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Towards Autonomous Control System in Brazilian Navy's USV-Lab using MOOS-IvP framework

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Abstract: This article aims to describe the implementation of an autonomous control system for the Brazilian Navy's Unmanned Surface Vehicle Laboratory (USV-Lab) using the MOOS-IvP framework. The main goal of this project is to enable an existing vehicle to be a laboratory for research of maritime autonomous systems, to perform unmanned maritime missions, following desired routes without human intervention or being remotely piloted. The paper starts with the importance of autonomous maritime vehicles and presents MOOS-IvP framework as a validated tool for autonomous maritime systems development. In succession, the main objectives are set, the physical system and components are shown and the proposed software and communication are structured. The work comprises the development of control interface, the integration of sensors and actuators, the tuning PID controllers, and specific software settings, along with several hardware modifications. The methodology consisted in progressive testing, from simulations to local operations as made in Guanabara Bay in Rio de Janeiro and Bay of All Saints in Bahia. Results revealed the system's effectiveness and robustness in maintaining configured routes, enabling its use in a Brazilian Navy military reconnaissance exercise, as well as serving as a laboratory for future research.

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Keywords: Autonomous Maritime Systems, MOOS-IvP, Unmanned Surface Vehicles, Guidance Navigation and Control.

1. INTRODUCTION

Autonomous maritime navigation reflects significant advancements in safety and efficiency of maritime activities. While the concept of autonomous ships is not recent, with Dynamic Positioning becoming common in offshore industry in the 1970's and the validation of first autonomous cargo ship in 1980's accordingly to Ahvenjärvi (2016), nowadays they are being widely used for several applications. Its appeal lies in its potential to reduce human error described in Zhang et al. (2021) and enhance resource utilization as suggested by Liu et al. (2022). There are also advantages concerned to unmanned navigation related to increase of operational range of research and commercial fleets.

In the military domain, the role of unmanned navigation is also increasingly prominent, escalating operational capabilities while mitigating human risk. The Edge Computing, covered in Cameron (2018), when applied to military applications reinforce the strategical importance of autonomous navigation in unmanned vessels. This concept consist by processing maximum of data on-board, rather than in command and control centers, enabling higher level decision-making, especially in degraded communication scenarios. This capability ensures autonomous vessels can efficiently undertake surveillance, mine detection, and other operational tasks with less dependency on information traffic.

In this context, the Brazilian Navy, with the important role in defence of Brazilian EEZ (known as "Blue Amazon"), which spans over 5.6 million square kilometer of maritime area (Marinha do Brasil (2023)), is seeking the development of its autonomous navigation capacities, especially for reconnaissance missions. This exploration have been achieved by the use of Unmanned Surface Vehicle Laboratory (USV-Lab) from the Naval Systems Analysis Center (CASNAV)(Brazilian Ministry of Defense (2014)), and several state-of-art integration frameworks. The USV-Lab initiative is a testament to the Navy's strategy to harness autonomous navigation's potential, paving the way for sophisticated maritime operational tactics.

In 2023, MOOS-IvP (Mission Oriented Operating Suite - Interval Programming) framework (Benjamin (2008)), in acknowledgement to its system integration capabilities, was tested and implemented in USV-Lab. As an open-

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source platform engineered for conception of autonomous marine vehicles, MOOS-IvP ensures the efficient integration of diverse subsystems and sensors, essential for autonomous navigation. Its solid architecture is the basis for complex algorithm-based decision-making. MOOS-IvP's has been widely used as low cost system in AUVs (Autonomous Underwater Vehicles) and USVs (Autonomous Surface Vehicles) conceptions such in development of laboratory ASV as in DeFilippo et al. (2021), Hydrographic Survey ASV in Manda et al. (2015), and several others surface vehicles as in Mattos et al. (2016).

Although widely implemented frameworks by USV community are standard MOOS-IvP and ROS (Robotic Operating System), these enable the development of several algorithms and improvements by community. It include state-of-art concepts in machine learning as seen in Wu et al. (2020) Sarhadi et al. (2022), thereby representing a robust platform for further advancements.

1.1 MOOS-IvP

MOOS-IvP is a framework composed of two open-source software projects, providing full marine autonomy suit Benjamin (2008). It offers functions for message passing and a collection of tools and libraries to achieve autonomy in unmanned marine platforms.

The framework is composed by:

- MOOS (Mission Oriented Operating Suite) - a set of C++ libraries and tools that support message passing between processes
- IvP-Helm (InterVal Programming Helm) - a set of MOOS based applications of monitoring and autonomous decision making capabilities tools, focused on marine platforms

MOOS-IvP features a modular architecture where all information exchange occurs with the *MOOSDB* acting as a central server, and the other applications as clients that send and receive information. Each application runs independently, meaning there is no connection between applications except through the *MOOSDB*.

The *IvP Helm* operates as a MOOS application within the topology, using a structure called *IvP Behavior* to define the platform's autonomy. *Behaviors* are isolated systems dedicated to a specific type of mission for the autonomous vehicle; for instance, some are designed for obstacle avoidance, maintaining the ship's course, among others. Depending on the *behavior* selected for a particular autonomous mission, the *IvP Helm* will iteratively provide a different course and speed for the ship Benjamin (2008).

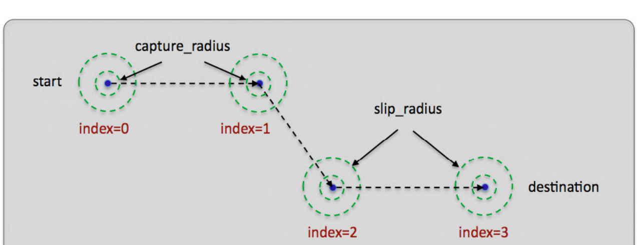

Fig. 1. Waypoint Behavior (Benjamin (2008))

The Waypoint behavior facilitates movement through a series of designated points on the x-y plane. The main parameter involved is the collection of waypoints. Additional important parameters include the inner and outer radius surrounding each waypoint, which define the criteria for progressing to the next point. Figure 1 illustrates this concept.

1.2 Contributions

While integrating the USV-Lab, which will be further detailed, with MOOS-IvP, the following objectives were established for the conception of an autonomous navigation laboratory:

(1) Implementation of an autonomous path planning system through the MOOS-IvP framework;
(2) Design of speed and heading controllers for the path planning system

This project also developed an human-machine interface for remote control and monitoring. And by detailing the implementation of a laboratory USV platform for autonomous navigation studies in Brazil, this paper aims to offer a useful resource for the research community. This platform serves as a versatile base for testing and integrating various control systems, significantly advancing the development and understanding of guidance, navigation and control (GNC) in maritime systems.

2. SYSTEM DESCRIPTION

The USV-Lab (Unmanned Surface Vehicle Laboratory) is composed of a 7.7m Flexboat SR 760 integrated with navigation and perceptions sensors, and onboard computers, forming a mobile laboratory for autonomous maritime systems research.

Fig. 2. USV-Lab

2.1 Sensors and Actuators Overview

The vessel was designed with sensors and actuators (Table 1) that enabled the operation of an autonomous control system.

The hydraulic actuator is used for the rudder actuation and throttle and gear actuation and made by the two linear actuators.

System's Sensors and Actuators

Sensors	Components
	Simrad HS80A GNSS compass
	Simrad RF300 rudder feedback unit
	Simrad 4G Radar
	Sonar Sidescan EdgeTech 4125
	Cisco Network Switch
	Intelbras PTZ camera
	NetNode Mesh Radio
	Omnidirectional antenna
	MiniPlex-3E-N2K
Actuators	
	Outboard 200HP Mercury OptiMax motor
	Octopus Autopilot hydraulic linear drive
	Two V0-F Vinitrônica-12V linear actuators

Table 1. List of main sensors and actuators used in the autonomous vessel.

2.2 Control System Infrastructure

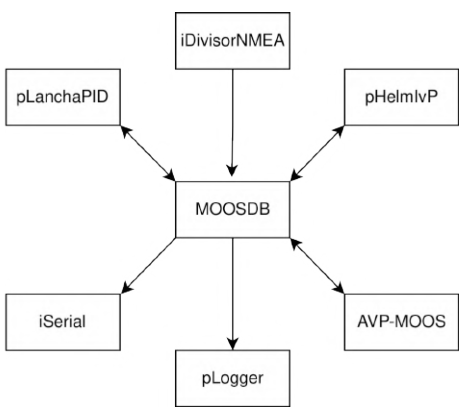

Fig. 3. Control System Topology

The MOOS-IvP modules were developed and deployed in a local portable computer Linux platform. The basic scheme is seen in Figure 3.

Each application performs a specific function, contributing to the autonomy of the vessel as a whole and enhanced code modularization. The function of each application can be defined as:

(1) *iDivisorNMEA*
Translates messages from the Gateway connected to the NMEA0183 network, providing translated sensor data to the MOOSDB.

(2) *pLanchaPID*
A PID controller with anti-windup and output limitations for speed and heading control. The script was designed to allow real-time adjustment of the K_p, K_d, and K_i parameters during the vessel's navigation through the AVP-MOOS interface, which improved the parameter tuning process.

(3) *pHelmIVP*
A native multi-objective autonomous decision making *MOOS-IvP* application. It was used to generate trajectories and compute the current desired heading of the vessel.

(4) *iSerial*
Receives the output from the PID Controller running in the pLanchaPID application and sends the appropriate command via a USB-Serial cable to a control board developed by CASNAV, which aims to enable action on the boat through simple commands to change the rudder angle, motor throttle, and motor gear control.

(5) *AVP-MOOS*
A graphical interface developed using Python aimed at monitoring the vessel, seamlessly integrating sensor signals for real-time visualization and providing an intuitive platform for navigation control at a base station. In addition to remote and autonomous control, the interface also allows the change of controller parameters in real-time as we can see in Figure 5.

(6) *pLogger*
Responsible for creating a history of all activities performed during a mission by the USV-Lab.

2.3 Network and Communication

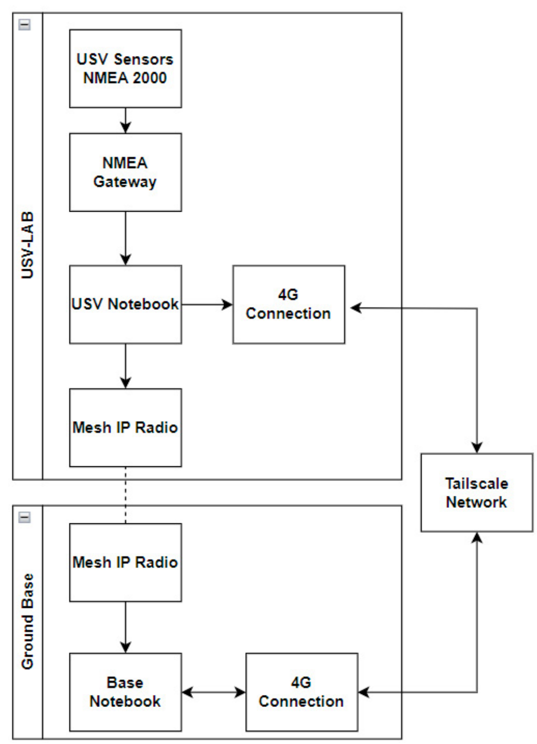

Fig. 4. Network Diagram

During the tests, the network structure represented in Figure 4 was utilized. The AVP-MOOS interface operated on a laptop at the ground base, while the control system ran on a linux mini desktop aboard the USV-Lab. Both systems were connected via a radio data link and a 4G internet connection. Control via 4G connection was facilitated through VPN, which enables a direct connection between the two computers over the internet, akin to a local network setup.

Fig. 5. Human-Machine Remote Ground Control Interface

3. RESULTS

3.1 PID Controller Calibration

Various tests were conducted in Guanabara Bay using the USV-Lab with the aim of calibrating the controller. The output u at time t is computed by a PID controller with fixed defined upper and lower bounds and anti-windup for the integral gain:

$$I_{error}(t) = \begin{cases} u^+ & \text{if } I_{error}(t) > u^+ \\ u^- & \text{if } I_{error}(t) < u^- \\ \displaystyle\int_{\tau=0}^{t} e(\tau)d\tau & \text{otherwise} \end{cases} \quad (1)$$

$$PID(t) = K_P \cdot e(t) + K_I \cdot I_{error}(t) + K_D \cdot \frac{de(t)}{dt} \quad (2)$$

$$u(t) = \begin{cases} u^+ & \text{if } PID(t) > u^+ \\ u^- & \text{if } PID(t) < u^- \\ PID(t) & \text{otherwise} \end{cases} \quad (3)$$

where u^+ and u^- are the maximum and minimum rudder angles respectively.

The obtained values for the heading controller's parameters can be seen in Table 2, with the standard speed for the tests being 5 knots. In Figure 6, we can observe the heading control response for a desired value of 185º, where the response had an overshoot of approximately 36% and a response time of about 15 seconds. In figure 7, we have the speed controller response; initially, the USV-Lab was moving at approximately 2 knots and was commanded by the controller to reach a speed of 5 knots. The response had an overshoot of approximately 16%, and from the graph, we can see the controller's capability to maintain the desired speed over time approximately.

The tuning of the heading controller was made by following the Ziegler and Nichols (1942) method, increasing the K_P until the ultimate gain the makes the system unstable, and then cutting the gain by around half the value. The addition of the integral term, however, made the system too slow and did not improve the overshoot, and therefore the authors decided to include the derivative term to slow down the system. The main reason of the overshoot was due to a delay in the system coming from the rudder's angle sensor, which, at the time of this work's development, could go up to more than one second, limiting the system's performance.

Regarding the speed control, it was also tunned according to the previous method, but was fine tuned empirically. It is also worth mentioning the limiting precision of the speed reading coming from the GPS sensor.

The Conclusion section includes future steps and improvements regarding the controller limitations.

Table 2. Parameters of Heading and Speed Controller

Parameter	Heading	Speed
K_p	0.9	6.0
K_i	0.0	1.3
K_d	0.2	0.3

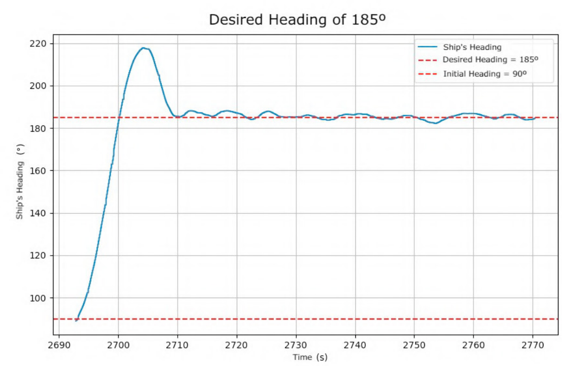

Fig. 6. Response of the Heading Controller

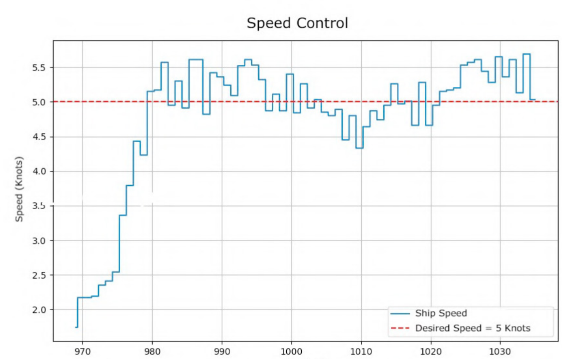

Fig. 7. Response of the Speed Controller

Despite achieving satisfactory results for our application, the speed control directly affected heading control during turns. When performing sharp turns, there was a loss of speed, and the controller accelerated the vessel, causing it to deviate from the planned path. Although other solutions existed, such as using a bank of linear controllers Cepeda-Gomez et al. (2021), we chose not to use the speed control due to development time constraints, and decided to maintain a constant engine regime (Figure 8) during the operation of the USV-Lab, meaning that we did not change the speed actuator output.

In Figure 8, the USV-Lab was set to navigate through a set of points similar to those used in mine hunting. Observing the path of the vessel's turns, we can notice that the proposed solution of using the heading controller and a constant engine regime for speed maintenance showed satisfactory results and served as a test for future Operational Exercises of the USV-Lab. As an overall result for the controller performance, it effectively stabilized the ship's heading in a timely manner, ensuring the vessel adhered to the desired path at the predetermined speed of 5 knots, but further enhancement in could be achieved by employing a faster actuator. In the analysis of speed control, the pursuit of improved outcomes involves the acquisition of finer speed data readings, conceivably through the application of sensor fusion techniques as in Gehrt et al. (2020).

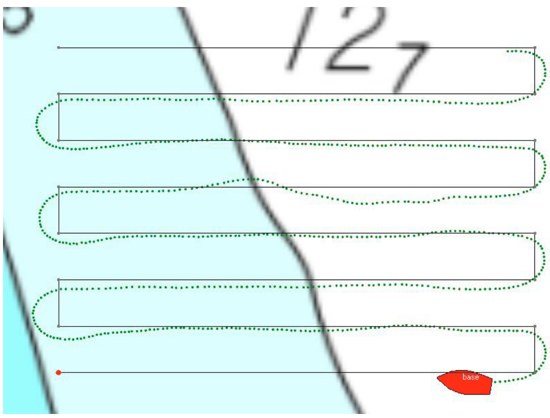

Fig. 8. USV-Lab trajectory with constant engine regime

3.2 Autonomous vs Human-Controlled navigation

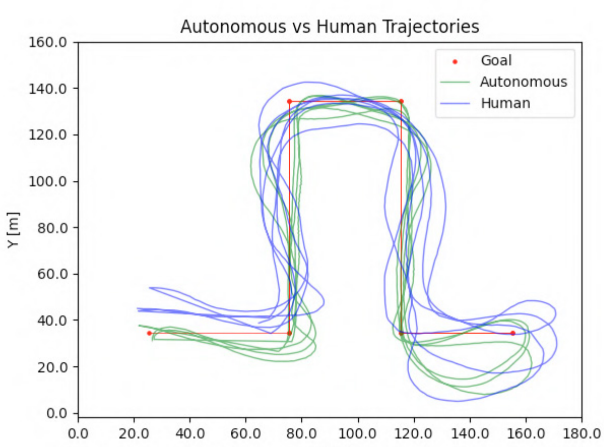

Fig. 9. Performance Evaluation: Autonomous vs. Human-Controlled Navigation Along a Desired Path

The performance comparison between an automatic controller and human manual control for following a desired path reveals compelling insights into autonomous navigation. In our study, we analyzed the trajectories generated by both methods, with the automatic controller depicted at Figure 9 in green and the human-controlled path in blue on a shared plot. For a fair comparison, the human pilot had access to their current position on the map, as well as the waypoints, thanks to a digital marine chart plotter, hence having the same informations as the automatic navigation. Visually, it is evident that the autonomous trajectory consistently maintains closer proximity to the desired goal path, exhibiting a remarkable degree of regularity across multiple trials. Conversely, while the human-controlled trajectory displays deviations from the desired path, it still demonstrates a commendable level of adherence, albeit with slightly less consistency. Quantitative analysis further corroborates these observations, with the mean squared error

$$\mathrm{MSE}(d, \hat{d}) = \frac{\sum_{i=0}^{N-1}(d_i - \hat{d}_i)^2}{N}$$

serving as a key metric for evaluating path accuracy, being d the distance between the vessel and the desired path, and $\hat{d}$ is the desired distance, which is always 0.The MSE for the autonomous trajectory averaged at 49.82, significantly outperforming the human-controlled counterpart, which yielded an MSE of 75.55. These findings underscore the efficacy of autonomous control systems in achieving precise and reliable navigation outcomes, highlighting their potential for enhancing efficiency and reliability in various real-world applications.

3.3 Brazilian Navy Clarification Exercise

From October 23 to 27, 2023, the Brazilian Navy carried out the MINEX-23 Clarification Exercise, aiming to improve the training of its units in the conduct and execution of Mine Warfare operations. In this exercise, the USV-LAB was used for the first time in Underwater Mine Hunting operations. During the operation, the Ocean Patrol Vessel "Apa" acted as mother ship, having all the necessary equipment for launch and communication with the USV-Lab (Figure 10).

Fig. 10. USV-LAB alongside the Oceanic Patrol Vessel 'Apa' in Operation Minex-23

The ship's Combat Operations Center suited the USV-LAB Command and Control station, where the Naval Systems Analysis Center team used the AVP-MOOS interface developed in this work to control the USV-Lab.

The exercise included supervised autonomous and remote-controlled navigation of the USV-Lab, as well as the use of a side-scan sonar attached to the remotely operated USV-Lab for real-time detection of underwater mines. Due to confidentiality, additional details about the execution of the exercise were not described in this work.

4. CONCLUSION

The work achieved its two main objectives: the implementation of an autonomous path planning system (including remote control) and the design of speed and heading controllers.

The tests conducted on the USV-Lab yielded successful results, demonstrating the effectiveness of PID control within its hydraulic system and the interface's functionality with MOOS-IvP. Additionally, communication between the ground station and the vessel was established seamlessly. The control system received validation during the MINEX-23 Clarification Exercise, where this unmanned surface vehicle was effectively utilized in mine hunting operations.

Next steps of this works includes:

- The development of a control board that gets the rudder angle readings directly, improving the reading delay
- Design a Kalman Filter sensor fusing the GPS and the IMU for better speed calculations
- Implementation of a multiple output control algorithm, such as Gain Scheduling or MPC to deal with the non-linearity of the Heading behaviour on speed changing

Going in the direction of autonomous navigation, it is recommended to effectively implement *Collision Avoidance* using AIS, cameras and radars. These innovations could increase the accuracy, reliability and capabilities of the USV-Lab, expanding the applications of autonomous marine vehicles in different operational scenarios.

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