N-BOAT: An Autonomous Robotic Sailboat

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***Abstract* - This article presents the ongoing development of an autonomous sailboat control architecture and a prototype sailboat constructed for experimental validation of the proposed architecture. The main goal of the project is to allow long endurance autonomous missions for ocean monitoring. In order to accomplish such objective, the system relies on wind forces propulsion instead of motors. We present the mathematical model using PID and Fuzzy controllers to control the sail and the rudder. Furthermore, we also present a study of the hardware architecture that enables better control performance of the system.**

Keywords - Sailboat; robotic; autonomous.

I. INTRODUCTION

Long endurance autonomous monitoring of ocean waters is an important and difficult task due to several constraints imposed by the harsh environment of the seas. One of the biggest challenges is how to provide enough energy for an autonomous water vehicle for missions with endurance of months or years. The use of wind propelled boats is a good alternative to tasks that require long duration missions since the propulsion energy requirements are smaller when compared to boats propelled by motors. These boats are called windvane servomechanism (Belcher, 1982).

While traditional motorboats can be easily controlled due to their simplicity, there are considerable differences to develop the control laws of an autonomous sailboat. In order to control the displacement of a robotic sailboat from a given point to another point within a navigable space, several issues and conditions must be addressed, such as wind direction, wind speed, boat heading sea currents.

A control loop for such kind of boat uses the above mentioned information to position the sail and the rudder with respect to the wind so that the boat can head and displace to the desired position. In such system, sensors are used to obtain the wind speed and direction, which are provided to the control loop.

In the next sections, this article presents the overall system architecture, its electronics and the control law modeling and implementation and finally preliminary results that have been simulated using Matlab

II. RELATED WORKS

There are several autonomous sailboats that already presented interesting performance and serve as a reference for N-Boat design. Among them, we highlight Avalon (Erckens, 2010), which was developed to run on the Microtransat challenge, which requires a tough design to endure the harsh oceanic conditions. Avalon was designed to be fast and precise, and relies on a robust control software based on fuzzy logic both for the rudder and sail control.

Another project, which is considered the first successful robotic sailboat is the Roboat (Stelzer, 2012). It also participated on the Microtransat, and was also developed to monitor a certain area of interest and to

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conduct marine research. It was created by INNOC researchers, Roboat is an enhancement of a simpler boat, the Roboat 1 (Stelzer, 2012).

Finally, another related project is the FASt (Alves, 2008), a robotic sailboat developed by the Porto Engineering Faculty. It presents similar characteristics to the other mentioned boats, with the difference that it uses reconfigurable computing (FPGAs) in its embedded digital control system.

III. System Architecture

The system architecture is distributed within two processing units to obtain a reliable, flexible and powerful system. In the proposed system, low level control decisions executed in real time are responsibility of a dedicated microcontroller - an AtMega328 which is built-in on an Ardupilot module. The Ardupilot module was originally designed to be used in Unmanned Aerial Vehicles (UAVs), but we decided to use it as the low level controller of N-Boat. Moreover, Ardupilot includes several sensors, such as inertial and barometric that are useful for a sailboat control system.

The Ardupilot performs communica-tion with various sensors and actuators on the system, with a robust control law that would works in a stable manner. This module also interconnects sensors and the high level pro-cessing unit, a Raspberry Pi, which is responsible for high level navigation decisions, planning and external communication. Figure 1 shows an overview of the proposed architecture.

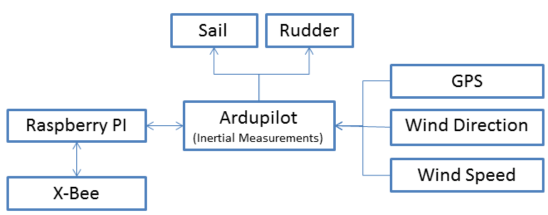

Figure 1. Electronic Architecture

A. Processing Module

The processing module is the central part of the robot. It is distributed in an AtMega microcontroller (Ardupilot), responsible for low level control decision and a high level controller based on an ARM processor on a Raspberry Pi board.

RaspberryPi is a complete computer running Linux operation system, which gives great flexibility for the system, such as the possibility of easily adding cameras, Wifi, and several other different devices. Although the system can run on speeds up to 700MHz or more, the ARM processor is adjusted to decrease its speed to save energy when no processing is needed.

This module is connected with the Ardupilot via a RS-232 serial port. This computer also is connected to a base station using a Xbee radio link of up to 1 mile.

B. Sensing Module

The sensing and actuation module, as the name suggests, consists of all sensors and actuators on the sailboat. Next we briefly describe each sensor used.

GPS: The GPS used was an EM-406 SiRF III module, which provides date, time, latitude, longitude, speed, altitude and heading angle. It can be seen on Figure 2.

Figure 2. GPS.
http://multilogica-shop.com/receptor-gps-de-20-canais-em-406a-sirf-iii

Wind Sensors: A shell type anemometer is used to measure wind speed. This sensor works from the pressure of the fluid reaches its surface, causing it to turn. The system counts the number of turns, and therefore can compute the rotation speed. The wind direction is obtained through a windsock, or weather vane. Basically, the direction is given from the voltage value provided by the sensor, which has an internal potentiometer. Pictures 3 and 4 show such sensors.

Figure 3. Anemometer type Shell
Image Source: (SparkFun Electronics, 2013)

Figure 4. Weathervane arrow type
Image Source: (SparkFun Electronics, 2013)

Compass: The system also includes a 3 axis digital compass shown on Figure 5.

Figure 5. Compass
Image Source: (SparkFun Eletronics, 2013)

IV. Mathematical Modeling

A mathematical model of the boat is proposed in order to determine the varia-bles, and consequently the equations to be used on the control system. Such modeling is divided on three main modules: coordinate system, kinematics and dynamics.

A. Coordinate System

A system with six independent coordinates is used to model and study the boat's kinematics positioning and guidance. Such robotic system uses location based on reference points (Erckens et al, 2010).

When controlling an underwater vehicle it is important to obtain its position and velocity with respect to an inertial reference frame fixed to the Earth, but as the dynamic of the vehicle is modeled in reference to a moving frame, trans-formations are needed, which depends on isolated coordinates to another reference according to SNAME (Society of Naval Architects and Marine Engineers) (SNAME, 1950) as shown on Table 2.

Thus, a system was designed using two Cartesian references: the Earth inertial frame {X, Y, Z}, where the source of reference is located in the plane tangent to the area of interest, and a body referential {Xb, Yb , Xb,}, which undergoes translational and rotational movements of the body depending on the source and generally coincides with the center of mass of the vehicle. Such values are summarized on Table 1.

Table I. Nomenclature of rotations.

N1	N2	V1	V2	$\tau 1$	$\tau 2$
X,Y,Z	ϕ,θ,ψ	U,V, W	P,Q, R	X,Y,Z	K,M, N

Table II. SNAME notation, used in marine vehicles.

Moveme nt / Rotation	Position / Angle Euler	Linear Speed / Angular	Force / Moment
Moveme nt in X (Onda)	X	U	X
Moveme nt in Y (swing)	Y	V	Y
Moveme nt in Z (Elevatio n)	Z	W	Z
Rotation in X (Rolar)	Φ	P	K
Rotation in Y (throw)	Θ	Q	M
Rotation in Z (yaw)	Ψ	R	N

N1 and N2 are, respectively, the positions and orientations of the reference inertial frame fixed to the body and relative to the earth; V1 and V2 are the linear and angular velocities in the reference frame fixed to the body; $\tau 1$ and $\tau 2$ are the forces and moments exerted on the body.

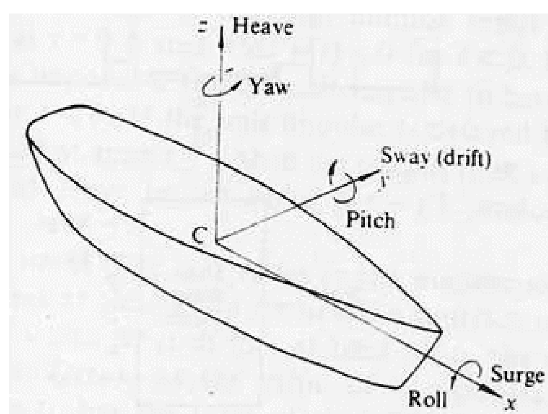

Figure 6. Coordinate System
http://www.oceanica.ufrj.br/deno/prod_academic/relatorios/2009/Maues%20e%20Henrique/relat2/Relatorio_Htm.htm

B. *Kinematics*

Given the orientation of the object in question in relation to the frame of the earth, it is possible to get any of the guidelines by means of three elementary rotations:

$$R_{X,\phi} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi - & \sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix}$$

$$R_{X,\theta} = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}$$

$$R_{X,\psi} = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

C. *Dynamics*

The dynamics has been divided into:

- **Hydrodynamics**
- **Moment of Inertia**
- **Viscous Damping**
- **Lift**
- **Effort Sail**
- **Center of mass**

After calculating all these parts of the dynamic force and the moment, the following expression is obtained:

$$(M_{RB}+M_{A\text{(Hydrodynamics)}})\nu + (C_{RB}\text{ (Dynamics (center of mass))}(\nu)+C_{A\text{(Hydrodynamics (Coriolis e centrípeto))}}(\nu))\nu + (D_k\text{ (Lift (moments generated by the keel))}(\nu))\nu + D_h\text{ (Lift (forces acting on the hull))}(\nu))\nu + g(\eta) = \tau_s + \tau_r \Leftrightarrow (M_{RB}+M_A\text{ (Hydrodynamics)})\nu = \tau_s + \tau_r - (C_{RB}\text{ (Dynamics (center of mass))}(\nu)+C_A\text{ (Hydrodynamics (Coriolis e centrípeto))}(\nu))\nu - (D_K\text{ (Lift (moments generated by the keel))}(\nu) - D_h\text{ (Lift (forces acting on the hull))}(\nu))\nu - g(\eta)$$

D. *Controller and Results*

From the obtained mathematical model, and analyzing the intrinsic limitations for sailboats, two controllers were developed: A PID controller which controls the movements of the rudder to correct the angles and the other was Fuzzy control which controls the movements of the sail. Tests were made with controllers in open loop and closed loop.

1) *Open Loop*

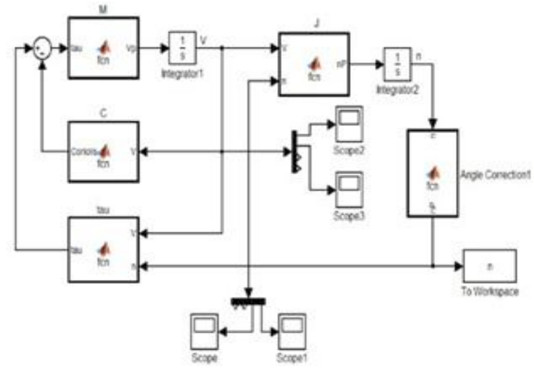

Figure 7. Open loop controller block diagram.

One of the tests performed in open loop starts with the body at rest, with orientation of $-\pi$ rad, and with $\upsilon tw = [-5,0]T$. Furthermore, we adjusted the value of the rudder angle 0 rad, and, varying the angle of the sail, it was possible to analyze the behavior of the path made by boat. Figure 8 shows that path. Finally, it was deduced empirically that the value of the rudder angle would be for an angle sail $\pi/6$ rad, in order to maintain this orientation of $-\pi$ rad.

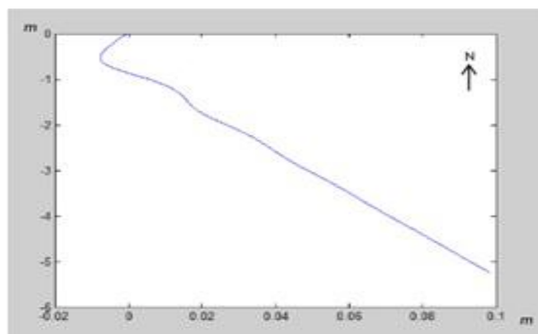

Figure 8. Simulated boat displacement (x,y).

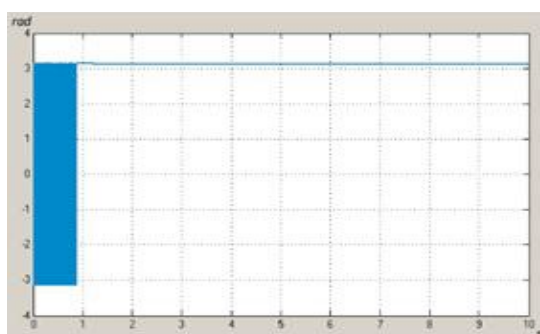

Figure 9. Representation of the angle yaw.

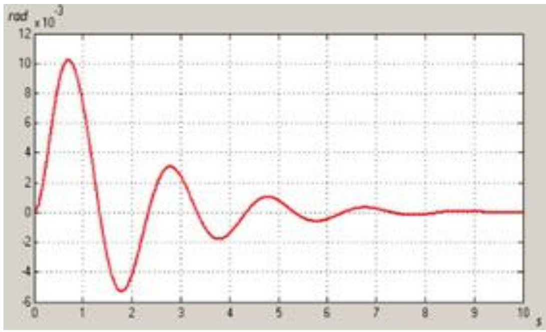

Figure 10. Representation of the angle roll.

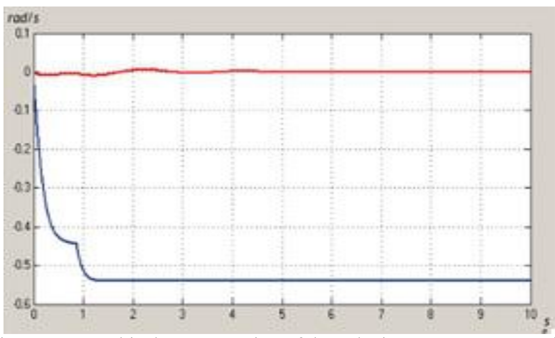

Figure 11. Graphical representation of the velocity components u and v (blue and red line respectively).

2) Closed Loop

As regards the control of the rudder is designed as a PID controller is the error input of orientation (the orientation desired orientation less current).

We also used the three components to calculate the rudder angle (output).The values of the gains were calculated from an empirical analysis of the behavior of the boat, with Tune from Matlab and with a snapshot of 10 seconds (due to non-linearity of the model, it is necessary to indicate the length of the linearization Matlab). The values are shown below:

K_p	K_i	K_d
0.68	0.125	-0.130

Aiming to control the sail, initially studied the behavior of the robot movements to a particular orientation, later to build a controller based on fuzzy logic for representing and controlling these movements.

It is noted that the choice of inference method focused on the Takagi-Sugeno due to the fact that the outputs are based on functions which are given different weights for the input variables of the system. It is stated that this controller has two inputs (the orientation error and its derivative) and an output will be the angle of the sail, that is, how tight or taut rope must be sail.

The set of rules implemented in the controller is represented below:

1.If (teta is A1) and (velTeta is B1) then (roS is roS1)

2.If(teta is A1) and (velTeta is B2) then (roS is roS2)

3.If (teta is A2) and (velTeta is B1) then (roS is roS3)

4.If (teta is A2) and (velTeta is B2) then (roS is roS4)

The controller output is comprised of four different equations that makes defuzzification. These equations are of the type A ψ + BΔ ψ + C, where A is a coefficient that will multiply the error, and B will multiply the error derivative and C is a constant. Thus, the output will take the value of the result of the previous equation. Then shows the four equations output from our system:

roS1 = 0.01602 ψ + 0.01646 ψ + 1.09
roS2 = 0.0353 ψ + 0.0219 ψ + 0.19
roS3 = 0.0353 ψ + 0.0219 ψ - 0.19
roS4 = 0.01602 ψ + 0.01646 ψ - 1.09

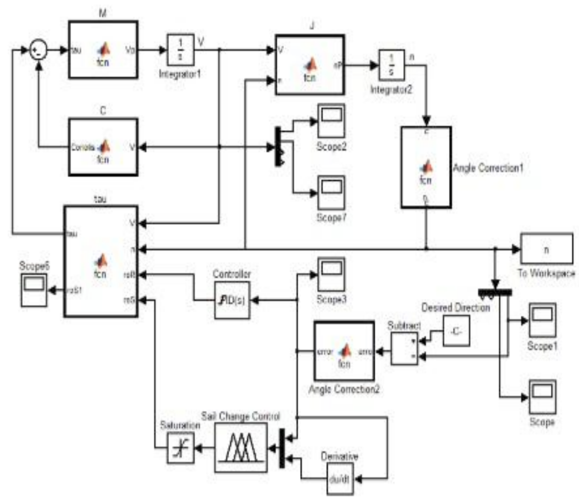

Figure 12. Block diagram in Matlab model overall closed loop

V. RESULTS

In an experimental model, simulated in MatLab, the control law matches the initial expectations. As seen in the control figures 8-11, the desired objectives were achieved. Each graphics presented shows clearly both the route that the boat should do according to the entries, as the angle for each axis in the coordinate system. For an experimental setup, sensor data can be obtained and the proposed system used to send commands to the sail motor and rudder, according to the end position desired.

VI. Conclusion

This work presents an architecture and a basic control law model for autonomous sailboats. The presented results were validated with simulations and show that the control laws match the expected performance for displacement of the boat in a particular region.

As the simulations validated the pro-posed model, we are already working on an experimental setup to test the control algorithm on the real sailboat, which is already assembled.

Acknowledgements

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