# Modelling of an Intelligent Control Strategy for an Autonomous Sailboat - SenSailor

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***Abstract*—This paper studies the mathematical model required to implement an intelligent control system for the autonomous sailboat SenSailor Drone. This work presents the required equations and defines the hardware configuration and interactions between sensors and actuators in the system to be mounted. The proposed model was developed in Python, and it is feasible to interact with open source tools of machine learning. The generated trajectories will be used as input trajectories to train a Neural Network that identifies a plant model and gives an optimal controller for the desired behaviors.**

***Index Terms*—Sailboat, non-linear control, model analysis, autonomous vehicles**

## I. Introduction

This work presents the design and optimization of a control system to improve the automatizing of the sailboat SenSailor Drone, initially designed in the Polytechnic University of Catalonia. This autonomous surface-navigation vehicle can follow a predetermined route and recollect information through incorporated scientific devices to promote maritime investigation projects. The initial model of the boat has a control system developed with micro-controllers, using electronic Arduino hardware. These devices are preferred multiple times because of their user-friendly programming environment and their considerably accurate results for purposes that do not require rigorous control. Nevertheless, more robust and precise systems are chosen for applications that demand more exactitude and faster response velocity [3]. Therefore, this investigation proposes the creation of a mathematical model which describes a control system developed through artificial intelligence to provide more stable and trustworthy results.

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### A. Autonomous Sailboats

Nowadays, the development of autonomous vehicles is one of the most popular areas of investigation, especially for scientific explorer applications [4]. The ability of these drones to stabilize and orientate themselves depends on a variety of external parameters like wind, water, obstacles, etc [5]. Most of the previous projects developed in this area consider the wind force, velocity, and direction as the main factors that destabilize the system. In 2018, the International Automatic Control Federation presented a mathematical model to compensate for the wind's effect and keep the vessel stable. To fulfill this objective, the wind's direction and velocity were measured from two references: absolute and relative to the sailboat position [1]. Similarly, the International Conference of Robotic Investigation in 2015 presented a design for the autonomous sailboat Aelous. For its simulation, the actual wind data was obtained from a stationary meteorological station, while the apparent wind was calculated through the Extended Kalman Filter (EKF) algorithm [2]. Another challenge in the design of autonomous vehicles is the possibility of finding obstacles. This was a parameter considered in an investigation in China.

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It presented an autonomous vessel control system based on the D* algorithm that allowed the generation of displacement routes taking two coordinates (current and destiny position). The obstacle avoidance system incorporated was programmed using the YOLOv3 algorithm, that consist of a convolutional neural network for object identification [6].

### *B. SenSailor*

The SenSailor's structure is composed of a 2 meters long shell and a rigid sail. The materials used include polyester resin, fiberglass, nautical wood, and textiles to improve the sail's aerodynamics. For its power system, it possesses a solar array that recharges the principal battery. In addition to its exploration equipment, the sailboat owns sensors. It obtains the necessary data to identify obstacles, sea currents, wind direction, and other factors that can disturb the ship's balance. Based on this information, the control logic takes charge of sending the appropriate signals to three servomotors that work as the system's actuators. Two of them allow the control of the rudder's direction to define the course. The third servomotor orientates the sail's aileron to take advantage of the wind force. As a consequence, it is possible to use a low-power motor and to save resources.

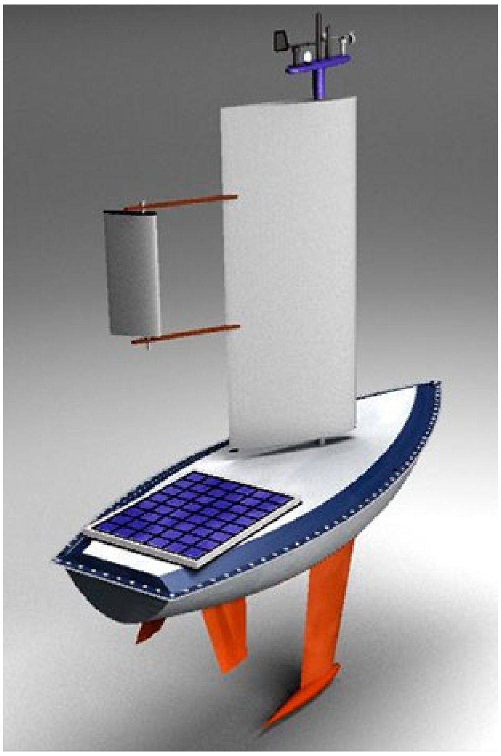

Fig. 1: CAD Model of the SenSailor Drone

## II. Methodology

### *A. Background Investigation*

State of the art allowed summarizing relevant information about previous and current investigations developed in the same field of study as the current project. Based on those references, it was possible to determine the fundamental characteristics and the most proper methods to model the vessel. There made some assumptions to simplify the system analyzed [7]. For example, the waves were despised since the boat is supposed to navigate only near the shore or lakes. It was also decided that the most critical external agent was the wind. The variables that define the behavior and current state of the vessel were: position coordinates, bow angle, sail angle, linear velocity, angular velocity, mass, and acceleration.

### *B. SenSailor Drone Modeling*

The control equations are based on Newton's laws applied to the sailboat. In turn, geometric factors are integrated into the vehicle itself as shown in Figure2 and equation 1 to 9 [8].

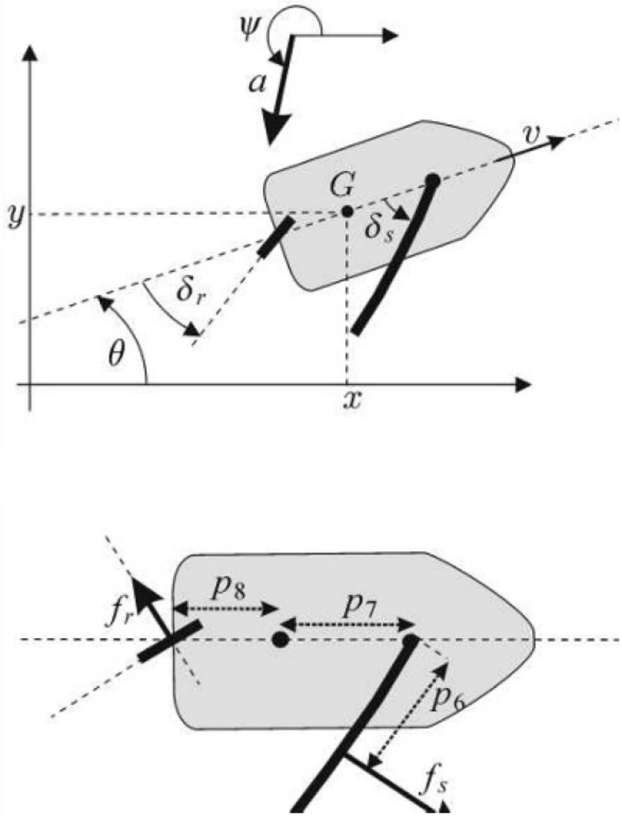


Fig. 2: Sailboat Diagram

$$x' = vcos(\theta) - \alpha_d acos(\psi) \tag{1}$$

$$y' = vsin(\theta) + \alpha_d asin(\psi) \tag{2}$$

$$\theta' = \omega \tag{3}$$

$$v' = \frac{f_s sin(\delta_v) - f_r sin(u_1) - \alpha_v v^2}{M} \tag{4}$$

$$w' = \frac{f_s(p_6 - p_7 cos(\delta_v)) - p_8 f_r cos(\delta_r) - \alpha_w w}{J} \tag{5}$$

$$f_s = \alpha_s a sin(\theta - \psi + \delta_v) \tag{6}$$

$$f_r = \alpha_r v sin(\delta_r) \tag{7}$$

$$\delta_v = \{if \sigma \leq 0; \pi - \theta + \psi \tag{8}$$

$$\delta_v = \begin{cases} if \sigma \leq 0; & \pi - \theta + \psi \\ else; & sign(sin(\theta - \psi)) \end{cases} \tag{9}$$

where;

TABLE I: Model variables

| *Variable* | *Description* | *Units* |
|---|---|---|
| (x,y,$\theta$) | Coordinates for position and orientation | (m ,m ,rad) |
| v | Linear velocity | m/s |
| $\omega$ | Angular velocity | rad/s |
| $f_s$ | Wind force | N |
| $f_r$ | Water force | N |
| $\alpha_w$ | longitudinal friction coefficient | $Nsm^{-1}$ |
| $\alpha_w$ | rotational friction coefficient | $Nsmrad^{-1}$ |
| $\alpha_r$ | lift coefficient for the rudder | $Nsm^{-1}$ |
| $\alpha_s$ | lift coefficient for the sail | $Nsm^{-1}$ |
| $\alpha_d$ | drift coefficient | $m^{-1}$ |
| $p_6$ | geometric factor | m |
| $p_7$ | geometric factor | m |
| $p_8$ | geometric factor | m |
| $\delta_v$ | Sail angle | rad |
| $\delta_r$ | Rudder angle | rad |
| M | Mass | kg |
| J | Angular inertia | $kgm^2$ |
| a | Wind speed | m/s |
| $\psi$ | Wind orientation | rad |

### C. UML and algorithm programming

The displacement of the vessel was modeled through two methods that define the two main basic moves. The first one, rotate, increases the bow angle in the number of degrees according to the angular velocity of the ship. The second method, move, generates a linear translation, changing the current coordinates as a function of the linear velocity components in the vertical and horizontal axis. For negative velocities, the angles or coordinates decrease. Combining these basic motions makes it possible to describe a wide variety of routes for the vessel. The method fleet race allows the boat to move from its current state to a new specified position. First, the ship rotates until its bow points in the destiny direction. Then, it uses the move method to get to the final spot. Finally, if there is another destination point, the process starts over; otherwise, the boat remains still. It requires two indicator variables to recognize if the desired angle and final coordinates have been reached. This way, the vessel decides whether it needs to rotate, move, or keep its current position

Another task that the vessel can fulfill is the scanning area, which consist in covering a wide rectangular area subdivided by a grid. The program receives the parameters to define the

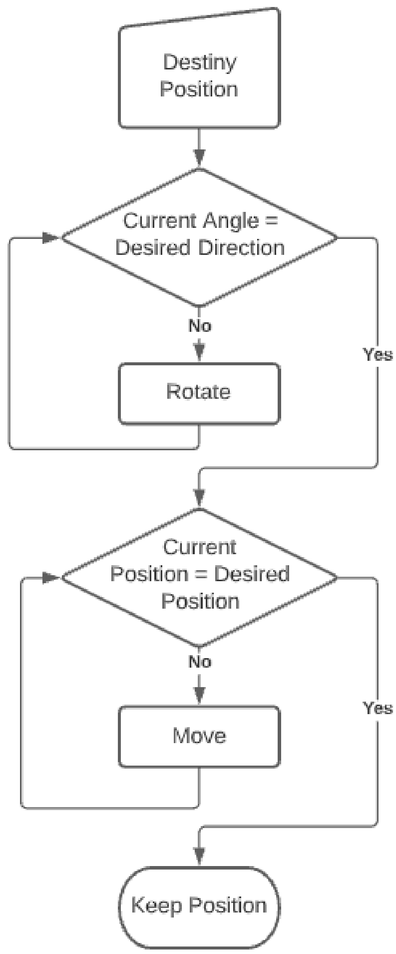


Fig. 3: Flow chart - Process to reach a desired position.

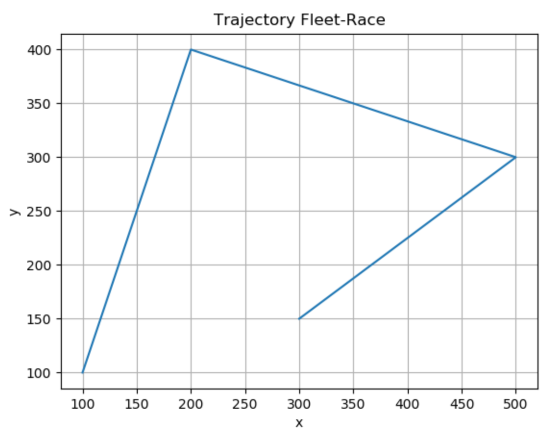


Fig. 4: Theoretical path - Fleet Race

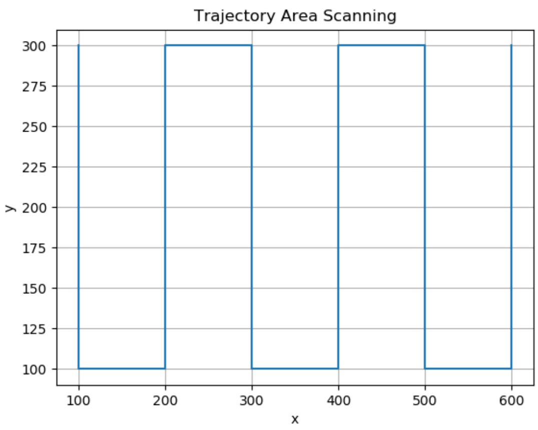


Fig. 5: Theoretical path - Area Scanning

initial and final position of the vessel and the number of divisions. With this data, it calculates the different points to describe the whole route to travel through the complete area. Each displacement from one point to another is development by the same fleet race function, based on the basic rotate and move methods.

### *D. Design and Construction of the Autonomous Sailboat*

The boat construction design considered recommended structural and fuselage materials, which were to create a strong internal structure mainly made of aluminum profiles, the hull of the boat and the rest of its outer body will be built with fiberglass hardened with resin. The internal system and electronics of the sailboat will have 3-cell Li-Po batteries of long duration with a voltage of 11.1v at 5Ah which will be the main power source for the sensors and actuators. The central processing unit in charge of motion management and positioning will consist mainly of an Arduino board and an autopilot. However, the Arduino does not have the robustness required to implement an intelligent control system. To support the artificial intelligence processing, a GPU of specialized purpose in machine learning processing will be needed, for which the NVIDIA Jetson embedded system will be added to the control circuit. To collect the necessary data about the physical variables involved in the study a set of sensors will be used, including a vane, to recognize wind direction; an anemometer, to measure wind velocity; a distance sensor; a GPS, for GPS positioning, and a Inertial Measurement Unit, which integrates an accelerometer and a gyroscope to provide information about the velocity, rotation and inclination in the three axis, acceleration, inertial momentum, and other magnitudes of interest of the sailboat. For the execution of the change of movement through the sail and rudder, 2 servomotors will be used to regulate its angular position and thus correct the course to be followed by the sailboat.

### *E. Design of a Model-Reference Neural Controller*

The NN Controller uses two neural networks, one for the controller and the other for the plant. The plant must be

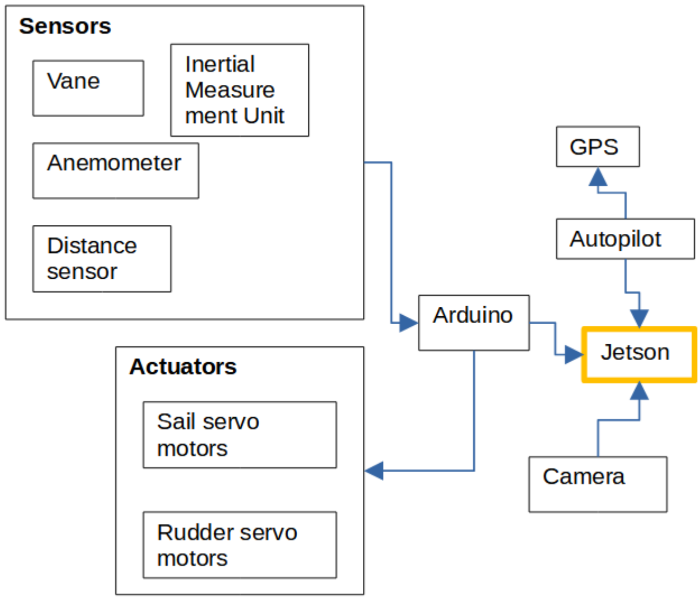


Fig. 6: Block diagram: interaction between sensors and actuators

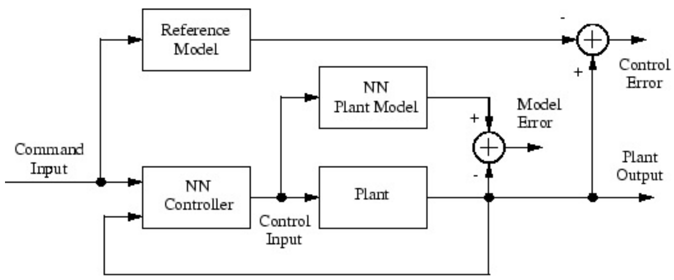


Fig. 7: NN Model-Reference Controller

identified in the first place. Then the controller is trained so that the plant output follow the reference model output as shown in Figure 7.

The Reference model of the SenSailor boat is constructed according to its dynamic and kinematic equations. The objective is to control the movement of the boat.

Each network has two layers, and the number of neurons in the hidden layer can be changed to optimise the system's functioning. It is necessary to identify the reference inputs, the controller outputs and the plant outputs.The plant model has to set inputs, controller outputs, and plant outputs, as shown in Figure 8.

## RESULTS

### *F. Simulation Design and Algorithm Explanation*

An autonomous sailboat simulator was made in Python using libraries such as pygame to control external physical equations that allow the modeling of the behavior of the sailboat to be used in the programming of the control system of the boat. For the simulator, object-oriented programming was

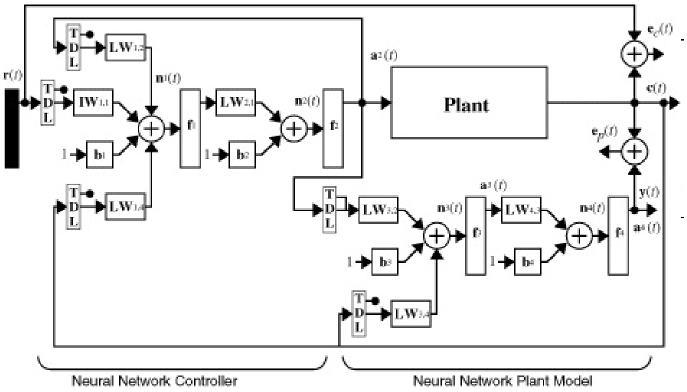


Fig. 8: NN Plant and Controller Descriptions

used. The structure of the program is shown by a UML of the simulator in Figure 9. There is a main class called Barco.py which is responsible for having all the parameters of the boat including position, velocities and forces. Another important class is Viento.py which creates a physical object that performs the action of pushing the boat, causing it to acquire an external force to generate the movement. The theoretical equations of the sailboat's movement and the controller are included in the code to obtain the graphics of the trajectories simulated. This way, it is possible to compare the ideal and experimental behavior of the system.

## Conclusions

The investigation achieved the desired goals since it was possible to model the behavior of the autonomous sailboat SenSailor. The mathematical model defined the dynamics of the vessel, allowing the design of the intelligent control system. The wind's velocity and direction were considered as the principal external disturbance, being one of the variables of the proposed equations. The efficiency of this control strategy was demonstrated by getting an experimental response with high proximity to the theoretical results expected. For its implementation, the electronic component NVIDIA Jetson was considered as an appropriated tool because of its high response velocity in artificial intelligence, its ability to support multiple high-resolution sensors in parallel and reduced programming complexity.

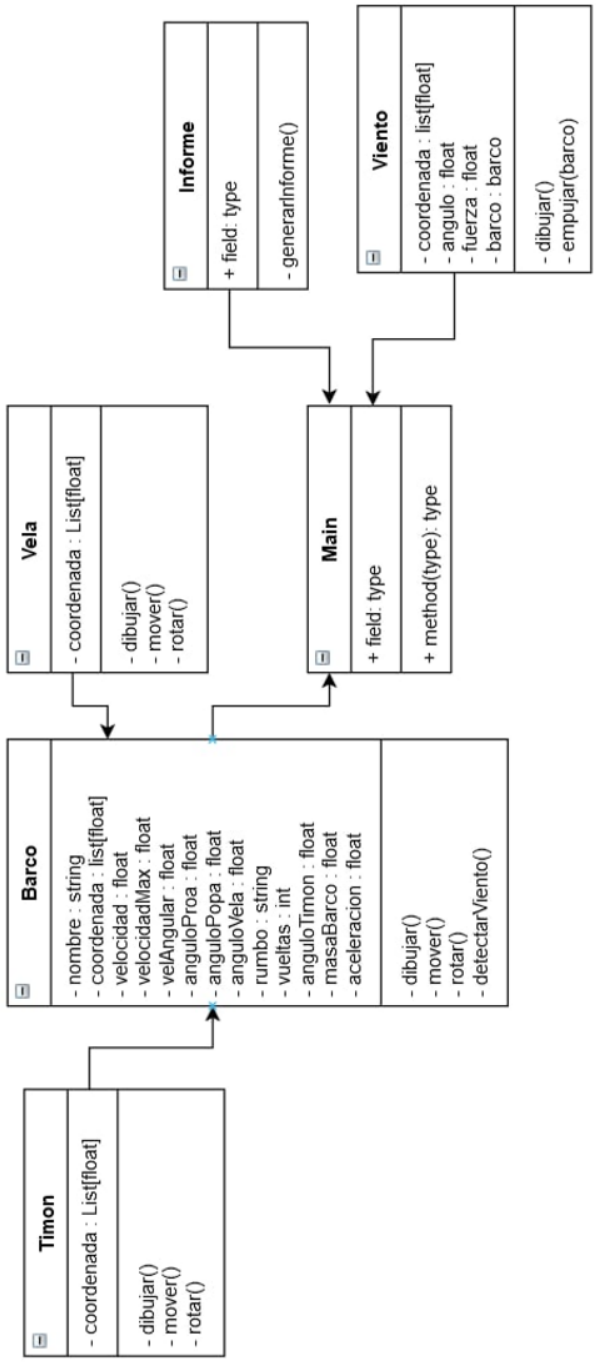


Fig. 9: Structure of the program

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