Mémoire-- Projet

Master I Intelligence Artificielle et Robotique

Sailboat robot (or catamaran) for photography and surveillance in the lagoon.

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Abstract

This research paper explores the design and development of an autonomous surface vehicle (USV), specifically a catamaran model, for monitoring coral nurseries in a lagoon environment. The study builds upon existing literature and research projects in the field of USVs, focusing on software and hardware architectures. The shape of the boat hull is investigated, with emphasis on the twin-hull catamaran and its advantages in terms of stability and payload capacity. The kinematic and dynamic modeling of the USV is also examined, considering the three degrees of freedom and their implications for control algorithm design. Two control techniques, PID controllers and back-stepping controllers, are discussed, highlighting their respective characteristics and benefits. Ultimately, this research aims to contribute to the advancement of USV technology for efficient and reliable monitoring of coral nurseries in lagoon ecosystems.

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 crucial ecosystems that support a diverse range of species and offer several ecological and economic benefits. Nevertheless, these sensitive habitats encounter various hazards, including pollution, human activities, and climate change. To protect coral reefs and ensure their long-term survival, it is essential to implement effective conservation strategies and monitoring efforts. Unmanned Surface Vehicles (USVs) have emerged as a promising solution for data collection and surveillance in marine environments, providing several advantages, such as cost-effectiveness, adaptability, and reduced human risk.

This thesis aims to develop a control system for a USV designed explicitly for lagoon surveillance of coral nurseries. The primary goal is to enable autonomous missions that navigate through complex lagoon environments, collect high-quality data, and contribute to the monitoring and conservation of these critical areas.

The control system is crucial in ensuring the efficient and precise operation of the USV. It involves integrating various components such as perception systems, path planning algorithms, and motion control mechanisms to facilitate intelligent decision-making and accurate maneuverability. This research aims to optimize the control system to enhance the USV's capabilities for surveying coral nurseries within lagoon ecosystems.

The study will focus on designing and implementing control algorithms tailored to address the unique challenges posed by lagoon environments. Factors such as water currents, variable depth, presence of obstacles, and the need for precise navigation pose significant obstacles that must be overcome to achieve successful and efficient surveillance missions. This dissertation aims to develop a control system that enables the USV to adapt and respond to these challenges effectively by analyzing and improving existing control strategies.

Moreover, the research will explore the integration of advanced sensing technologies, such as underwater cameras and environmental sensors, to enhance the data collection capabilities of the USV. By incorporating real-time data acquisition and analysis, the USV can provide valuable insights into the health and dynamics of coral nurseries, contributing to scientific research and aiding in conservation efforts.

Overall, this thesis aims to advance the field of USV control systems for lagoon surveillance of coral nurseries. By addressing the unique challenges of lagoon environments and harnessing the potential of autonomous technologies, this research aims to contribute to the preservation and sustainable management of coral reefs, ultimately ensuring their resilience and safeguarding their crucial role in marine ecosystems.

1.1 Literature Review

The goal of this project is to implement an autonomous surface vehicle, specifically a catamaran model, to be used in our lagoon for monitoring coral nurseries. Over the years, numerous research projects have been conducted in this field, exploring different boat models and electronic components for the vehicle. However, the software and hardware architectures of these research projects show striking similarities, which will be studied and leveraged to advance this project based on their findings.

The shape of the boat is an important factor to consider in designing an aquatic vehicle. There are two main types of hulls that are recurrent in the articles we have studied: the twin-hull catamaran (Blaich, et al., September 17-20, 2013) and the single-hull boat (O., et al., 2012). The most popular model by far is the twin-hull catamaran, as indicated by J.E. Manley (Manley, 1997) in his article titled "Development of the autonomous surface craft 'ACES'." The catamaran was preferred over a kayak for its greater stability in roll and higher payload capacity. The catamaran shape also provides redundant buoyancy, so even if one hull is damaged, complete loss of buoyancy would not occur, allowing more time for the drone's rescue. For the construction of the boat's hull, several options exist, such as using polymer or fiberglass, with polymer being the most robust option and fiberglass being the cheaper option. Using off-the-shelf hulls is also a common choice.

Two types of twin-hulls have also been considered for this research, the classic twin-hull and the Small Waterplane Area Twin-Hull (SWATH). It is designed to minimize the effects of waves and provide a stable platform for operations in rough seas. Two fully submerged hulls connected to a platform above water using vertical struts make up the basic architecture of the SWATH. While it may appear simple in design, a fair bit of expertise is needed to make a functional SWATH. (Beck, et al., 2008). Moreover, SWATHs are typically used for scientific research in rough seas. On the other hand, is the classic twin-hull, two hull and a platform directly connected. Considerably easier to design and build than a SWATH, and adjustments can generally be made on the fly while not having to worry too much about changing hydrodynamic properties.

It is important to also consider the kinematic and dynamic modelling of the USV while planning its design. This potentially saves us a lot of time and resources while making a working prototype. When developing the kinematics and dynamics of the twin-hull, three degrees of freedom will be considered (Gonzalez-Garcia, et al., November 2019). The degrees of freedom considered are what can be controlled or affected directly by actuation from the boat, namely, the surge, the sway and the yaw. Understanding the kinetics and dynamics directly correlates to being able to design an acceptable control algorithm for the USV, also, as this research paper mainly focuses on using the Virtual RobotX simulation (Bingham, et al., 2019), to design a control system, the knowledge acquired while studying the modelling of the boat will be helpful when adjusting the control system for a real-life prototype.

PID controllers, or Proportional-Integral-Derivative controllers, are widely used in control systems to regulate and stabilize processes. They continuously calculate an error signal by comparing the desired setpoint and the actual output of the system. The proportional term generates an output proportional to the current error, the integral term integrates the past errors over time to eliminate steady-state errors, and the derivative term predicts the future error based on the rate of change of the error. By tuning the coefficients of each term, PID controllers can adapt to various system dynamics and provide robust control.

On the other hand, back-stepping controllers (Gonzalez-Garcia, et al., November 2019) are a class of nonlinear control techniques commonly employed for systems with high-order dynamics and complex nonlinearities. Unlike PID controllers, back-stepping controllers construct a series of virtual subsystems by designing appropriate Lyapunov functions for each subsystem. These virtual subsystems are interconnected to gradually drive the system towards the desired trajectory or setpoint. Back-stepping controllers use a recursive approach, where the control law for each subsystem depends on the outputs and derivatives of the subsequent subsystems. This methodology enables the control of complex nonlinear systems by sequentially stabilizing them, leading to enhanced tracking accuracy and stability in challenging control scenarios.

PID controllers offer a favorable option for novice developers in the realm of Unmanned Surface Vehicles (USVs) due to their simplicity, broad applicability, and robustness. The straightforward nature of PID controllers facilitates understanding and implementation, supported by abundant learning resources. Their ability to handle diverse operating conditions and disturbances enhances their suitability for practical applications. Established tuning methods aid in parameter adjustment, furthering control performance. Moreover, the incremental development approach enabled by PID controllers enables skill development and the gradual refinement of the control system.

2. Objectives

The primary aim of this investigation is to create and execute a resilient USV management system that allows for self-governing exploration and data gathering of coral nurseries in lagoon habitats. The proposed system will take advantage of advanced technologies and algorithms to guide the USV through intricate lagoon topography, proficiently gather survey data, and optimize mission objectives in order to support coral reef preservation initiatives.

2.1 Research Methodology:

2.2 Review of Existing Literature:

- Undertake an exhaustive review of literature to identify the current cutting-edge in USV management systems and their usage in marine environments.
- Analyze existing research on coral nursery survey methods and identify gaps in knowledge related to USV-based survey techniques.

2.3 System Design and Integration:

- Create a comprehensive system architecture for USV management, integrating sensors, actuators, and communication systems that are essential for coral nursery survey missions.
- Explore and choose suitable sensing technologies for environmental mapping, obstacle detection, and coral health assessment.

2.4 Path Planning and Navigation:

- Create efficient path planning algorithms that enable the USV to navigate through lagoon environments while evading obstacles and adhering to survey requirements.
- Incorporate real-time data processing and decision-making capabilities to adjust the USV's course based on environmental conditions and sensor feedback.

2.5 Experimental Validation:

- Perform field experiments in lagoon environments to evaluate the performance and effectiveness of the developed USV management system. Evaluate the accuracy, reliability, and efficiency of the system's survey capabilities in comparison to conventional methods.

3. Modelling the Boat

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 serves as a framework for measuring and quantifying the USV's movement and behavior. Three axes are defined, X-axis (u), representing longitudinal direction or forwards/backwards motion; the Y-axis (v), representing the transverse direction or lateral motion of the USV; Z-axis, which is omitted as it pertains to vertical motion, which is not relevant in this context and finally, r, which represents the rotation of the USV around its vertical axis.

The Earth frame of reference serves as a global coordinate system that provides a reference framework for describing the position and motion of the USV relative to the Earth's surface. The X-axis represents east-west direction, aligned with longitude. Y-axis represents north-south direction, aligned with latitude and Z-axis represents elevation or altitude.

The USV frame of reference can be related to the Earth frame of reference, this allows for mapping the USV's coordinates and motion to the global Earth coordinates. Establishing this relationship makes it possible to accurately determine and communicate the USV's position, orientation and movement in relation to the Earth's surface, resulting in effective navigation and coordination with other Earth-based systems or objects.

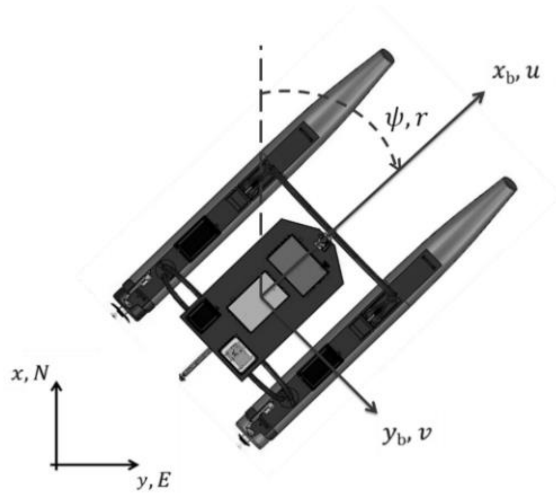

Figure 1 Schematic diagram of DOF of the WAMV (Sarda, et al., 2016)

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).

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

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

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

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

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

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

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

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

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

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.

Table 2 describes the parameters used while explaining the dynamic model of the USV. Even though a prototype has not been made in this paper, this research can be used at a later stage to make a proper model in MATLAB or similar software before building a real boat.

3.4 Propulsion system

It is how the USV will achieve mobility in the waters. In the simulation environment, the WAMV (Bingham, et al., 2019) has been configured to use two thrusters. So that the algorithm implement can be carried over to a real-life prototype, the system has been designed to use differential thrust, instead of making use of the angular thrust of the aft thrusters in the simulation, there is also no rudder in the system.

Figure 2 Thrust configuration of Twin hull

Differential thrust refers to the technique of modulating the thrust output of two or more propulsion units to steer a vessel. By adjusting the thrust on one side of the vehicle relative to the other side, the vehicle can turn and maneuver. The difference in propulsive force on each side of the vehicle will cause a rotation or change in direction.

With differential thrust, precise maneuvering at low speed can be achieved without the use of rudders. In the context of our application, station keeping for taking pictures of coral nurseries will be more manageable. The propulsion unit is also simplified and cheaper to implement as the thruster will be fixed with no moving parts aside from the propeller blades.

Straight line motion requires port and starboard thrusters to run at the same speed, which means that differential thrust is zero.

$$T1 = T + \Delta T \tag{19}$$

$$T2 = T - \Delta T \tag{20}$$

$$T1 = T2 = T \tag{21}$$

T1 and T2 represent the thrust of the first propulsion unit and second propulsion unit respectively. T stands for the baseline thrust and ΔT is the additional or reduced thrust to be applied on one side relative to the other. By controlling the value of ΔT , the USV can be steered or turned. For straight line motion, T1, T2 and T will all be equal.

3.5 Guidance Navigation and Control

Proper sensing capabilities are needed to enhance the performance of the USV (Li, et al., 2019).The WAM-V in the simulation environment was configured with an Inertial Measurement Unit (IMU) and Global Positioning System (GPS) sensors. These sensors are necessary to improve the performance and facilitate control of the USV.

The IMU consists of sensors such as accelerometers and gyroscopes which will provide readings for the linear velocity and angular velocity of the vector. These values allow us to estimate the acceleration, change in direction and velocity of the boat. By making use of this information, the USV's control can be adjusted to respond to external forces such as the wind and waves. The IMU also provides measurements of the vehicle's pose, which is essential for stabilizing the USV and maintaining the proper orientation while moving towards a target. IMU data can also be used alongside GPS data to augment the accuracy of navigation and localization, the continuous motion information provided by the unit can help estimate position and trajectory of the USV when GPS data becomes temporarily unavailable.

The GPS sensor provides real time location information that allows the USV to locate itself on the earth frame of reference. Using this data enables navigation and route planning to reach predetermined locations. This also allows the USV to be autonomous in navigation, only needing to be supplied with destination GPS coordinates and being able to complete missions on its own without human intervention.

The GNC is implemented in a ROS environment, figure 2 shows the flow of data in the system.

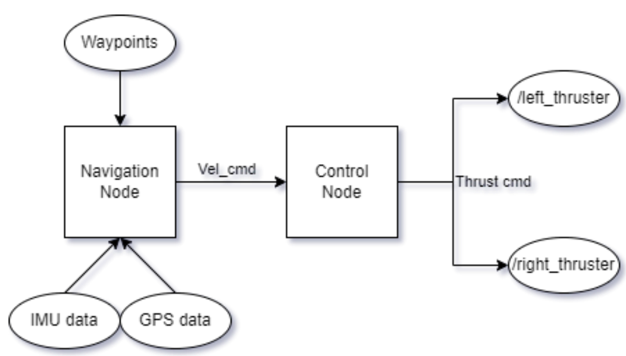

Figure 3 GNC of the USV

The algorithm used for the GNC is represented in a flowchart in figure 3. A destination latitude and longitude are made available to the navigation node, the current GPS latitude and longitude, along with the pose information of the USV is also recorded. The distance between the destination waypoint and current position of the USV is calculated and if it is still far from the desired position, navigation data is computed and is published to the appropriate ROS topics.

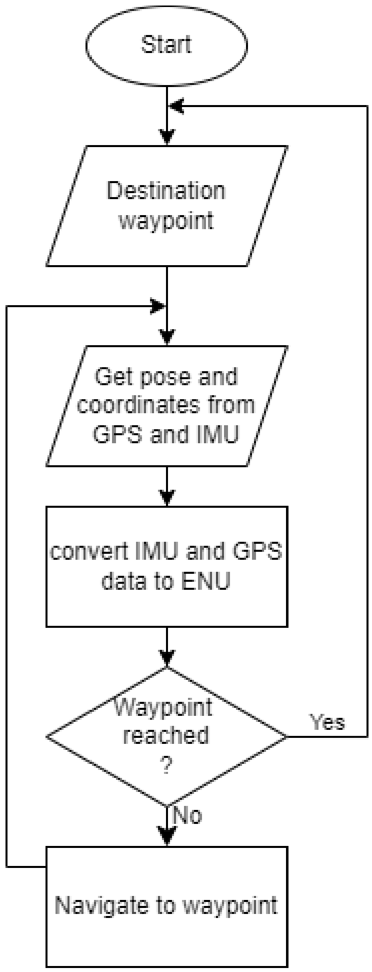

Figure 4 GNC Wayfinding flowchart

3.6 Navigation

In order for the control node to work, the desired linear velocity and angular velocity need to be computed. Figure 5 is a flowchart showing the process for computing those values. The desired position and desired pose or heading are input in the algorithm, then using the current position of the USV, the distance or error, from the goal destination is calculated. If the USV is found to be far from the destination, the linear and angular velocities are calculated.

3.6.1 Linear velocity

The forward movement of the USV is controlled by linear velocity. While a PID controller could have been used, a P controller will suffice and is more computationally efficient. The vector's linear velocity is directly proportional to its error in position. As it gets closer to its destination, its linear velocity decreases proportionally, allowing for a gentler approach and resulting in less overshoot.

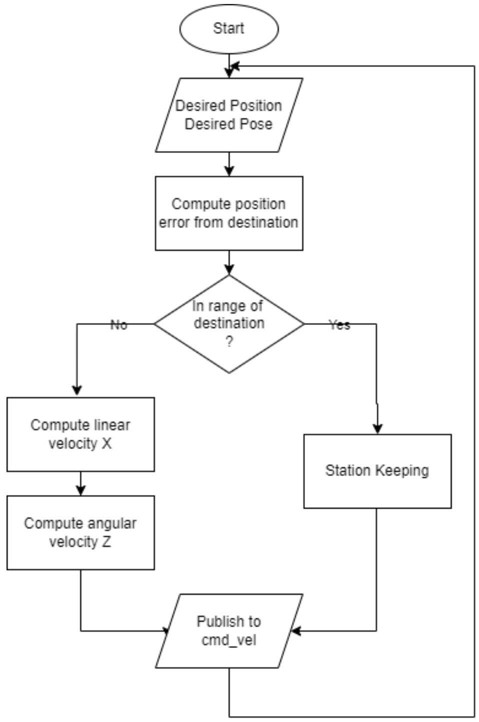

Figure 5 Navigation to destination

3.6.2 Angular Velocity

It is responsible for controlling the heading (yaw) of the USV. A PID controller is used as it provides better and more accurate control for the heading. The proportional component provides a response proportionate to the error in heading, the integral component helps eliminate steady-state errors and the derivative component helps eliminate oscillations and overshoot.

3.7 Thrust control

The linear and angular velocities are obtained ad used to calculate the thrust values. The left thrust value is calculated as the difference between linear and angular velocity. The right thrust value is calculated as the sum between linear and angular velocity. The thrust commands are then constrained to be within a specific range, ensuring that the thrust commands withing operating limits of the thrusters.

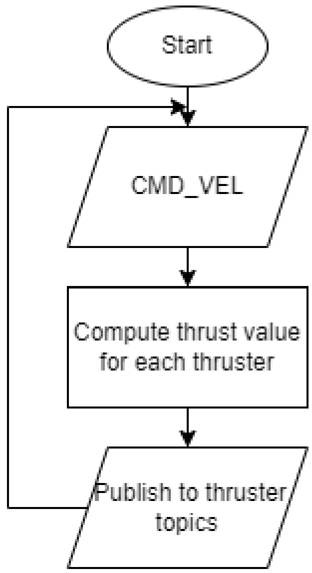

Figure 6 Thruster Control

3.8 Design Analysis

When prototyping the USV, several factors need to be analyzed to ensure that the vector will be able to operate in a safe and appropriate manner.

3.8.1 Buoyancy

One crucial aspect to analyze when building the USV will be its buoyant force. The buoyant force needs to be calculated to know if the USV will be able to float. In order to achieve floatation, the buoyant force of the USV needs to be greater than its own weight.

$$Fb = \rho g V_{Submerged} \tag{22}$$

Where, Fb is the buoyant force, ρ is the density of water, g is acceleration due to gravity and $V_{Submerged}$ is the volume of the USV below the waterline, this includes thrusters, hulls and the USV's frame.

3.8.2 Required thrust

Computing the required thrust of a USV is important during the design phase for a variety of reasons. The proper size of the propulsion unit will be determined, the thrust generated by this unit should be able to overcome forces resisting the propulsion of the USV and make it move at the desired speed. An underpowered or overpowered propulsion unit will impact the USV's performance and efficiency. The speed and maneuverability of the USV is directly influenced by the thrust, by computing the required thrust, the USV's ability to achieve the desired speed and maneuver effectively in different sea conditions can be assessed. This helps ensure that the USV has enough power to operate against external forces and stay in control. Knowing the required thrust enables us to optimize energy consumption by choosing appropriately sized thrusters and power units. By knowing what model of thrusters will be used, the remaining payload of the boat can be computed.

Equation (23) is the equation of motion of the USV when moving in the forwards/backwards direction and ignoring the lateral speed and yaw rotation.

$$(m - X_{\dot{u}})\dot{u} = F_0 - X_u u \tag{23}$$

In order to compute the minimum required thrust, Equation (23) is calculated with no forces acting on the USV.

$$0 = F_0 - X_u u \tag{24}$$

$$F_0 = X_u u \tag{25}$$

With, $X_u u$ being the total linear drag force in the longitudinal direction. It is computed using Equation (26).

$$X_u u = 2X_{u\mathrm{Hull}} u + X_{u\mathrm{Frame}} u \tag{26}$$

$X_{u\mathrm{Frame}} u$ is the linear drag force that affects the frame of the USV and $X_{u\mathrm{Hull}} u$ is the linear drag force that affects the hulls of the USV, both in the longitudinal direction.

$$X_{u\mathrm{Hull}} u = C\mathrm{d}_{\mathrm{hull}} \tfrac{1}{2} \rho u \mathrm{A}_{\mathrm{hull}} u \tag{27}$$

$$X_{u\mathrm{Frame}} u = C\mathrm{d}_{\mathrm{Frame}} \frac{1}{2} \rho u \mathrm{A}_{\mathrm{Frame}} u \tag{28}$$

Equations (27) and (28) describe the linear drag for both the hull and frame of the USV. Where $C\mathrm{d}_{\mathrm{hull}}$ is the drag coefficient of the Hull, ρ is the density of water, $\mathrm{A}_{\mathrm{hull}}$ is the area at eh front of the vector in contact with water and finally, u being the longitudinal velocity.

By taking these aspects into account while designing a real-life prototype, measures can be taken so as to optimize the system and select the right equipment for the job. By getting components that are just right, the overall cost of the USV can be brought down.

4. Control experiments and results

The simulation environment may open-source, however, it was very difficult finding reference material for the version used in this research project. After having coded the navigation and control nodes, attempts at tuning the PID controllers on the boat were mostly unsuccessful and often resulted in the boat overshooting its target or just spinning on itself. After a lot of digging, a GitHub repository (Samak & Samak, 2023) using almost the same setup as this project was found, using the PID controller values as starting point the following tests and results will study the effects of PID tunes on the behavior of the boat, namely its linear velocity and angular velocity while moving towards its target.

4.1 Straight line movement

To assess the effectiveness of a pre-adjusted P controller and a haphazardly configured P controller, various significant criteria will be taken into account. These criteria consist of the accuracy, steadiness, and capacity of the control mechanism to traverse the lagoon in a straight line. The pre-adjusted P controller, which is cautiously set up based on prior knowledge and expertise, is anticipated to showcase superior performance in terms of accuracy and stability. In contrast, the haphazardly configured P controller, lacking any predetermined adjustments, may exhibit a greater degree of variance and uncertainty in its control response.

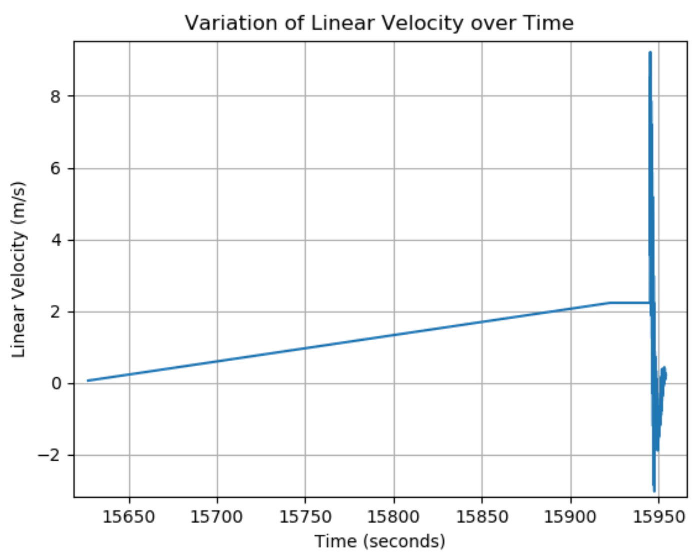

Figure 7 Variation of Linear Velocity over Time (pre-tuned controller)

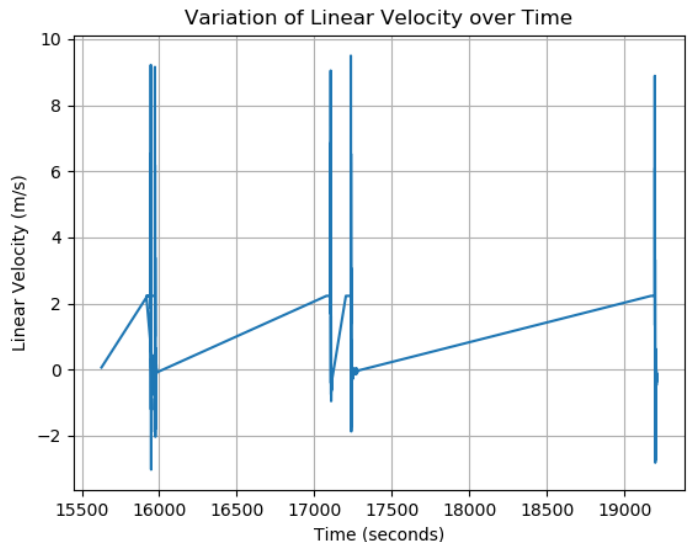

Figure 8 Variation of Linear velocity (Randomly tuned controller)

When comparing the conduct of a randomly adjusted PID controller and a pre-adjusted PID controller for changes in angular velocity over time, a number of noteworthy distinctions can be discerned. The randomly adjusted PID controller, lacking methodical parameter optimization, may display erratic and unforeseeable reactions to alterations in angular velocity. It may experience difficulty in competently following desired angular velocity profiles, resulting in fluctuations, overreactions, or delays in achieving the intended response. On the other hand, the pre-adjusted PID controller, meticulously calibrated according to prior knowledge and expertise, is anticipated to exhibit more meticulous and stable control over angular velocity variations. It should demonstrate better tracking performance, quicker response times, and superior suppression of fluctuations or overreactions. By contrasting the behaviors of these two PID control approaches, valuable insights can be obtained concerning the significance of proper adjustment for attaining precise and dependable control of angular velocity variations in unmanned missions within coral nurseries.

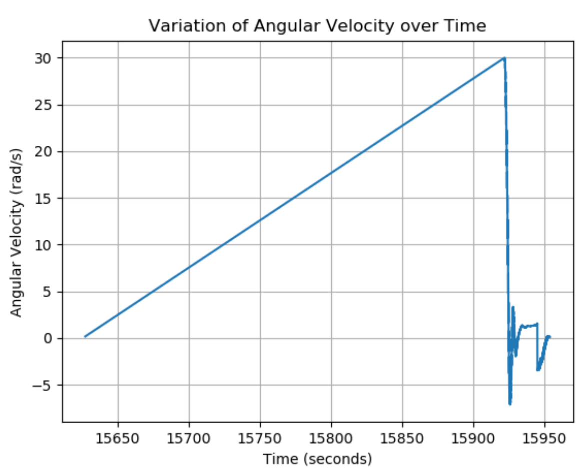

Figure 9 Variation of angular velocity (pre-tuned PID controller)

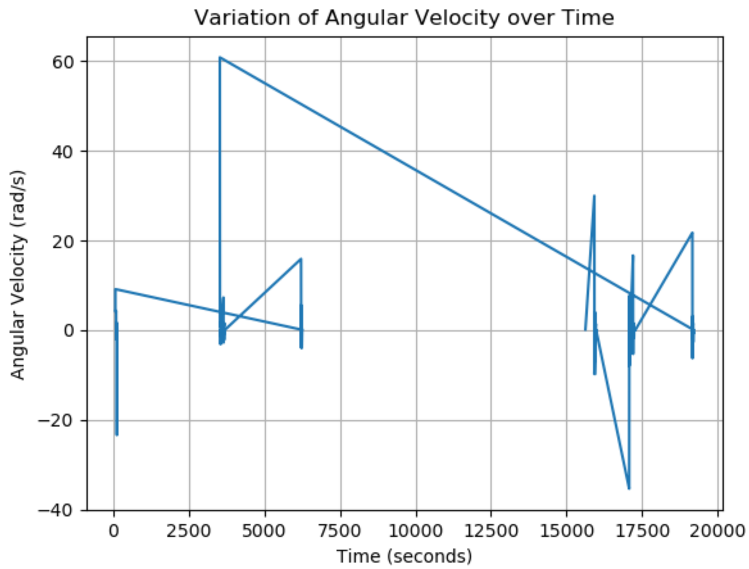

Figure 10 Variation of angular velocity (Random PID tune)

4.2 Mission

The occurrence where the USV initially follows the predicted path but has a tendency to surpass it and then faces difficulty in getting back on track can be attributed to diverse factors. One explanation may be the insufficient adjustment of controls, resulting in excessive control actions as the USV approaches the target location. This overshooting may be aggravated by the dynamics of the system, environmental interferences, or inaccuracies in sensors. Moreover, the response time and delay of the control system can also contribute to the challenge of smoothly returning to the anticipated path. Nevertheless, the USV's capacity to reach the vicinity of the target locations and return to its starting point indicates that the overall control system possesses some level of efficiency and resilience. Refining the control parameters and addressing potential causes of overshooting and instability can aid in enhancing the USV's trajectory tracking performance.

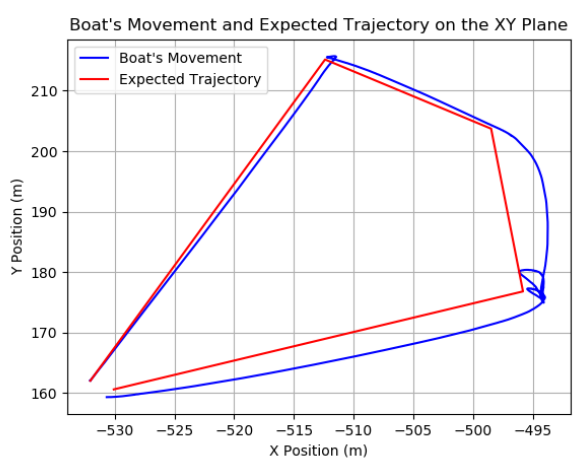

Figure 11 Expected and actual trajectory of USV

5. Conclusions and Future works

The mathematical modelling of a USV has been studied with the goal of being able to further the research in this paper at a later date. A control system developed with the intention of needing minor adjustments when applied to a working prototype has been created in a simulated environment. This research has been focused on controlling a twin-hull making use of two rudderless thrusters, due to their simple mechanical features and flexible steering capabilities, namely, differential steering. The driving force of the USV is produced by the combined effect of the port and starboard propellers, while the turning force is influenced by the variance in thrust and the gap between the two propellers. This offers direction for creating a model of typical rudderless USVs with twin propellers.

While the control system developed during this project works, it is not perfect and still needs a lot of tuning. Using the data and experiments carried out, the PID control system can be further adjusted and built upon. With more research and time, other types of controllers, such as a back-stepping controller, adaptive controllers and Model Predictive controllers can be studied and implemented. The understanding of kinetic and dynamic models gained while working on this project, will be used during the second part of the Master's program to build a proper tuning system for the PID controllers.

In future works, a proper system for tuning and simulating controller parameters will be implemented in MATLAB. The station keeping properties of the USV will need to be worked on and further adjustment to the PID controller will be done. An underwater camera system will be designed as well as an intelligent system for detecting and capturing underwater images of coral nurseries will be implemented. More sensors will also be need to be studied such that obstacle avoidance will be possible.

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Appendix

The code

The code and URDF file used in this project can be found on [GitHub](https://github.com/Lav-Singh/Sailboat-robot-or-catamaran-for-photography-and-surveillance-in-the-lagoon).

```
"""
// Project Title   : Sailboat robot (or catamaran) for photography and surveillance in the lagoon.
// Purpose         : Development of a control system in a simulated environment so that it can be used in a working prototype
// Language        : Python and ROS
// Author          : Ramessur Lav Singh
// Github          : https://github.com/Lav-Singh/Sailboat-robot-or-catamaran-for-photography-and-surveillance-in-the-lagoon
// Date            : 19 June 2023

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"""

class Navigation:
    def __init__(self):
        # Initialize Navigation
        self.cur_pos      = None # Current 2D position (x, y)
        self.cur_rot      = None # Current (yaw)
        self.cur_position = None # Current 3D position (x, y, z)
        self.cur_rotation = None # Current 3D orientation (roll, pitch, yaw)
```