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Robust control for twin-hull USV meant for lagoon surveillance

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Abstract

The protection and monitoring of coral nurseries are essential for preserving marine ecosystems. This research focuses on developing an unmanned surface vehicle (USV) to aid in coral nursery surveillance and monitoring in lagoon environments. The objective of this project is to design a twin-hull USV equipped with robust control algorithms for autonomous navigation in dynamic maritime conditions. A control system was developed using both PID and H-infinity control algorithms to manage the USV's navigation and station-keeping. The twin-hull model was simulated in a 3DOF framework using the Virtual RobotX platform, with Line-of-Sight (LOS) guidance enhancing waypoint tracking. The hybrid control system, combining H-infinity for linear velocity and PID for angular velocity, showed improved resilience to environmental disturbances, resulting in smoother transitions and more accurate waypoint tracking. LOS guidance further enhanced system reliability. The developed system lays a solid foundation for future work, with further tuning of the control loop and prevention of overshoots as the next focus.

Contents

Abbreviations

USV	Unmanned Surface Vehicle
DOF	Degrees of Freedom
ENU	East-North-Up
WAMV	Wave Adaptive Modular Vessel
IMU	Inertial Measurement Unit
GPS	Global Positioning System
GNC	Guidance, Navigation, and Control
ROS	Robot Operating System
PID	Proportional-Integral-Derivative

1. Introduction

Coral reefs are an important ecosystem of our plant. They harbor a rich variety of aquatic life, provide coastal protection and contribute significantly to the global economy. However, human activity and climate change have been damaging these fragile environments. To ensure the survival of these vital organisms, we need to design effective conservation strategies that rely on accurate monitoring and data collection.

Unmanned Surface Vehicles (USVs) are emerging as a powerful tool in this effort. They offer a safer, more cost-effective solution for surveying marine environments, reducing the need for human presence in difficult-to-navigate areas. This research focuses on developing a robust control system for a USV designed to autonomously navigate and monitor coral nurseries in lagoon environments.

The main goal of this project is to create a control system that allows the USV to carry out missions with minimal human intervention, even in challenging conditions like strong currents or rough seas. Either by using a pure PID controller or a hybrid approach, combine H-infinity control for linear movement and PID control for angular velocity, the USV can navigate these complex environments more effectively.

Navigating in lagoon environments can be challenging. Shallow waters, changing currents, and various obstacles create a dynamic environment where precise control is crucial. The control system being developed in this study is designed to handle these challenges by making real-time adjustments to the USV's path and speed. This allows the vehicle to smoothly transition between waypoints and effectively "hold station" in difficult conditions, ensuring the success of data collection missions.

Through simulations, this study evaluates the performance of the hybrid control system under a variety of conditions, comparing it to traditional PID control. The focus is on how well the USV can maintain smooth, stable navigation and stay on course, especially when dealing with disturbances like waves. The results aim to show how this approach improves the USV's performance, making it a more reliable tool for monitoring and protecting coral reefs.

In summary, this research paper focuses on developing a robust control system that will enable USVs to carry autonomous missions in lagoon environments. This will contribute to the broader effort of preserving our coral reefs.

1.1 Literature review

The purpose of this research is to aid in the development of an unmanned surface vehicle (USV), in particular, a twin-hull catamaran. The ultimate goal is to use this USV for lagoon surveillance and coral nursery monitoring. While there is a significant number of USV designs that have been researched and published, most of them share common components and design philosophies in terms of software and hardware. This provides a good foundation for this project.

When designing a USV, the first thing to consider is the hull design. The literature highlights 2 types of hull design: the twin-hull catamaran (Blaich, et al., September 17-20, 2013) and the single-hull boat (O., et al., 2012). The most popular choice is often the twin-hull design, chosen for its stability, higher payload capacity (Manley, 1997) and resistance to getting flipped over, all of which make it a great choice for autonomous missions. Other advantages of the twin-hull would be features that increase its survivability such as, buoyancy redundancy ensuring that the vessel will stay afloat in the event that one hull is damaged. This would allow it to “limp” back to a collection point instead of sinking and potentially losing equipment and data. The vessel used as a model in this project, the Wave Adaptive Modular Vehicle (WAMV), has hulls made of polymer, a durable, buoyant material, although expensive to fabricate. With recent advances in 3D printing technology, the hull could also be designed in computer aided design software and 3D printed using suitable filament(Mitchell, 2022). Recent advances in 3D printing technology offer an alternative method for fabricating USV hulls. While this approach could streamline production in future projects, the costs and time involved in printing large parts may limit its feasibility for this research. A more affordable approach would be to fabricate fiberglass hulls, being highly durable and repairable. Like 3D printing, fiberglass hulls can also be fabricated without depending on a manufacturer.

The Small Waterplane Area Twin-Hull (SWATH) design was also considered as a potential format. This type of hull minimizes the impact of waves, making it highly effective in rough open sea environment (Beck, et al., 2008). The downside is that this model is a lot more complex and the conditions of the target environment, lagoon, in this project do not warrant the need for such a robot. A more straightforward hull design like the catamaran offers stability and ease of construction, making it the practical choice.

Before attempting to programmatically control a robot, one must first understand the mathematics and physics that act upon it. Understanding the dynamics of the vessel will make designing a control scheme much more effective. The twin-hull model operates on six degrees of freedom, however to simplify research and development, we will consider the three degrees of freedom model provided by (Fossen, 2011). Surge, sway and yaw, these 3 axes of movement must be controlled for effective navigation and obstacle avoidance. To test and refine the control algorithm, the Virtual RobotX simulation environment (Bingham, et al., 2019) is being used, this saves us the trouble and resources of building or buying a full-size USV. While it may be a simulation, when developing a USV for real world applications, we will have a system that will only need some re-tuning and adjustments to the control loop.

The simplest and most popular controller used is the humble PID controller (Gonzalez-Garcia, et al., November 2019). It is easy to implement, fast and suitable for most applications. Using the error between the desired pose and actual pose, the output signal is adjusted accordingly. While PID is suitable for stable environments, it may struggle in maritime scenarios where wavs and currents could lead to less precise navigation. That’s why we look at robust control algorithms, like, H-infinity control. H-infinity control is well suited for environments with lots of uncertainties and disturbances. As opposed to PID, which relies on a fixed response, H-infinity control minimizes the worst-case impact of disturbances while ensuring greater stability even in unpredictable environments. (Cutipa Luque, 2020)

In this project, we have implemented two control loop systems for comparison: one using a purely PID controller and the other utilizing a hybrid control system. The PID controller serves as a baseline, providing a straightforward control loop that adjusts based on the error between the desired and actual positions. While it is simple and effective under ideal conditions, it has been observed to struggle in more complex environments, such as when navigating in the lagoon, where currents and waves introduce significant disturbances.

To address these challenges, we also developed a hybrid control system that combines H-infinity control for linear velocity with PID control for angular velocity. This system provides a more robust and adaptable solution, capable of maintaining smooth navigation even in unpredictable conditions. The hybrid control loop leverages the strengths of both controllers, ensuring stability against environmental disturbances while still allowing for precise heading adjustments.

Augmenting both control loops is the Line-of-Sight (LOS) guidance system, which ensures that the USV tracks and follows predefined waypoints efficiently. The LOS system helps the USV determine its desired heading by continuously calculating the direct path to the next waypoint. In the purely PID-controlled system, the LOS guidance supports basic course corrections, but in the hybrid system, it significantly enhances performance by working in tandem with the robust control capabilities of the H-infinity algorithm, ensuring smoother transitions between waypoints and more accurate trajectory tracking, even under varying environmental conditions.

2. Objectives

The primary objective of this research is to design and implement a robust control system for a USV, capable of performing autonomous missions and data gathering in dynamic and challenging lagoon environments. The control system combines hybrid control strategies—such as H-infinity for linear velocity and PID for angular control—to ensure smooth navigation, even under rough sea conditions. By integrating well-established technologies and algorithms for Line-of-Sight (LOS) guidance and state estimation, the USV will maintain effective station-keeping and precise waypoint navigation. This system will prioritize stability, smooth transitions, and adaptability in response to environmental disturbances, ensuring both equipment durability and mission success.

2.1 Research Methodology

This section outlines the research approach, system development, and validation processes used to design and implement a robust control system for the USV, focusing on its performance in dynamic lagoon environments.

2.2.1 Review of Existing Literature:

- Review the latest developments in USV control systems, with particular emphasis on hybrid control strategies (H-infinity and PID) for autonomous marine vehicles.
- Analyze literature on Line-of-Sight (LOS) guidance techniques and their application in autonomous navigation for rough sea conditions.
- Identify knowledge gaps related to robust station-keeping and smooth navigation in dynamic environments such as coral nurseries.

2.2.2 System Design and Integration:

- Develop a hybrid control system incorporating H-infinity control for linear velocity and PID control for angular velocity to ensure smooth navigation and effective station-keeping.
- Integrate sensors and actuators necessary for real-time environmental feedback, focusing on robustness in dynamic environments with wave disturbances.
- Design a flexible system architecture, prioritizing sensor data integration for path correction and control optimization.

2.2.3 Path Planning and Navigation:

- Develop and optimize path-following algorithms that allow the USV to navigate through dynamic and unpredictable lagoon environments while minimizing deviations from the expected path.
- Implement Line-of-Sight (LOS) guidance, ensuring real-time adjustments to the USV's heading and speed based on feedback from sensors.
- Incorporate station-keeping functionality, focusing on the system's ability to maintain its position in the presence of external disturbances, such as rough waves or currents.

2.2.4 Experimental Validation:

- Conduct simulation-based experiments using rough sea conditions in Gazebo to validate the control system's performance, with a focus on smoothness of navigation, waypoint transitions, and station-keeping.
- Compare the hybrid control system's performance against traditional PID control under both ideal and challenging conditions.
- Evaluate system performance metrics, such as stability, accuracy of station-keeping, and smoothness of movement, to assess improvements over last year's control implementation.

3. Modelling the USV

This chapter discusses the modelling of the Unmanned Surface Vehicle (USV), using the framework proposed by Fossen (Fossen, 2011). The purpose of a model is to depict how external forces, including gravity and friction, impact an object. Different physical laws can be used to derive a model, and simplifications can be made by making certain assumptions about the physical properties of the object. These assumptions may include considering symmetry, neglecting coupling inertia, assuming travel at low velocities, and other relevant factors.

Table 1 Standard notation of USV motion (SNAME, 1950)

DOF	Motions	Forces and Moments	Linear and Angular velocities	Position and Euler Angle
1	Surge	X	u	x
2	Sway	Y	v	y
3	Yaw	N	r	ψ

3.1 Coordinate Systems and Kinematics

The USV is modelled as a 3 DOF system (x, y and r axes) (Fahimi, 2009). The kinematics are explained in two sets of coordinate systems: the USV frame of reference (u, v, r) and the Earth frame of reference (x, y, r).

The USV frame of reference provides a localized coordinate system that is essential for measuring and analyzing the movement and behavior of the USV. This frame is defined by three key axes: the X-axis (u), which corresponds to the longitudinal direction, capturing forward and backward motion; the Y-axis (v), which represents the transverse direction, capturing lateral or side-to-side motion; and the Z-axis, which, although relevant for vertical motion, is typically excluded in surface vehicle analyses. Additionally, the rotational motion about the vertical axis is represented by the yaw rate (r).

In contrast, the Earth frame of reference functions as a global coordinate system, offering a fixed framework for describing the USV's position and motion relative to the Earth’s surface. Within this frame, the X-axis is aligned with the east-west direction (parallel to lines of longitude), the Y-axis aligns with the north-south direction (parallel to lines of latitude), and the Z-axis corresponds to elevation or altitude.

Establishing a relationship between the USV frame of reference and the Earth frame of reference is critical for accurate navigation and coordination. By mapping the USV’s local coordinates and motion onto the global Earth coordinates, it becomes possible to precisely determine and communicate the USV’s position, orientation, and movement relative to the Earth’s surface. This capability is fundamental for ensuring effective navigation and seamless integration with other Earth-based systems or objects.

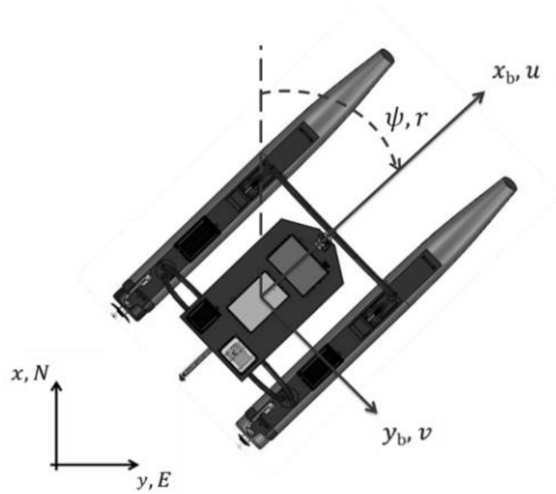

Figure 1 Schematic diagram of DOF of the WAMV (Sarda, et al., 2016)

In order to transform the equation from the USV frame of reference to the Earth frame of reference, the kinematics equation in Equation (3) is used.

$$\dot{\eta} = J(\eta)V \tag{1}$$

Where η = [x y ψ] ^{T} is the position (x and y) and yaw (ψ) of the USV in the Earth frame of reference and η-dot represents the vector of the linear velocities in the x and y directions, as well as the angular velocity in the yaw direction. J(η) is described by the transformation matrix in (4).

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

V = [u v r] ^{T} is a vector that denotes the linear velocity in the u and v directions, along with the angular velocity in the r direction. This interpretation is applicable in the USV frame of reference or body coordinate system. Therefore, the kinematic equation of the USV is described by equations (5) to (9).

$$\dot{\eta} = \begin{bmatrix} cos\,\psi & -sin\,\psi & 0 \\ sin\,\psi & cos\,\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} cos\,\psi & -sin\,\psi & 0 \\ sin\,\psi & cos\,\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} \tag{4}$$

$$\dot{x} = ucos\psi - vsin\psi \tag{5}$$

$$\dot{y} = ucos\psi \ + vsin\psi \tag{6}$$

$$\dot{\psi} = r \tag{7}$$

3.2 Dynamics of the USV

This part discusses the motion of the USV and develops its dynamic model by examining the forces acting upon it. The dynamic model used for the USV uses Fossen's model (Fossen, 2011) as a starting point. For analysis simplification, the USV is considered as a rigid body. The dynamics equation of the USV is formulated in a matrix representation.

$$M\dot{V} + C(V)V + D(V)V = \tau + \tau_{wind} + \tau_{wave} \tag{8}$$

The matrices M, C(V) and D(V) describe how inertia, Coriolis and Centripetal forces and Damping forces affect the USV. Vector τ represent the actuating force and moment generated by the thrusters. τ_{wind} and τ_{wave} are external forces originating from the wind and waves. The matrices are expressed in the equations (11) to (13).

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & -my_g \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ -my_g & mx_g & I_Z - N_{\dot{r}} \end{bmatrix} \tag{9}$$

$$C(V) = \begin{bmatrix} 0 & 0 & -m(x_g r + v) + Y_{\dot{v}} v + \frac{y_{\dot{r}+N_{\dot{v}}}}{2} r \\ 0 & 0 & (m - X_{\dot{u}})u \\ m(x_g r + v) - Y_{\dot{v}} v - \frac{y_{\dot{r}+N_{\dot{v}}}}{2} r & -(m - X_{\dot{u}})u & 0 \end{bmatrix} \tag{10}$$

$$D(V) = \begin{bmatrix} X_u & 0 & 0 \\ 0 & Y_v & Y_r \\ 0 & N_v & N_r \end{bmatrix} \tag{11}$$

$$\tau = \begin{bmatrix} X_{T1} + X_{T2} \\ 0 \\ (X_{T1} - X_{T2})c \end{bmatrix} \tag{12}$$

As this research is conducted in a simulation environment (Bingham, et al., 2019), environmental disturbances τ_{wind} and τ_{wave} can be neglected. (Li, et al., 2019) suggests that the sway force resulting from yaw rotation ($Y_{\dot{r}}$) and yaw moment brought about by acceleration in the sway direction ($N_{\dot{v}}$) are much smaller than the inertial and additional mass terms. Taking into account that the USV center of gravity is parallel to the USV frame of reference in the horizontal direction, $y_g = 0$.

X_{T1} and X_{T2} are the thrust force by the two thrusters used in the system. These forces are outlined as

$$X_{T1} = \frac{F_0}{2} + \frac{\delta}{2} \tag{13}$$

$$X_{T2} = \frac{F_0}{2} - \frac{\delta}{2} \tag{14}$$

where, F_0 represents the total thrust force and δ is the differential thrust force. The magnitude of δ changes the rotational speed of the heading of the USV.

When applying these assumptions, the dynamic model is reduced to

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g & I_Z - N_{\dot{r}} \end{bmatrix} \tag{15}$$

$$C(V) = \begin{bmatrix} 0 & 0 & -m(x_g r + v) + Y_{\dot{v}} v \\ 0 & 0 & (m - X_{\dot{u}})u \\ m(x_g r + v) - Y_{\dot{v}} v & -(m - X_{\dot{u}})u & 0 \end{bmatrix} \tag{16}$$

$$D(V) = \begin{bmatrix} X_u & 0 & 0 \\ 0 & Y_v & 0 \\ 0 & 0 & N_r \end{bmatrix} \tag{17}$$

$$\tau = \begin{bmatrix} F_0 \\ 0 \\ \delta c \end{bmatrix} \tag{18}$$

Table 2 The notation and description of parameters used in the dynamic model

Notation	Description
$X_{\dot{u}}$	Additional mass when moving in direction u.
$Y_{\dot{v}}$	Additional mass when moving in direction v.
$N_{\dot{r}}$	Additional mass when moving in direction r.
X_u	Sum of linear drag force when sailing in translational direction u.
Y_v	Sum of linear drag force when sailing in translational direction v.
N_r	Sum of linear drag force when sailing in rotational direction r.

3.3 State Space Representation

In this section, the dynamic model of the USV is converted to state-space representation, for the development and implementation of robust control. The control strategy of this paper, computing the linear and angular velocity to be achieved by the USV based on previous and current values of the linear and angular velocities of the vessel qualifies as a MIMO system, which benefits from this approach.

3.3.1 Defining State Variables

The state vector **x** captures the USV's key dynamics, linear velocities u and v along the x and y axes, and the angular velocity r around the vertical axis:

$$x = [u\ v\ r]^T \tag{19}$$

3.3.2 Input Vector

The input vector to our H-Infinity controller will include the linear and angular velocities, $v\ and\ r$. These inputs represent the control objectives that the controller will regulate to achieve the desired motion and orientation of the USV.

$$u = [v\ r]^T \tag{20}$$

3.3.3 State-Space Model Equations

The linear mathematical model of the USV is expressed in state-space form as follows:

$$\dot{x} = Ax + Bu \tag{21}$$

$$y = Cx + Du \tag{22}$$

Where:

- A is the system matrix, describing the interaction between the state variables.
- B is the input matrix, relating the control inputs (linear and angular velocities) to the state dynamics.
- C is the output matrix, mapping the state variables to the system outputs.
- D is the feedthrough matrix, representing the direct influence of inputs on the outputs.

Where the matrices are as follows:

$$A = \begin{bmatrix} 0.3986 & 0 & 0 \\ 0 & -0.0659 & 2.6559 \\ 0 & 0.2655 & -2.0048 \end{bmatrix} \tag{23}$$

$$B = \begin{bmatrix} 0.0078 & 0 \\ 0 & 0.0066 \\ 0 & -0.0050 \end{bmatrix} \tag{24}$$

$$C = I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{25}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{26}$$

Matrix C is an identity matrix, indicating that the output vector y directly corresponds to the state vector x.

Matrix D is a zero matrix, indicating that there is no direct feedthrough from the input to the output. This simplifies the control law as we can focus on state feedback, the controller can also focus on stabilizing an controlling the system by managing the state variables (velocities and yaw rate) instead of counteracting immediate effects of the control inputs on the outputs. It also smooths the system's response and makes it more predictable. This is an advantage in marine environments where sudden sharp responses often lead into instability.

3.3.4 Linearization

The system was linearized around 0 velocities to simplify the mathematical expressions and make the analysis and design of the control system more straightforward and also to reduce the complexity of the system dynamic, by removing cross coupling terms such as Coriolis effects. The USV will not be a high-speed application and will often be station keeping, it makes sense to design the controller around the velocities it will experience most often.

A potential problem with linearizing the system at zero velocities is that if the USV were required to operate at significantly higher speeds—such as in high seas or open ocean environments, which are far different from the lagoon environment for which the controller was originally designed—there is a significant risk that the USV could become uncontrollable. This discrepancy arises because the dynamics at higher speeds can be vastly different, potentially leading to instability or poor performance of the control system.

3.3.4 H-Infinity Synthesis

Using parameters extracted from the URDF file of the WAM-V, MATLAB was employed for H-infinity synthesis. The matrices in part 3.3.3 represent the system dynamics in state-space form. To perform H-infinity synthesis, weighting matrices are defined:

- **W1:** Assigns weights to the system outputs, placing more emphasis on controlling yaw, which is crucial for maintaining the vessel's orientation.
- **W2:** Penalizes control effort, ensuring that the controller does not demand excessive actuator inputs.
- **W3:** This matrix is not used in this case, meaning there is no direct output weighting.

The *augw* function is used to augment the system with these weights, creating a new system that includes the penalties for performance and control effort. After synthesis, it was observed that the A_k matrix showed signs for instability on yaw control and the gamma value stayed quite large, even after lots of tuning the best that was achieved was 2.3177075e+04 which is half of the starting value. While testing the control of the USV using a purely H-infinity controller, the following was observed:

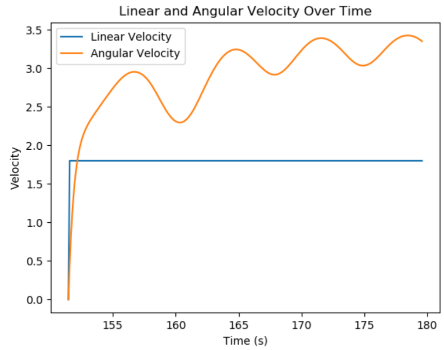

Figure 2 Linear and Angular velocity control using purely H-infinity

While linear velocity was capped to 1.8 m/s, it still remained stable. However, angular control displayed oscillatory behavior, signaling that h-infinity struggles with yaw control in this particular configuration. It might be due to the fact that the WAM-V is primarily used in a three-thruster configuration (Bingham, et al., 2019) and we are attempting control with a twin-thruster configuration.

3.3.5 Hybrid control

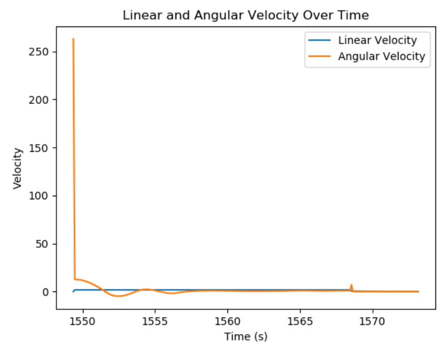

Figure 3 Hybrid control, angular velocity spike from PID

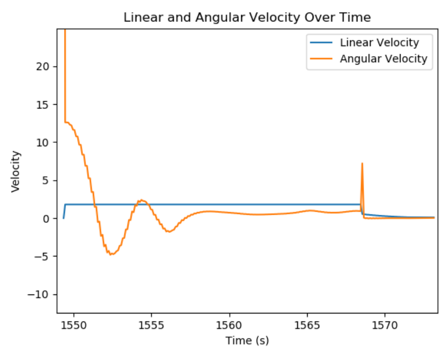

Figure 4 Hybrid control, dampening of oscillations

The oscillatory behavior in the system, as initially observed when using the H-infinity controller for both linear and angular velocities, proved to be unacceptable for our application. The significant oscillations in angular velocity, in particular, posed a risk to the stability and precision required for the USV's operation. To address this issue, we revisited last year's results, where a PID controller was successfully implemented to manage the angular dynamics. Given its proven effectiveness, the PID controller was reimplemented using the same configuration to specifically control the USV's angular velocity.

As illustrated in the graph, the hybrid control approach—combining H-infinity for linear velocity with PID for angular velocity—demonstrates a significant improvement in system stability. While there is a characteristic initial spike in angular velocity, typical of PID controllers during large initial corrections, this transient behavior is quickly damped out. The system then settles into a stable regime with minimal oscillations, as evidenced by the smooth and consistent linear velocity curve and the rapid stabilization of angular velocity.

This adjustment not only mitigated the oscillatory behavior but also ensured that both linear and angular velocities remained within acceptable bounds during operation, even under challenging conditions. The graph underscores the effectiveness of this hybrid control strategy, which successfully addresses the limitations encountered with a pure H-infinity control approach and enhances the overall robustness of the USV in dynamic environment

3.4 LOS guidance and lookahead-based steering

Another improvement from the M1 project is the guidance system. In the previous implementation, the USV was made to use its position as reference and constantly computed its distance and heading error for the control loop. A better approach is to use the Line of Sight (LOS) guidance law.

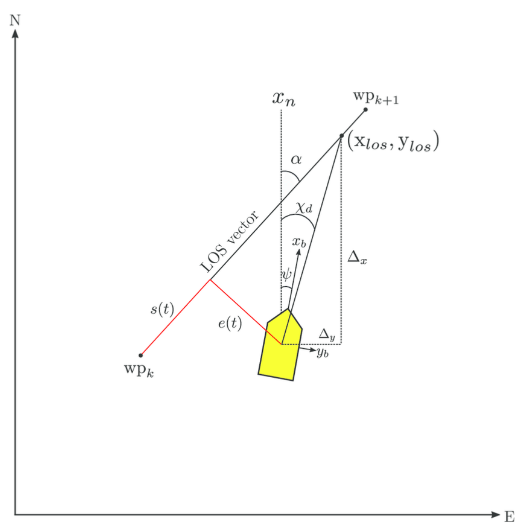

Figure 5 LOS Guidance (Ohrem, 2015)

Figure 5 is a geometric representation of LOS, where (x_b, y_b) denotes the current position of the USV, wp_κ and $wp_{\kappa+1}$ are waypoints that define a straight-line path. The path tangential angle is obtained by the following equation:

$$\alpha = \operatorname{atan2}(y_{k+1} - y_k, x_{k+1} - x_k) \tag{27}$$

Atan2 being the four-quadrant version of arctan constrained to $[-\,{}^{\pi}/_{2}, {}^{\pi}/_{2}]$. The USV coordinates in the path-fixed reference frame can be written as:

$$\begin{bmatrix} s(t) \\ e(t) \end{bmatrix} = \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix}^{T} \begin{bmatrix} x - x(k) \\ y - y(k) \end{bmatrix} \tag{28}$$

Where s(t) is the along-track distance and e(t) are the cross-track error. When the USV follows the path, only e(t) is relevant because it converges to the straight-line when $e(t) \rightarrow\ 0$, e(t) can be re-arranged as:

$$e(t) \ = \ -(x - x_k)\sin(\alpha_k) \ + \ (y - y_k)\cos(\alpha_k) \tag{29}$$

After defining the LOS guidance, a lookahead-based algorithm is formulated:

$$x_d = \alpha_k + \arctan\left(\frac{-y_e}{\Delta}\right) \tag{30}$$

The second term in the expression represents the angle between the velocity vector and the path, ensuring that the velocity is directed towards a point located at a distance $\Delta > 0$ ahead on the path. The desired course angle x_d is then converted into a yaw angle command ψd.

$$\psi d = x_d \ - \ \beta \tag{31}$$

$$\beta \ = \ arcsin(\frac{v}{U}) \tag{32}$$

3.5 Propulsion System

The propulsion system is crucial for enabling the USV's mobility in the water. In the simulation environment, the WAM-V model (Bingham et al., 2019) is configured to use two fixed thrusters that employ differential thrust for maneuvering, which eliminates the need for rudders or angular adjustments of the thrusters.

Figure 6 Thrust configuration of USV

Differential thrust refers to the method of controlling the USV's direction by modulating the thrust output of the two propulsion units. By adjusting the thrust on one side of the vessel relative to the other, the USV can achieve turning and maneuvering. This technique is particularly effective for precise low-speed operations, such as station-keeping for tasks like coral nursery monitoring. Additionally, the use of fixed thrusters simplifies the propulsion system, reducing the complexity and cost by avoiding moving parts other than the propeller blades.

Thrust Configuration:

- For straight-line motion, the port and starboard thrusters operate at equal speeds, resulting in zero differential thrust:

$$T1 = T2 = T \tag{33}$$

- To achieve steering, differential thrust is introduced by varying the thrust on one side:

$$T1 = T + \Delta T \tag{34}$$

$$T2 = T - \Delta T \tag{35}$$

where $T1$ and $T2$ represent the thrust produced by the first and second propulsion units, respectively, T denotes the baseline thrust, and ΔT represents the differential thrust applied to steer the USV. For straight-line navigation, $T1$,$T2$, and T are equal, ensuring balanced propulsion on both sides.

3.6 Navigation

Figure 7 illustrates the control loop used for the USV's navigation. As detailed in Section 3.3.5 on Hybrid Control, H-infinity control is applied for linear velocity, while PID control is used for angular velocity, enabling robust and precise maneuvering.

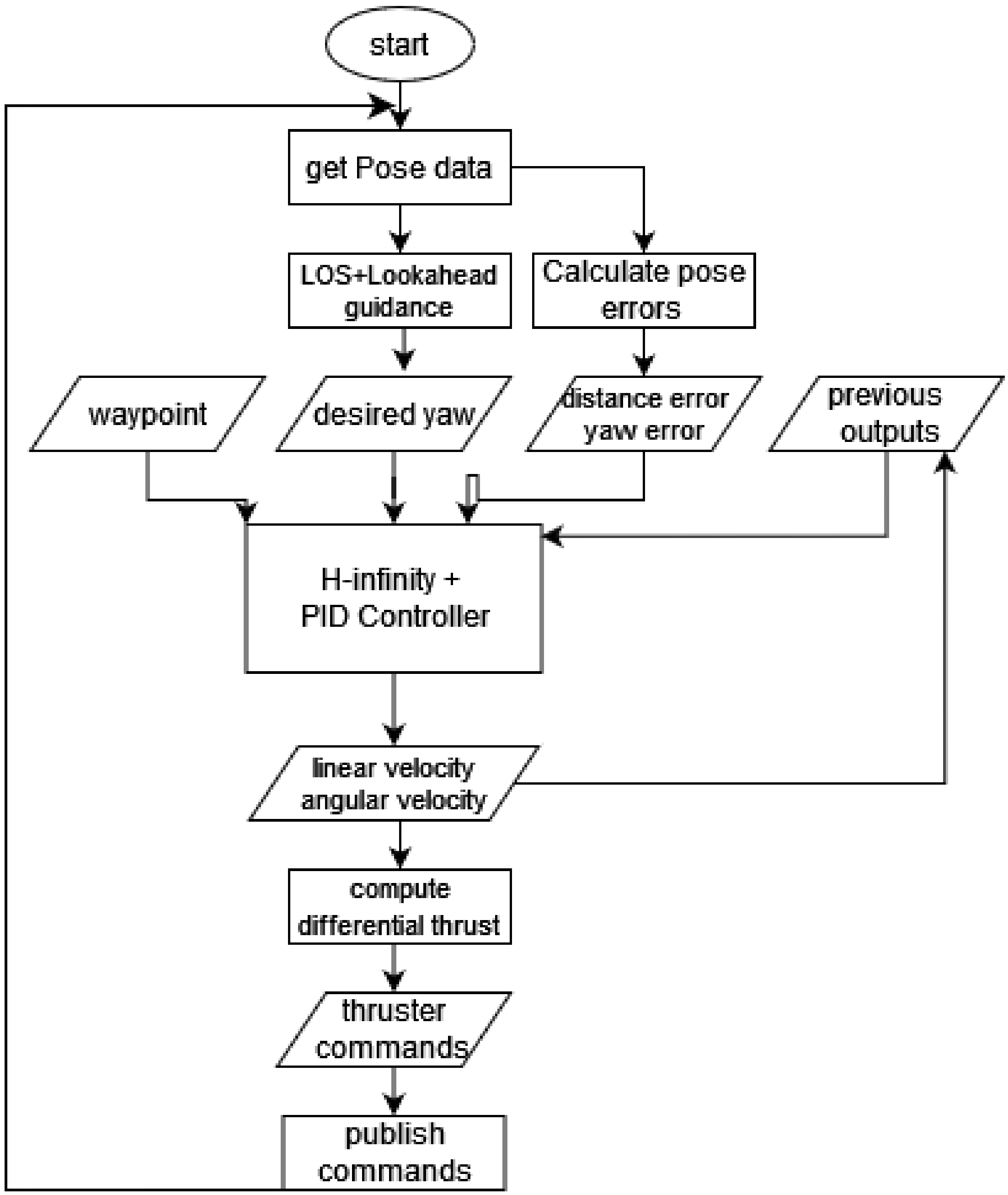

Figure 7 Control loop of the USV for robust control. The loop integrates H-infinity control for linear velocity and PID control for angular velocity, ensuring precise and stable navigation.

4. Control experiments and results

This chapter evaluates the improvements made to last year's PID control system and assesses the performance of the hybrid robust control system implemented this semester. A comparative analysis of both systems will also be conducted.

4.1 Experimental setup

The experimental environment consists of Gazebo 11.12.0, running with ROS Noetic on Ubuntu 20.04 LTS, and the control algorithms are implemented in Python 3.8.10. The test course used is the official course provided by RobotX for their 2022 VRX competition (robonation, 26 August 2019). The USV model employed in this research is the WAM-V, also supplied by RobotX.

To assess the robot's performance, the following operational scenarios will be evaluated: straight-line motion, turning maneuvers, and station keeping, as these represent the expected tasks of the robot. The tests will be conducted under three different conditions:

- **No Wind, No Waves**: Ideal conditions.
- **Normal Wind, Normal Waves**: Realistic conditions.
- **Strong Wind, Big Waves**: Extreme conditions.

4.2 Testing navigation

Each simulation was run with the exact same parameters on the USV. The thresholds for determining if the goal had been reached remained constant at 5 units in L2 distance error. The maximum linear speed was set to 1.8 units, and the lookahead distance for LOS Guidance was fixed at 4.5 units.

The position data was collected during the execution of the control loop, each time a loop was executed, the position and the waypoint were recorded in a logfile. The charts were then produced by reading those log files and plotting the results using Matplot library. The blue line is the path taken by the robot while the red dotted line is the straight-line path between the waypoints.

4.2.1 Ideal conditions

To simulate ideal conditions, the gain of the waves and the wind coefficients have been set to zero in the world model file of the environment.

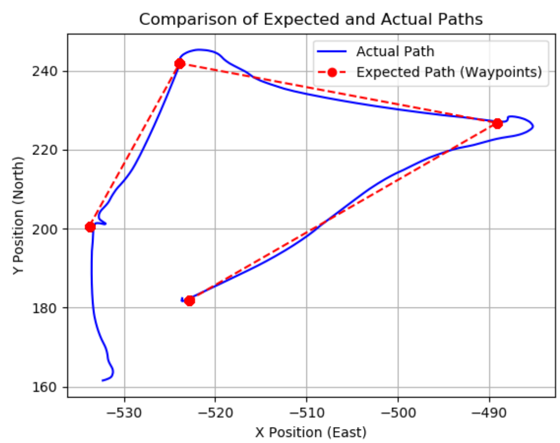

Figure 8 PID navigation under ideal conditions

In ideal conditions, PID control shows sharper, more abrupt turns during heading corrections, particularly at waypoint transitions. The USV closely follows the expected path, but the aggressive corrections lead to overcompensation in some areas, causing the trajectory to be less fluid.

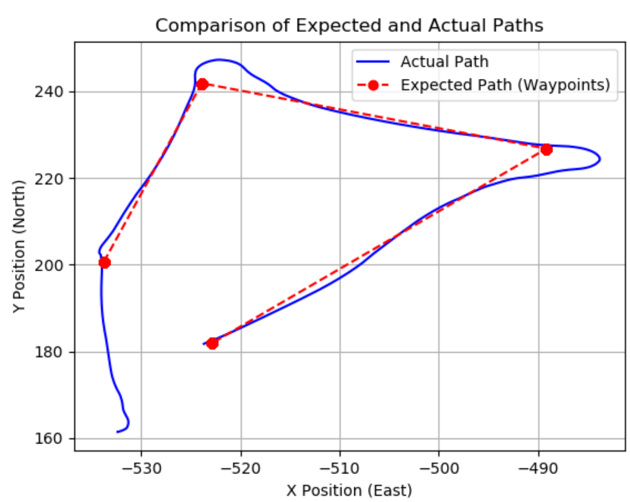

Figure 9 Hybrid Control under ideal conditions

In ideal conditions, hybrid control demonstrates smoother, more gradual turns compared to PID control. While the actual path deviates slightly from the expected waypoints, the transitions between waypoints are less abrupt, resulting in a more fluid trajectory. This smoother movement helps maintain better control and stability, even though waypoint adherence is slightly less precise. The hybrid approach's ability to make continuous adjustments contributes to a more stable overall performance.

4.2.2 Normal conditions

To simulate normal conditions, the gain of the waves and the wind coefficients have been set to their default values of “0.1” and “.5 .5 .33” in the world model file of the environment.

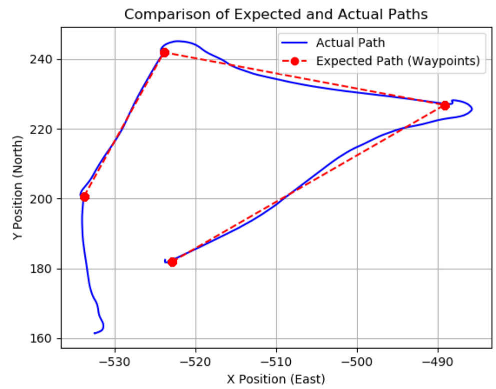

Figure 10 PID control under normal conditions

PID control shows sharper, more abrupt turns during heading corrections, particularly at waypoint transitions. While the USV closely follows the expected path, these aggressive corrections can lead to overcompensation, resulting in a less fluid trajectory that potentially compromises control and stability.

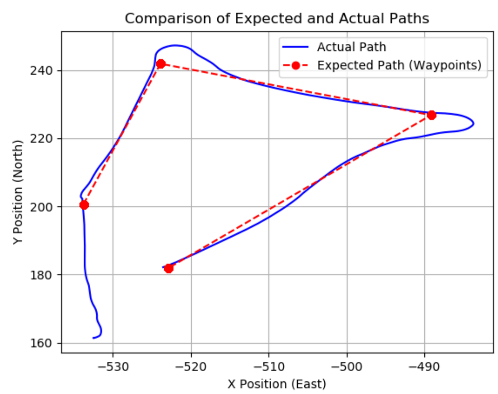

Figure 11 Hybrid control under normal conditions

Hybrid control illustrates smoother more gradual turns. Path adherence is less precise than PID control, but it makes smoother transitions between waypoints. This smoother trajectory helps mitigate external disturbances, contributing to better stability and control.

4.2.3 Extreme conditions

To simulate extreme conditions, the gain of the waves and the wind coefficients have been set to significantly higher values of “1.0” and “5 5 10” in the world model file of the environment.

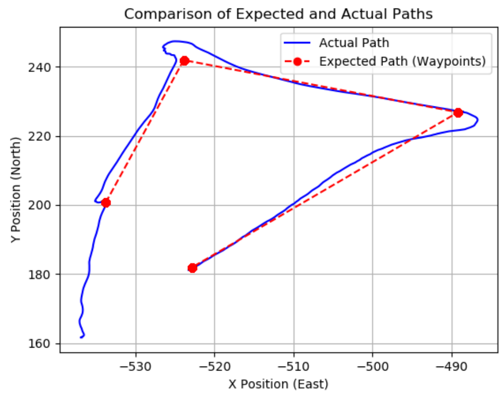

Figure 12 PID control under extreme conditions

PID control in these conditions demonstrated sharper turns during heading correction. This aggressive turning behavior could cause problems in high-disturbance environments. In some instances, the overcompensation caused the USV to overshoot and lose its mark.

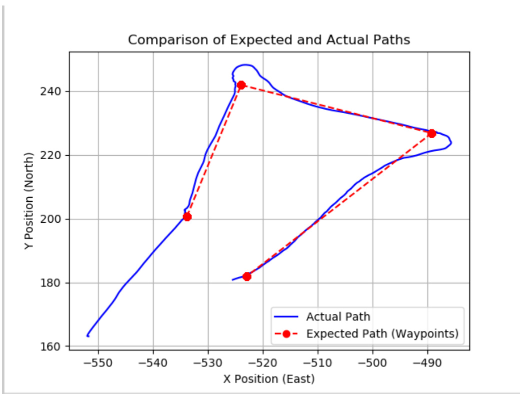

Figure 13 Hybrid control under extreme conditions

Hybrid control effectively mitigated the impact of waves on the USV's ability to reach the waypoints. Compared to PID control, it made smoother turns rather than abrupt changes, which is advantageous when transporting sensitive equipment. More importantly, it contributes to maintaining control, allowing the USV to effectively hold its station even in these conditions.

4.3 Observations

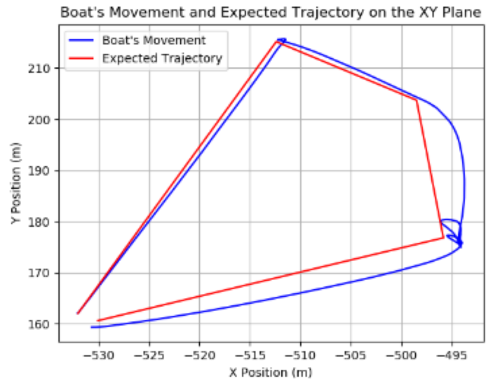

Figure 14 M1 PID Control chart

There have been significant improvements in the control loop of the USV compared to last semester's attempt. Although the USV doesn't follow the path as precisely, as shown in Figure 14, it rarely loses sight of the objectives and no longer struggles during waypoint transitions. While PID control still follows the straight-line path between waypoints better, hybrid control enables smoother navigation, which will be beneficial for equipment durability. Station keeping, using hybrid control also proved to be more consistent than PID control.

The system is not perfect, there were times when making a rather sharp turn, the USV overshot its waypoint and went astray, when checking the heading error, it was still withing acceptable bounds but the distance error to the waypoint kept increasing as the USV kept moving away. The control loop has to be updated to account for this scenario.

5. Conclusion

The mathematical model of a twin-hull and the forces acting upon it has been studied and converted to state-space form, advancing the research for future applications. A control system was developed in a simulation environment with the objective of requiring minimal adjustments when applied to a working prototype. This research focused on controlling a twin-hull USV actuated with two rudderless thrusters, chosen for their mechanical simplicity and capacity for differential steering, which allows both propulsion and turning through varying thrust.

While the control system showed promise, there remain some limitations. Augmenting the PID control system with Line-of-Sight (LOS) guidance improved its ability to track waypoints, significantly reducing the tendency to lose track of the target. However, the system still exhibited jerky motion during waypoint transitions, especially when sudden course corrections were required. To address this, H-infinity control was explored. Although H-infinity control proved unsuitable for angular velocity regulation, it demonstrated exceptional performance in managing linear velocity. This led to the development of a hybrid control system, wherein angular velocity is handled by PID, while linear velocity is controlled by H-infinity. This hybrid approach has shown greater resilience to environmental disturbances, producing smoother transitions between waypoints and improved station-keeping capabilities.

Despite these advancements, challenges remain. Future work should focus on implementing a system to detect overshoots and automatically correct the USV’s orientation to prevent runaway scenarios. Additionally, fine-tuning the control gains will be essential for improving the hybrid system’s precision in following a predefined trajectory. These adjustments will be critical to optimizing the overall performance of the control system.

The knowledge gained from this project, particularly the kinetic and dynamic modeling of the USV, provides a solid foundation for developing a more advanced surveillance vessel. Expanding the current 3 DOF model into a 6 DOF model would allow for even more accurate simulations, enhancing the USV's control and operational capabilities in real-world environments. The next phase of this research will focus on developing the USV's surveillance functions, including sensor integration and image capture, to create a fully autonomous system capable of coral nursery monitoring and lagoon surveillance.

References

Beck, E. et al., 2008. SeaWASP: A Small Waterplane Area Twin Hull Autonomous Platform for Shallow Water Mapping. *Monterey Bay Aquarium Research Institute.*

Bingham, B. et al., 2019. *Toward Maritime Robotic Simulation in Gazebo.* Seattle, WA: Proceedings of MTS/IEEE OCEANS Conference.

Blaich, M. et al., September 17-20, 2013. *Design of a Twin Hull Based USV with Enhanced Maneuverability.* Osaka, Japan, IFAC.

Cutipa Luque, J. C. &. R. P., 2020. Robust Control and Fuzzy Logic Guidance for an Unmanned Surface Vehicle. International Journal of Advanced Computer Science and Applications.. *International Journal of Advanced Computer Science and Applications,* 11(8), pp. 766-772.

Fahimi, F., 2009. *Autonomous Robots Modeling, Path Planning, and Control.* Edmonton, Alberta, Canada: Springer.

Fossen, T. I., 2011. *HANDBOOK OF MARINE CRAFT HYDRODYNAMICS AND MOTION CONTROL.* Trondheim, Norway: John Wiley & Sons, Ltd.

Gonzalez-Garcia, Alejandro, Castañeda & Herman, November 2019. *Control of a Double Thruster Twin-Hull Unmanned Surface Vehicle: Experimental Results.* Manzanillo, Colima, Mexico, s.n.

Li, C. et al., 2019. Modeling and Experimental Testing of an Unmanned Surface Vehicle with Rudderless Double Thrusters. *Sensors.*

Manley, J. E., 1997. *Development of the autonomous surface craft "ACES".* s.l., Oceans '97, pp. 827-832.

Mitchell, P. &. O. R. &. L. M., 2022. *On the Development of Waterjet-Powered Robotic Speedboats: An Open-Source, Low-Cost Platform for Education and Research..* Seville,Spain, s.n.

O., Y. et al., 2012. *Development of unmanned surface vehicle (USV) for sea patrol and environmental monitoring..* Kuala Terengganu, Malaysia , s.n., pp. 20-22.

Ohrem, S., 2015. *Development of a Dynamic Positioning System for Merlin WR200 ROV,* s.l.: Norwegian University of Science and Technology.

robonation, 26 August 2019. VRX Technical Guide. *Maritime RobotX.*

Sarda, E. I., Qu, H., Bertaska, I. R. & Ellenrieder, K. D. v., 2016. Station-keeping control of an unmanned surface vehicle exposed to current and wind disturbances. *Ocean Engineering,* Volume 127, pp. 305-324.

SNAME, 1950. *Nomenclature for Treating the Motion of a Submerged Body Through a Fluid.* New York, NY, USA: The Society of Naval Architects and Marine Engineers.

List of Figures

Appendix

The Code

The Control node and URDF file used in this project along as instructions on using it can be found on GitHub at the following address: https://github.com/Lav-Singh/Robust-Control-for-Twin-Hull-USV.

```
'''
// Project Title    : Robust Control for twin-hull USV for lagoon surveillance
// Purpose          : Research and Development of a control loop in a simulated environment
// Language         : Python
// Author           : Ramessur Lav Singh
// Date             : 8 September 2024

// Universite des Mascareigns (UdM)
// Master Artifical Intelligence and Robotics
'''


# Initialize lists to store the logged data
time_log = []
lin_vel_log = []
ang_vel_log = []

# Initialize lists to store the actual and expected paths
actual_positions = []  # List to store (x, y) positions of the USV
expected_positions = []  # List to store waypoint positions

# Initialize the PID controllers for linear and angular velocities
linear_pid_nav = PIDController(kP=1.0, kI=0.01, kD=0.05, kS=50)  # Navigation PID
angular_pid_nav = PIDController(kP=21.0, kI=0.27, kD=2.4, kS=50)  # Navigation PID
linear_pid_station = PIDController(kP=1.9, kI=0.12, kD=1.8, kS=50)  # Station-Keeping PID
angular_pid_station = PIDController(kP=1.7, kI=0.11, kD=1.3, kS=50)  # Station-Keeping PID

```