifications of the system. Sensor data acquisition, processing of navigation instructions, and autonomous generation of motor and rudder setpoints represent the operational workflow engaged in response to supervisory input.

#### **2.1.5. Balance Control of Robotic Boat**

Balance control of a robotic boat involves the intricate management of its stability and orientation while navigating through various water conditions. This process relies on a combination of sensors, feedback systems, and control algorithms to ensure that the boat maintains an optimal center of gravity and resists tipping or swaying. Key components of balance control include gyroscopes and accelerometers, which provide real-time data on the boat's motion and posture. These sensors detect changes in pitch and roll, allowing the control system to make precise adjustments to the propulsion and steering mechanisms. Moreover, implementing adaptive control strategies enables the robotic boat to respond dynamically to external forces, such as waves or wind, effectively countering disturbances to maintain a steady course. Actuators play a crucial role in this system, adjusting the boat's hull configuration and center of buoyancy as needed to enhance balance. In summary, effective balance control in a robotic boat requires an integrated approach that combines hardware components with sophisticated software algorithms, ensuring reliable performance and stability across varying aquatic environments.

#### **2.1.6. USV Kinematic Model**

In the area of kinematics, an ocean vessel moves in six DOFs, that are defined by: surge, sway, heave, roll, pitch, and yaw (Li et al., 2019). But in reality, the six-DOF model is complicated to design. Because some DOFs in the USV model and in Robotic boat in general have inherent stability, and the model can be simplified (Li et al., 2019). The buoyancy of the USV stabilizes the regular motion so that heave can be ignored, and because of the sufficient longitudinal and lateral metacentric height of the USV, the motion of roll and pitch can also be ignored (Li et al., 2019). Therefore, the six-DOF model can be simplified to a three-DOF model to describe the planar motions of USV in surge, sway and yaw (Mu et al., 2018).

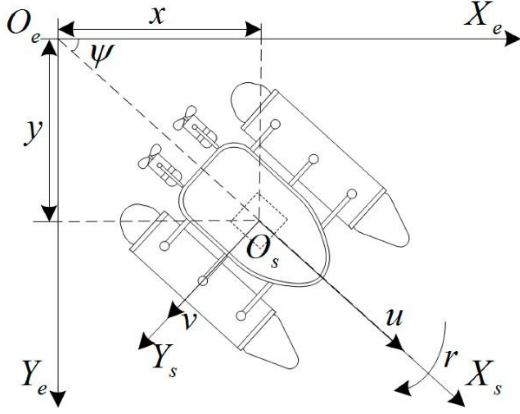


Fig. 1. Schematic diagram of three DOF of the USV (Li et al., 2019).

To estimate and determine the model equations of motion, two reference coordinates systems are needed and considered (Li et al., 2019). Those are the inertial or fixed to earth frame  $O_e X_e Y_e$  that may be placed to coincide with the USV fixed coordinates in some initial condition and the body-fixed frame  $O_s X_s Y_s$  in Figure 1 (Li et al., 2019). However the motion of the earth do not affects the USV easily, the earth-fixed frame  $O_e X_e Y_e$  can be considered to be inertial, the body axes  $O_s X_s$  and  $O_s Y_s$  coincide with the principal axes of inertia and are most of the time defined as follows:  $O_s X_s$  is the longitudinal axis;  $O_s Y_s$  is the transverse axis (Li et al., 2019). A kind of unmanned boat kinematic model characterized by unperturbed horizontal plane motion (Kolev et al., 2021). is given in Equation (1) as in (Li et al., 2019).

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta}) \mathbf{u} \quad (1)$$

In the case that  $\boldsymbol{\eta} = [x \ y \ \psi]^T$  is the position ( $x$ ,  $y$ ) and yaw ( $\psi$ ) of the unmanned surface vehicles in the earth-fixed frame,  $\dot{\boldsymbol{\eta}} = [\dot{x} \ \dot{y} \ \dot{\psi}]^T$  describes the vehicle linear North ( $\dot{x}$ ), East ( $\dot{y}$ ), and Z-axis angular velocities ( $\dot{\psi}$ ) in the earth-fixed frame (Li et al., 2019),  $\mathbf{u} = [u \ v \ r]^T$  is the vehicle surge velocity ( $u$ ), sway velocity ( $v$ ) and yaw rate ( $r$ ) and the transformation matrix  $\mathbf{J}(\boldsymbol{\eta})$ , related to yaw ( $\psi$ ) (Li et al., 2019)., is given in Equation (2) below:

$$\mathbf{J}(\boldsymbol{\eta}) = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

If we substitute Equation (2) into Equation (1) we get:

$$\begin{cases} \dot{x} = u \cos \psi - v \sin \psi \\ \dot{y} = u \sin \psi + v \cos \psi \\ \dot{\psi} = r \end{cases}$$

### 2.1.7 PID Controller

A simplified schematic diagram of the PID controller used to control the propulsion motor of the Unmanned Surface Vehicles is presented by (Bian et al., 2022). The optimum control is achieved by making a comparison of the set value of USV motion with the actual output value, and the PID controller adjusts the motor speed via the speed limiting link to minimize deviation between the set value and output values, and finally, the movement of USV is controlled by the servo structure

(Bian et al., 2022). The kind of PID control system can be formulated in the form highlighted in Equation (3)

$$u(t) = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(t) dt + K_p T_d \frac{de(t)}{dt} \quad (3)$$

the  $u(t)$  is the output of the controller, that is, the signal sent to the controlled object;  $r(t)$  and  $y(t)$  are the input and output signals of the system;  $e(t)$  is the input to the controller, that is, the error of the system determined by  $r(t)$  and  $y(t)$ ,  $e(t) = y(t) - r(t)$ . Deviations are collected by sampling and used as feedback to control the system (Bian et al., 2022). Nowadays most computerized control systems require digital inputs; therefore, the continuous analog signals in Equation (1) must be transformed using the transfer function (Bian et al., 2022). in Equation (4)

$$H(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D \cdot s \quad (4)$$

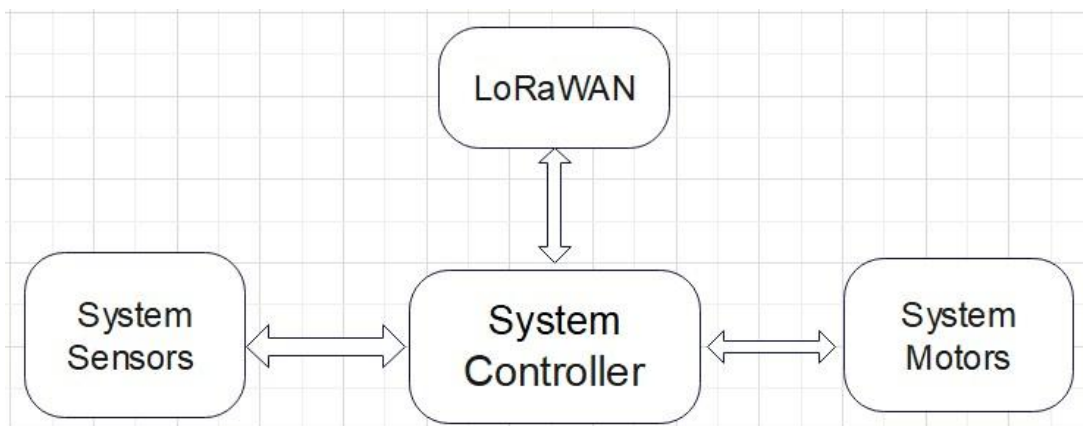
where  $K_D$  is the differential coefficient,  $K_P$  is the proportional coefficient, and  $K_I$  is the integral coefficient (Bian et al., 2022). The coefficients are related according to Equation (5)

$$K_I = K_p \frac{T}{T_i} \quad , \quad K_D = K_p \frac{T_d}{T} \quad (5)$$

where  $T_i$  represents integral time constant,  $T_d$  represents the differential time constant,  $T$  is the sampling period.

According to equations (3) to (5), the PID controller of the motor operates according to three parameters:  $K_P$ ,  $K_I$ , and  $K_D$ , and those three parameters represent changes in the proportional, integral, and differential functions of the PID controller, respectively, and have different functions in the controller:  $K_P$  mainly affects the response time of the system; if  $K_P$  is small, the response time is slow, and the system is basically non-oscillatory. In contrast, if  $K_P$  is large, the system will experience high-frequency oscillation (Bian et al., 2022). The main function of  $K_I$  is to eliminate steady-state error and increase stability of the system;  $K_D$  is mainly used to improve the dynamic performance of the system but can also prolong the time it takes for the system to adjust (Bian et al., 2022).

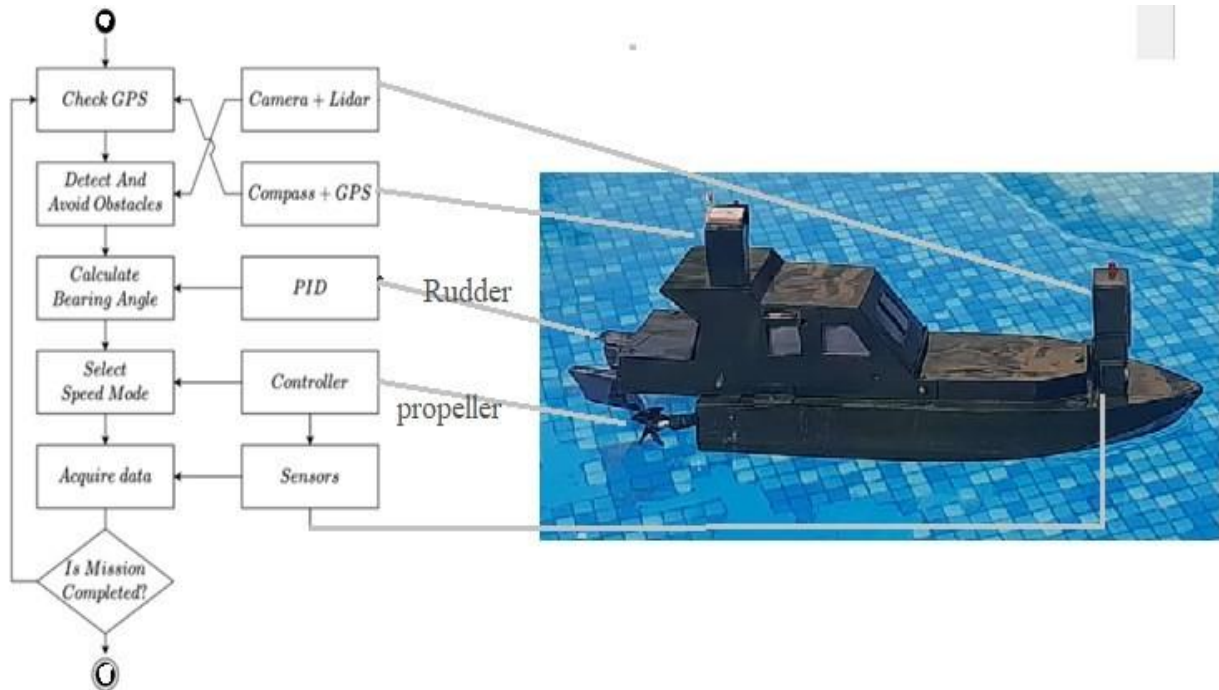
## 2.2. Architecture and Block Diagrams of the Proposed System



**Fig. 2:** General block diagram of the proposed system.

The designed architecture of the developed model as highlighted on Figure 2, is mainly composed of the system sensors for physical environment data measurement, system controller for decision making and the system motors as actuators.

### Architecture of the Autonomous System



**Fig. 3:** Proposed Robotic boat autonomous flowchart

The logic sequence of data of the main block in the architecture consists of bellow steps.

**Step 1:** “check the position of the Robotic Boat using a navigation system consisting of a compass and GPS” (Kolev et al., 2021).

**Step 2:** “determining the presence of obstacles along the path of the Robotic Boat and, if necessary, launching an obstacle avoidance program. A sensor subsystem equipped with LiDAR and a camera is used” (Kolev et al., 2021).

**Step 3:** “determining whether it is required to make a turn. If necessary, the bearing angle is calculated, and with the PID controller fed with the difference between heading and bearing angles, the boat changes its direction” (Kolev et al., 2021).

**Step 4:** “rotation speed of the propeller is established” (Kolev et al., 2021).

**Step 5:** “if the boat is on a monitoring mission, it performs measurements and writes the results into the database, including current GPS coordinates. And appropriate set of sensors is required onboard” (Kolev et al., 2021).

**Step 6:** “checking the end of the mission. If this condition is met, the boat stops” (Kolev et al., 2021). The flowchart as shown on Figure 3 is a combined instructions flow of autonomous and remote systems.

### 3. Experiments and Results

Based on the developed PID control algorithm for heading control system, a couple of experiments were carried out with the designed Robotic boat (Miao et al., 2018). Different waterways of different characteristics have been used for testing the implemented prototype. It is important to highlight that during the experiments that the compass module have to be located a bit far from the control module, communication module and GPS module, in fact their signal transmission tend to interfere with it (Miao et al., 2018). A separate power system will be used to minimize the signal interactions of the wireless communication module, microcontroller system, and the sensor signals (Miao et al., 2018).



**Fig. 4:** River experiment of Robotic boat

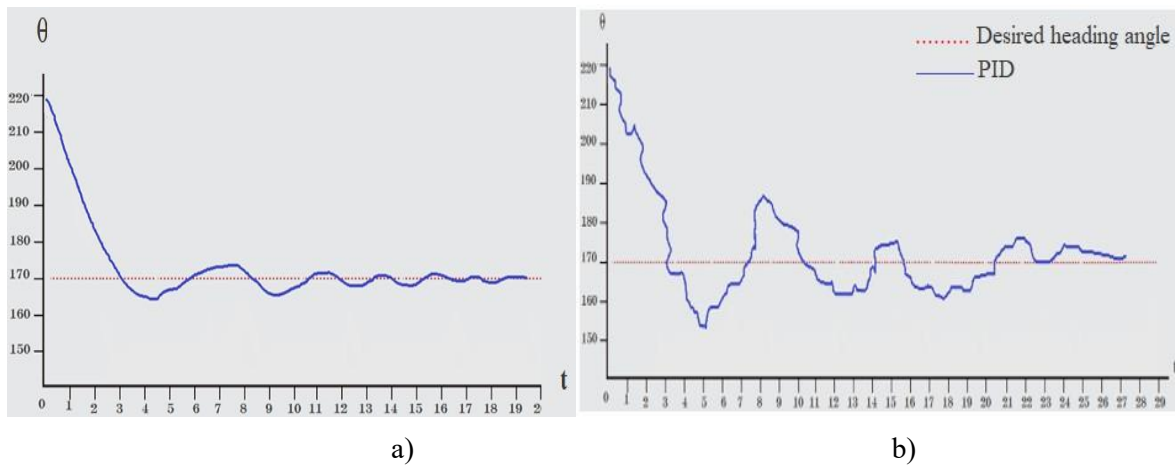
#### 3.1 Pool Experiments

Two types of experiment are carried out. The first experiment was to assess the performance of the Robot boat when it not autonomous, means when it is remotely controlled trough LoRa communication systems. a series of pool experiments are carried out to verify the reliability of the LoRa module (Miao et al., 2018). Multiple experimental set-up and situations are shown in Figure 4 and Figure 5.



**Fig. 5:** Pool experiment of Robotic Boat

Designing an effective PID controller in the Robotic boat system involves accurate selection of the proportional, integral, and derivative gains. Several classical methods facilitate this tuning process. The performance of the 2 movement is represented on the Figure 6 above. Curves obtained for different algorithms; the remote controlled and the PID controller response which are obtained in the pool experiments.



**Fig. 6:** Output of the LoRa and autonomous PID system

#### 4. Discussion

The findings showed a great potential for real-time monitoring with LoRa communication, the movement of the boat with a remote-control system through LoRa was satisfying and performed as expected. However, Environmental disturbances and nonlinearities in boat dynamics present particular challenges for PID control of Robotic Boat in the autonomous movement. pool waves and varying wind conditions generate sudden and strong disturbances that degrade longitudinal velocity and heading control accuracy unless the controller responds properly. Moreover, hydrodynamic forces on the boat around forward velocity change extensively in magnitude and direction for the same surge and yaw velocities, which complicates the realization of a fixed gain controller. Parameters such as boat mass and moment of inertia may vary dynamically with payload and water depth, respectively, while fixed gains cannot track such variations. In general, a straightforward PID controller provides satisfactory performance for primary control of Robotic Boat under certain limited conditions. This innovative solution can help improve security, protect the environment, and safeguard the lives of the local community. By addressing these challenges, the boat plays an important role in ensuring safety.

#### 5. Conclusion

This paper proposed a combination of autonomous and remote-controlled Robotic boat. The autonomous system is based on sensors. Mainly, GPS, ultrasonic and camera, and a PID control

algorithm for Robotic boat heading control system. The motion control system for the boat is designed based on the controller, and on the designed software system. The hardware system and software system for the Robotic boat proposed in this paper can provide reliable and accurate reference and technical support for the development of other USV systems (Miao et al., 2018). A large number of pool experiments and river experiments are carried out, to verify the effectiveness and reliability of the designed motion control system and the heading control algorithm proposed in this paper (Miao et al., 2018). Experiment results show that the proposed PID control algorithm performed the desired objectives, however improved PID like adaptive S-PID control algorithm may result in great performance. It is also noted that the control stability and the reliability are both better with LoRa communication system. Equipped with a camera, ultrasonic sensor, and GPS, the boat can effectively monitor the waterways and detect potential threats. The data is accurately transmitted and visualized, which allows the surveillance to be done as expected.

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