A Robust Architecture for Autonomous Sailboat Control

Double Blind[1]

***Abstract*— Autonomous sailing boats are becoming important marine platforms for performing different tasks, such as surveilance, water and environmental monitoring, among others. In this work we propose a novel architecture that is being implemented into a real autonomous sailing boat, named F-Boat. Our architecture includes control, external perception and navigation aspects. We introduce an overview of possible architectures and control models for autonomous sailing boats, detaching requirements and important characteristics for making higher level tasks possible. Based on this study directions, we develop two control techniques and a higher level task on the top of these techniques, which have been experimentally validated in simulation.**

Fig. 1. F-Boat - The Sailboat Autonomous Robot.

I. Introduction

The main reasons for using unmanned surface vessels (USV) of sailboat type are their reduced operating costs and the possibility of long endurance missions with real-time data transmission, which is allowed by current communication channels that include cell and sattelite phones technology. Applications included in the long duration category can bring great benefits to the naval industry and ocean monitoring, including reconnaissance and surveillance, buoys with intelligent sensors, autonomous transport of goods, and other tasks.

A fully autonomous sailing robot should perform the planning of trajectories without any kind of human assistance. An optimal route should be calculated based on a map and on meteorological data (wind force and direction), in order to navigate safely (avoiding collisions) and reliably in the most diverse types of situations. Hence, it should have some characteristics as being energetically self-sufficient, most using the wind force as the source of propulsion, to carry aboard all of its control, and to have obstacle avoidance capability. Although some developments and improvements of navigation techniques for sailboats have already occurred so far, efforts to make it completely autonomous are still considered by the scientific community.

Hence, in this direction, our purpose is to use cutting edge technology for the implementation of mechanical, electrical, and electronic equipments, and also their controllers, proposing the architetural design of an autonomous sailboat. To date, the sailboat robot named F-Boat has been designed and contructed, with all the electric and electronic components already embarked as shown in Figure 1. The devised architecture for F-Boat intends to support the development of strategies based on the use of Reinforcement Learning (RL) for the acquisition of basic navigation skills. A high-level RL-based navigation approach has been tested in simulation and the idea is to extend it using the proposed architecture in order to convey new techniques to be developed for robust navigation in long-running applications.

Thus, the contribution of this article is two fold. First, we introduce the architecture with the completely new mechanical and electronic design of F-Boat, and second, as well, we have done a detailed survey and introduce here the details of the low-level controllers that will be used to drive the vessel using simple control techniques, and giving further directions to the field. With basis on the literature, we show the reasons for devising very simple and already used controllers, with some adaptations, in order to control the vessel's path. For the rudder we devise a proportional, integral, and derivative (PID) controller and for the sail we propose an adapted fuzzy controller, that will correct the angular positioning of the sail depending on the wind direction. We also adopt here another control model for the sail using a mathematical formula based on polar coordinates. On top of this architecture, we created a very simple strategy for performing a jibe, which demonstrates that our approach can be used to strategize for very simple moves, both can be part of a higher level path planning and following strategy based on machine learning that is our future goal. Further more, we provide documentation for the mechanical and electronic design, which includes sensors as windsock, compass, barometer (for low pressure detection), cameras (360 degrees and 3D), a solar panels powering system, and a spare motor that can be used for rescuing and saving the sailboat in case of emergencies.

II. Autonomous Sailing Control Theory

There are several requirements involved on an autonomous sailing vessel, from its mechanical, electrical and electronic project design to its control. In this section, we provide a more detailed background on sailing guidance and control

[1]Double Blind Institution doubleblind@double.blind

models that can be applied in our sailboat, in order to further understand the adopted motion strategies. Roughly, a robotic sailboat can be characterized as a USV that that moves to a desired goal by way of the wind propulsion on a sail set and having its direction dictated by a rudder [BLIND]. In this kind of vessel, feedback from sensors data has a certain degree of difficulty and modeling these data generally involves non-linear mathematical variables. For example, controlling the position of the sail when there is a wind from a certain position or even controlling the rudder indicating which side the boat will turn generates a very high degree of complexity.

Basically, the guidance control problem of a sailboat is generally solved by way of determining an equation that optimizes the angles for the sail and the rudder, at the same time, considering the boat and target current positions, and variables such as wind direction, water current, boat velocity, and others. Notice that the goal may not be straight reachable for all possible wind directions. In fact, for some directions (e.g. against wind) the sailboat can not move straight forward. In these situations it should do a tacking, or a zig-zag, to reach the goal. Hence, the control problem can be divided in two different situations: (1) the sailboat can go straight to the goal given a certain pair of angles for the rudder and sail; and (2) the sailboat can not move forward, straight to the goal, due wind conditions, requiring a strategical maneuver.

This suggests using kind of a hierarchical controller that can be divided in, at least, two levels. The lower-level takes care of changing (if necesary) the sail and rudder angular positions, only, and can be implemented straight in some control board, such as the Pixhawk or Navio2. This level uses variables as actual linear and angular positions of the rudder and sail given by proprioceptive sensors constructed for this purpose and the target and current positions (from GPS). It can additionally use some IMU sensor for improving navigation. Its output are the desired motions of both the sail and rudder in order for the sailboat to straight reach the target. A higher level of control verifies and/or rectifies the trajectory given by some mission planner, from a waypoint to another, replanning the trajectory if necessary according to a certain situation. This is the case of dynamic obstacles or next point against wind for example. It uses variables as target and actual sailboat positions (given by GPS), wind direction and velocity, presence of dynamic or static obstacles (given by vision), and water current, between others. Its output are waypoints that are free of obstacles and allows the sailboat to move forward, which are straight given to the low-level control system. Using reinforcement learning in this level seems to be a good strategy [1].

The sailboat guidance system that we adopt in this work is basicaly done on the top of two low-level controllers. We use a simple proportional integral derivative (PID) for the rudder and a Takagi-Sugeno Fuzzy controller [2] for the sail due to its characteristic of being a nonlinear with variable gain controller [3]. The control module has a closed-loop form as will be described later. The Fuzzy logic approach used for the sail allows the treatment of expressions that involve quantities that are not exactly described, composed by linguistic variables. Fuzzy logic is based on the concept of fuzzy sets [4]. This approach is useful when there are non-linearities and/or parametric uncertainties and disturbances, which are generally present in the sail control. This basic control system with two levels has been tested and used in simulations (with Matlab) and shows to work well in a previous sailboat.

III. Related Work

Several literature works deal with related approaches [1], [5], [6], [7], [8], [9], [10], [11], [12]. There are also some initiatives to evaluate the navigation system in the broader context of mobile robotics, with proposals to define metrics and test scenarios [BLIND]. For our work objective, we have selected and classified the works related to the architectural design of sailboats and those of autonomous guidance systems of sailboat (involving control and navigation strategy).

We could find several approaches related to architectural design proposals that have inspired our current project [13], [14], [15], [16]. These sailboats basically use the sail to transform the force of the wind into their propulsion force, requiring energy only to power the internal systems necessary for autonomy, such as sensors, actuators and very simple on-board computers. Some of these autonomous sailboats are favored in tasks that require a higher level of persistence where energy self-sufficiency is desired, such as coastal surveillance and ocean data collection.

Work	**RDC**	**SLC**	**TGW**	**TCK**	**DSI**	**CMP**
[17]	3*	5*	1	1*	no	**yes**
[18]	3*	5*	1	2*	no	no
[19]	1	1*	1	1*	no	no
[20]	1	1	1	1*	**yes**	no
[21]	1	4*	1	-	no	**yes**
[22]	3*	5*	2	1	no	**yes**

TABLE I

Works on modeling, simulation and control of sailboats

Table I summarizes the most related works to ours tackling the control aspect. In relation to the control system responsible for generating rudder commands to achieve the control objective (RDC), the most used techniques are (1) PID [17][18][22], (2) non-linear, (3) fuzzy sets [19][20][21], and (4) using machine learning approaches.

In relation to sail control (SLC), which is the system that generates desirable references for controlling the angle of the sail, the techniques described in the table are (1) polar diagram [19][20], (2) linear, (3) fixed goal, (4) extreme search [21], (5) fuzzy sets [17][18][22], (6) Voronoy dagram and (7) mechanical.

In relation to the trajectory generation system (TGW), the techniques listed in the table are (1) using line of sight to destination (successive guidance) [17][18][19] [20][21], (2) following a straight segment [22], (3) using potential fields, and (4) using curve tracking.

The most used strategies to advance when the waypoint is in the dead zone doing the tacking (TCK as shown in Table I), can be classified as (1) reactive [17][19][20][22] and (2) deliberative [18].

A. State of the Art Comparison

The cells marked with an asterisk in Table I indicate our research focus, following some criteria. Dissemination of implementation (DSI) criterion indicates whether the authors provide an implementations that allows for reproducibility. Comparison (CMP) criterion indicates whether the work is compared to others to validate the contribution. Notice that the strategy used for trajectory following based on waypoints is denoted by the TGW criterium.

From column RDC, it can be seen that the most used techniques for sail control is the fuzzy sets approach, with 3 works, and the PID technique, also with 3 works. The main difference between works that use the PID technique is on how the controller parameters are calibrated and also whether the controller parameters are fixed or variable during the mission. On the other hand, there is a greater variety among works that use non-linear rudder control techniques, with each work having a different control law.

The *non-linear* works represent a variety of control techniques, with different levels of complexity and number of parameters for calibration. Thus, a fair comparison with these techniques is difficult, as each of them is different and takes considerable time to understand enough to implement and/or fine-tune the technique. Most comparisons are made by works that use non-linear techniques proposing their performance to linear techniques, such as PID, as it is easier to implement and adjust.

From the SLC column notice that there is a wide variety of strategies to control the sail. The most common are those that involve the use of the sailboat's polar diagram, that is seeking to maximize the sailboat's speed. A polar diagram is usually estimated using wind tunnel experiments or using a velocity prediction program (VPP). Given the difficulty, there has recently been a greater effort to try to control the sail using local search techniques such as extreme search. The other common control strategy is linear interpolation according to apparent wind, thanks to its simplicity and easy of implementation.

The TGW column clears that the most used approach to following waypoints is the line-of-sight strategy, where the sailboat always try to point its bow towards the destination. The second most common strategy is to go straight. The TCK column shows that the most common technique is reactive adhesion, being the most common those that follow the direction. Another common strategy is to follow the navigable direction closer to the wind as possible and to change direction when reaching the limits of some side corridor determined around the straight line connecting the two waypoints.

The column DSI shows three works that make it clear the dissemination of the implementation of the techniques. Among these, only two still have active links to access the implementations. This tendency of no reproducibility implies that interested researchers must implement the techniques already presented in the literature, in addition to implementing their own solutions. This is costly and ends up making comparison a difficult and unmotivated task.

IV. Architectural Design

Figure 2 shows an overview of our proposed hardware architecture, applied to the F-Boat, including a components diagram with communication, computers, sensors, rudder, sail, motors, power, cameras, and energy exchange between the components. Here we introduce the sensors and the vision processing, besides the electronics and basic propeller systems.

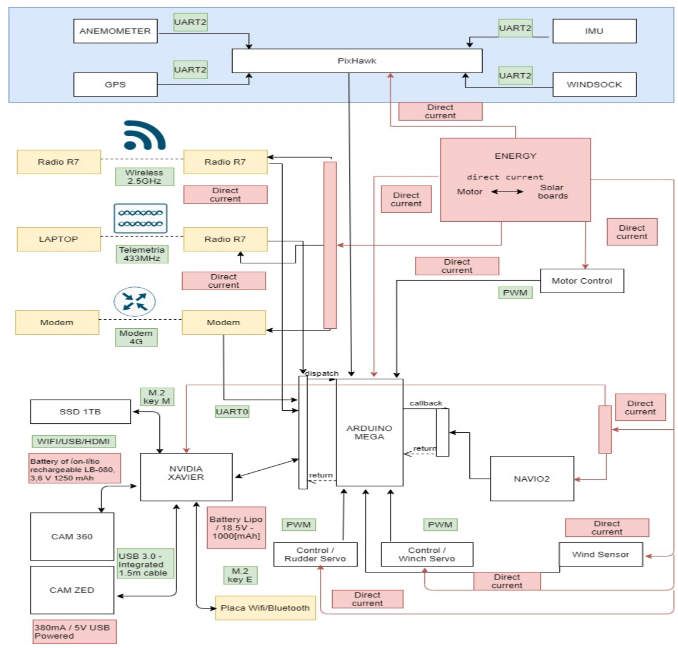

Fig. 2. Data and energy communications

A. Sensors and Visual Processing

F-Boat has an embedded SBC (nVidia Xavier) that provides enough processing power for allowing vision tasks. This boosts the stages of perception (object detection, classification, tracking, between others), localization (providing a reference path to the robot), planning (to define the new route), and control (to send orders to actuators). Basic sensory data necessary for short-term navigation include wind direction, GPS position, compass, and rudder and sail angles. Besides, other sensors as a 360 degrees panoramic camera and a Zed 3D stereo camera are also installed. These can be used in long-term missions. Actually, the literature has vast material on object detection and colision avoidance. Methods based on deep networks (CNN) combined with image segmentation have been successfully applied in recognition of images and videos [23]. A CNN aims to classify and detect objects where a bounding box that identifies a specific class of object is found. Semantic segmentation uses a concept for identifying each pixel of the image and a mask is applied to each one of them [24].

Examples of the semantic segmentation technique applied in marine images can be found using the U-Net [25] and the SegNet [26]. These models are trained using the Mastr1325 Dataset [27] and despite the relatively low training (829 training images and 100 epochs) they are able to obtain an accuracy greater than 96%. Our proposal is to segment the images obtained by the 360^o camera in real time and creation of a 2D map of possible obstacles within the sailboat's vision field. From this we can estimate its route through reinforcement learning in order to devise the best navigation strategy [1].

B. Embarked Electronics and Propulsion System

The basic electronic components used in F-Boat can be seen in Figure 2. The main subsystems are the radio link (receiver and transmitter) for eventual remote control, the telemetry system for sending data from payload applications and from the boat itself, and the low-level control system. The hardwware used in these components are: Pixhawk 2.4.6; Arduino Mega; Driver vnh5019 for actuators; Rudder linear actuator; Helm pot; Mini winch to activate the sail; Candle Pot; Nautical battery; wind sensors; GPS-IMU; 433 MHz telemetry; and a R7 radio (transmitter and receiver).

Our sailboat has two batteries that provide energy to the electrical motors and the various subsystems. We use photovoltaic panels in order to recharge the batteries. Besides, this project intends to use other renewable sources as water current and wind. The panels can be straight connected to the batteries serving only to charge them or the engines and batteries can be connected through a switch, in this case for activation of the electrical propeller of the vessel for an emergency situation. The photovoltaic panels should be optimized to always withdraw the maximum possible power, which depends on several factors including the radiation and temperature. Hence, the maximum power point tracking (MPPT) method is used here to guarantee that the panel operate at its full point of power at every instant.

As said, the sailboat has an electric propeller (motor) for conventional boats (PHA-DIGSW54 54Lbs), for salt water with fixed axis. This propeller will be used in emergency situations or complex manouvers and can be activated or deactivated in two ways. First one is by a human pilot using a ground station, through a PWM signal generated by an Arduino board, which is sent to its motor driver. And the second operation mode is autonomously, by proper commands on the control techniques running onboard the vessel.

V. Implementation of Control Strategies

In this session we present the block diagram that translates the system model as well as the implemented controllers. We start with the complete mathematical model that represents the boat's behavior, which is given by [28][29]:

$$\begin{aligned}(M_{RB}+M_A)\dot{v}+(C_{RB}(v)+C_A(v))v+(D_k(v)+D_h(v))v\\ +g(n)=\tau_s+\tau_r \Leftrightarrow (M_{RB}+M_A)\dot{v}\\ =\tau_s+\tau_r-(C_{RB}(v)+C_A(v))v-(D_k(v)-D_h(v))v-g(n)\end{aligned} \tag{1}$$

With regard to the rudder, we devise a PID controller where the input is the orientation error that is defined as the difference between desired and actual orientation. The three (PID) components are also used to calculate the rudder angle (output). Regarding the values for each component, these were obtained using an empirical analysis of the behavior of the sailboat with help of the software Matlab Tune, taking a snapshot every 10 seconds. Since the model is non-linear, it is necessary to indicate the linearization time to the Matlab in order to obtain the values (Figure 3). From the simulation execution, we achieved the gain values: K_p = 0.68 K_i = 0.125 K_d = -0.130, for N = 25. For the sail control we conducted a study of the behavior of the sailboat movements for a given orientation, in order to build later a controller based on Fuzzy Logic capable of representing and controlling these movements.

We note that the choice of the inference method focused on the Takagi-Sugeno is due to the fact that the outputs are based on functions, which are returning different weights for the input variables of the system. However, they are much more complex than the Mandani method [30][31]. It is stated that this controller has two inputs: the error of the orientation and its derivative. The output is the sail angle, which indicates how tight or stretched the sail rope should be. The type of membership function used for the input is the Bell type, which is given by:

$$bell(x;a,b,c)=\frac{1}{a+\left|\frac{x-c}{a}\right|^{2b}} \tag{2}$$

The rudder and sail control have been set to a desired orientation of $\pi+\pi/4$ rad.

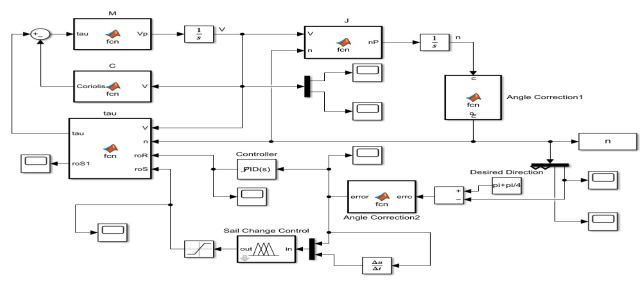

Fig. 3. Control structure with Fuzzy

VI. Experiments and Results

We test different panoramas for possible trajectories of the sailboat, which are analyzed here, both with the controller using PID for rudder and Fuzzy for sailing. An application example showing the control of the sail by a mathematical equation with the purpose of sailing using a zig-zag and/or a jibe is also presented later. For the purpose of results and due to lack of space in the article, we supressed some information such as how we use polar coordinates, hysteresis window, and also the details about how the maneuvers are done. Hence, we start performing calculations of the values of the hysteresis window to obtain the diagram and the results of the sail and rudder controls, after which the various waypoints are calculated so that the sailboat performs necessary maneuvers to reach a certain destination. After some research to understand the limitations of a sailboat's movements, high-level controls are carried out to determine the sail and rudder angle, depending on the control status: PID for rudder and Fuzzy for sail, and a mathematical formula for jibe / zig-zag using polar coordinates.

When entering in the jibe mode, the hysteresis values are calculated so that the waypoints are estimated. Since through the fuzzy approach the sail angle is corrected, it will have two inputs (the error of the orientation and its derivative) and an output which will be the sail angle, which in practical terms is related to how the tight or stretched the sail rope should be. The Takashi-Sugeno method for sailing turned out to be a misfortune as it only considers the error of orientation and its derivative, not paying attention to the wind values, which is the most important aspect of a sailing boat. For this reason we chose to control the sail using the jibe mode of navigation.

We can notice that controlling the sail using the zigzag for movement would be more interesting for a real sailboat. The changes for the rudder and sail angles during these maneuvers are displayed in Figures 4 and 5.

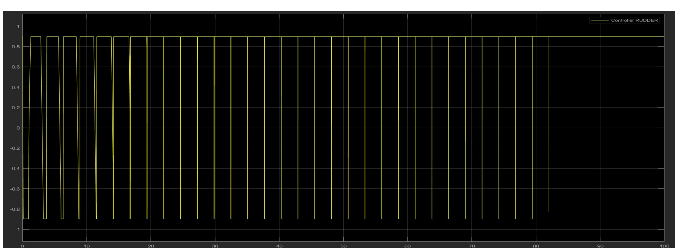

Fig. 4. Graphic representation of the rudder angle over time.

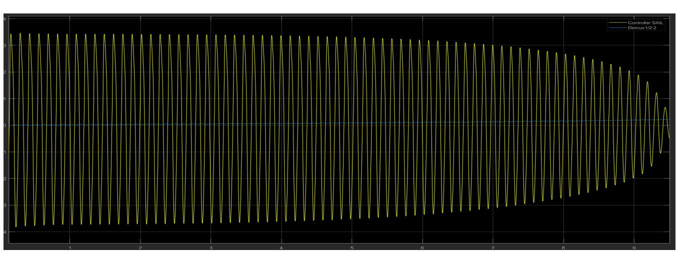

Fig. 5. Graphic representation of the sail angle over time.

In order to test the effectiveness of the devised controllers, on the top our our architectural design, we planned a simulated experiment in which the control system has to perform at least one jibe for navigation. The resulting diagram for this task can be seen in Figure 6. Basically, there are two zones in which the sailboat should not navigate, one is against wind and another is downwind. In practice, the boat can go completely downwind, but it is not as effective as the zigzags, which in technical terms is called a tacking downwind. To perform these maneuvers, a high-level command is needed to analyze whether or not it is possible for the boat to perform a particular maneuver and how to perform it. Notice that a boat with propellers can move in any orientation and weather conditions, without a significant impact on its movement. On the opposite, the wind direction strongly affects the course on a sailboat, which makes its control more complex. Fortunately, for a given wind speed and direction, it is possible to deduce the maximum angle that the sail must have to obtain the maximum speed using the polar velocity prediction (VPP) diagrams [32][29]. These diagrams are obtained by combining several factors as wind speed and direction, angle of the sailboat with the actual wind, speed of the sailboat, angle of attack of the sail with the apparent wind, friction factor, drag, propulsion, lift coefficient and drag, among others. Hence, it is possible to get the output values the maximum sail angle and maximum speed. After this thorough analysis, the sailboat is placed in a controlled environment, with low current forces and subject to weak wind gusts (of the order of 0-10 m / s). The average values of the maximum sail angles from 1 to 10 m/s and the respective parameterization of the curve was performed, considering the following equation:

$$\delta_{smax} = 0.0986\alpha_{tw}^2 + 0.55\alpha_{tw} - 0.1362 \qquad (3)$$

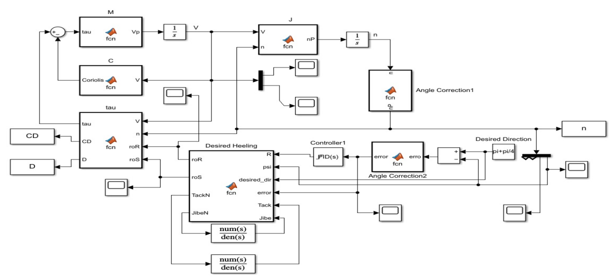

Fig. 6. Control structure with jibe

Due to the boat's dynamic and kinematic restrictions, it cannot navigate directly to all desired directions. It is necessary to perform maneuvers depending on the wind angle and the desired orientation. We constrained the sailboat heading to form an angle with the wind of [-30^o, 30^o] in order to avoid loosing speed. As mentioned above, in this situation the boat can not go forward, eventually stoping, having to perform a zigzag around it [-60^o, 60^o] through jibe manouvers. In Figure 4 and Figure 5 we can check the results of the vessel's trajectory, performing the various waypoint calculations so that the sailboat performs the necessary maneuvers to reach a certain destination.

VII. Conclusion

In this paper we propose the basic architecture of the autonomous sailboat F-Boat. To this end, we carried out a review of several autonomous sailboats proposals, including their architectural design with components and control systems. These studies have served as the basis for the development of a completely new robotic sailboat project, with autonomous navigability. We made an analysis of how the low-level models of the most commonly used controllers work and how they can provide feedback for further autonomous applications for the system. After this analysis, we decided to use PID and Fuzzy Takashi-Sugeno controllers for the rudder and sail, respectively. We include another control model for the sail using a mathematical formula based on polar coordinates. On top of this architecture, we created a very simple strategy for performing a jibe, which demonstrates that our approach can be used to realize simple manouvers.

It is still necessary to adjust some parameters, considering only the orientation error and its derivative, taking into account the most important aspect of a sailboat, which is the wind. We still have to conduce more research in order to make the controllers more robust and understand the limitations of a sailboat's movements. A More robut control strategy should determine the sail angle and rudder movement depending ot the control state. We also have to include the computer vision strategies to the controller, in order to develop more complex operations.

REFERENCES

[1] A. G. d. Silva Junior, D. H. d. Santos, A. P. F. d. Negreiros, J. M. V. B. d. S. Silva, and L. M. G. Gonçalves, "High-level path planning for an autonomous sailboat robot using q-learning," *Sensors*, vol. 20, no. 6, 2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/6/1550

[2] D. Huang and S. K. Nguang, *Takagi–Sugeno Fuzzy Control System*. London: Springer London, 2009, pp. 87–91. [Online]. Available: https://doi.org/10.1007/978-1-84882-678-6_8

[3] H. Ying, "The takagi-sugeno fuzzy controllers using the simplified linear control rules are nonlinear variable gain controllers," *Automatica*, vol. 34, no. 2, pp. 157–167, 1998. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0005109897001738

[4] G. J. KLIR and B. YUAN, *Fuzzy Sets and Fuzzy Logic: Theory and Applications*. New Jersey: Prentice Hall, 1995, p. 574.

[5] F. Le Bars and L. Jaulin, "The world robotic sailing championship, a competition to stimulate the development of autonomous sailboats," in *OCEANS 2015 - Genova*, 2015, pp. 1–5.

[6] C. Liu, S. Yang, T. Duan, J. Huang, and Z. Wang, "Motion control of an one-meter class autonomous sailboat," in *2018 IEEE 8th International Conference on Underwater System Technology: Theory and Applications (USYS)*. IEEE, 2018, pp. 1–6.

[7] A. G. Júnior, A. P. Araújo, M. V. Silva, R. V. Aroca, and L. M. Gonçalves, "N-boat: An autonomous robotic sailboat," in *2013 Latin American Robotics Symposium and Competition*, 2013, pp. 24–29.

[8] J. a. Esteves, L. i. Gomes, and A. Costa, "Collision avoidance system for an autonomous sailboat," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 3539–3544.

[9] H. Abrougui, S. Nejim, and H. Dallagi, "Modeling and autopilot design for an autonomous catamaran sailboat based on feedback linearization," in *2019 International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, 2019, pp. 130–135.

[10] D. H. dos Santos and L. M. G. Gonçalves, "Performance evaluation of propulsion control techniques for autonomous sailboat," in *2020 Latin American Robotics Symposium (LARS), 2020 Brazilian Symposium on Robotics (SBR) and 2020 Workshop on Robotics in Education (WRE)*, 2020, pp. 1–6.

[11] I. Astrov and A. Udal, "Neural predictive tracking control of catamaran model sailboat for situation awareness applications," in *2020 IEEE 24th International Conference on Intelligent Engineering Systems (INES)*, 2020, pp. 153–158.

[12] C. Viel, U. Vautier, J. Wan, and L. Jaulin, "Platooning control for sailboats using a tack strategy," *International Journal of Control, Automation and Systems*, vol. 17, no. 9, pp. 2310–2320, 2019.

[13] E. Chacon-Mosquera, "Autonomous sailboat prototype sensors and electronics implementation with machine learning for navigation," *Master's Thesis Barcelona: Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona*, 2021.

[14] S. Yang, C. Liu, Y. Liu, J. An, and X. Xiang, "Generic and flexible unmanned sailboat for innovative education and world robotic sailing championship," *Frontiers in Robotics and AI*, 2021.

[15] F. Plumet, C. Pêtrès, M.-A. Romero-Ramirez, B. Gas, and S.-H. Ieng, "Toward an autonomous sailing boat," *IEEE Journal of Oceanic Engineering*, vol. 40, no. 2, pp. 397–407, 2015.

[16] D. H. Santos, A. G. S. Junior, A. Negreiros, J. ao V. B. Souza e Silva, J. E. Alvarez-Jácobo, A. Araújo, R. V. Aroca, and L. M. G. Gonçalves, "Design and implementation of a control system for a sailboat robot," *Robotics - MDPI*, no. 24, 2016. [Online]. Available: https://www.mdpi.com/1424-8220/20/6/1550

[17] R. Stelzer, "Autonomous sailboat navigation: Novel algorithms and experimental demonstration," Ph.D. dissertation, Centre for Computational Intelligence, De Montfort University, Leicester, UK, December 2012.

[18] F. M. G. Martins, "eVentos 2 – Autonomous sailboat control," Master's thesis, Universidade nova de Lisboa, Portugal, 2013.

[19] M. Kang, J. Xu, J. Xu, and M. Du, *Autonomous Sailboat Local Route Planning*. Cham: Springer International Publishing, 2017, pp. 33–43.

[20] S. Lemaire, Y. Cao, T. Kluyver, D. Hausner, C. Vasilovici, Z.-y. Lee, U. J. Varbaro, and S. M. Schillai, "Adaptive probabilistic tack manoeuvre decision for sailing vessels," *arXiv preprint*, 2019.

[21] Z. Shen, S. Wang, H. Yu, and C. Guo, "Online speed optimization with feedforward of unmanned sailboat via extremum seeking without steady-state oscillation," *Ocean Engineering*, vol. 189, p. 106393, 2019.

[22] Y. Deng, X. Zhang, Q. Zhang, and Y. Hu, "Event-triggered composite adaptive fuzzy control of sailboat with heeling constraint," *Ocean Engineering*, vol. 211, p. 107627, 2020.

[23] A. Geron, *Hands-on machine learning with Scikit-Learn and TensorFlow : concepts, tools, and techniques to build intelligent systems*. Sebastopol, CA: O'Reilly Media, 2017.

[24] F. Sultana, A. Sufian, and P. Dutta, "Evolution of image segmentation using deep convolutional neural network: A survey," *Knowledge-Based Systems*, vol. 201-202, p. 106062, Aug 2020. [Online]. Available: http://dx.doi.org/10.1016/j.knosys.2020.106062

[25] O. Ronneberger, P. Fischer, and T. Brox, "U-net: Convolutional networks for biomedical image segmentation," in *International Conference on Medical image computing and computer-assisted intervention*. Springer, 2015, pp. 234–241.

[26] V. Badrinarayanan, A. Kendall, and R. Cipolla, "Segnet: A deep convolutional encoder-decoder architecture for image segmentation," *IEEE transactions on pattern analysis and machine intelligence*, vol. 39, no. 12, pp. 2481–2495, 2017.

[27] B. Bovcon, J. Muhovič, J. Perš, and M. Kristan, "The mastr1325 dataset for training deep usv obstacle detection models," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2019, pp. 3431–3438.

[28] G. P. C. S. R. Erckens, H.; Busser, "Avalon—navigation strategy and trajectory following controller for an autonomous sailing vessel." in *IEEE Rob. Autom. Mag.*, vol. 17, no. 45–54, 2010, pp. 153–158.

[29] C. Alves, "Sailbot – autonomous marine robot of eolic propulsion," Master's thesis, Instituto Superior Técnico, 2010.

[30] J. Abril, J. Salom, and O. Calvo, "Fuzzy control of a sailboat," *International Journal of Approximate Reasoning*, vol. 16, no. 3, pp. 359–375, 1997. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0888613X96001326

[31] R. Stelzer, T. Pröll, and R. John, "Fuzzy logic control system for autonomous sailboats," 08 2007, pp. 1 – 6.

[32] L. Gilbert, "Technical theoretical aspects of rc yacht racing," [Online; accessed 15-JULY-2021]. [Online]. Available: http://www.onemetre.net/design/VPP/PoorVPP.htm