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Project of Fault Tolerant Control using a Takagi-Sugeno Fuzzy logic applied in autonomous underwater vehicles.

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Abstract: The main problem suffered by Autonomous Underwater Vehicles (AUV) used for research and inspection of marine environments is the fault of thrusters during the trajectory, which can compromise the mission. So, in this paper was proposed a Fault Tolerant Control (FTC) using the Levi-Civita connection and a Takagi-Sugeno Fuzzy logic. First, was described the six degree-of-freedom (DOF) nonlinear equations of dynamics and kinematics of the AUV which has four horizontal thrusters and two vertical thrusters, and then we propose a Fault Tolerant Control of the AUV using a Takagi-Sugeno Fuzzy Logic. Using the Fuzzy logic, it was possible to distribute the forces and moments of the faulty thruster in the healthy ones using the same plane of action. The control performance was validated via numerical simulations of the AUV occurring fault of two horizontal thrusters in specific time during the simulation. Even with disturbance caused by variable current and fault of two AUV's thrusters, with this method it was capable of keeping good track of the AUV, enhancing the robustness, assuring asymptotic stability, and the success of the mission.

Keywords. *AUV, Fuzzy Logic, Fault Tolerant Control.*

Introduction. With the advance of robotics and mechatronics it has been an increase in the use of robots for inspection of underwater environments. It is also used in hydroelectric power plant inspection. There are many types of underwater vehicles available for these kind of task, as remotely operated vehicles (ROV) and autonomous underwater vehicles AUV).

This work has the objective to study the AUV’s which doesn't need an operator to make decisions during the mission, because it doesn't have cables to communicate with the surface. However, AUV's are limited by its battery and by the fault in its thrusters, which tends to happen despite of the cares during the AUV’s project (1,2). Despite the utmost care for the construction of an AUV, it is subject to failures. The maintenance cost can be extremely high, therefore, the study of fault tolerant dynamic systems is essential (2,3). This kind of system auto-adjusts itself in case of a fault detection and continues to fulfill its required function, although there can be some error.

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Usually, the faults occur due to seaweeds or ropes that get stuck in the thruster or to the infiltration of water in electronic components of the vehicle (1).

The outline of this paper is as follows: in materials and methods, a study of the kinematics and dynamics of autonomous underwater vehicles, capable of moving along the three dimensions and using 5 degrees of freedom is presented. Then, its shown the thruster configuration matrix, that relates the distribution of thrusters with the forces and moments applied in the vehicle and how the Fault Tolerant Control (FTC) deals with the partial faults of two horizontal thrusters. Finally, its discussed the simulation and the results of the FTC with the proposed conditions.

Materials and methods.

Modeling of the Vehicle:

When modeling an underwater vehicle, it is convenient to use two reference systems: one is a body-attached frame located in the center of mass of the vehicle, with the coordinates $X_0Y_0Z_0$, the other is an inertial frame located on Earth, with coordinates XYZ as seen in Figure 1, in the body reference frame the axis of $X_0Y_0Z_0$ coincides with the axis of the vehicle (4).

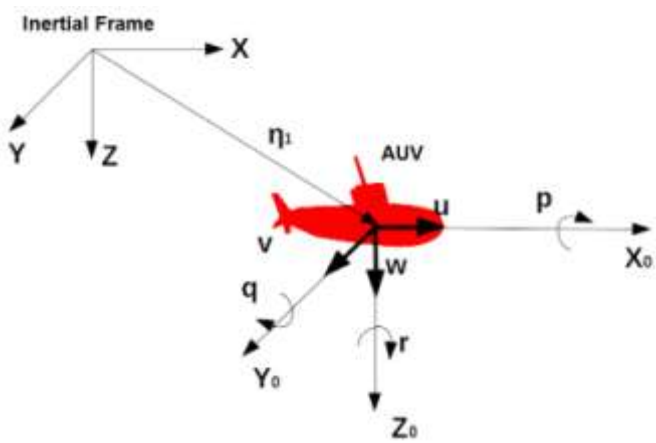

Figure 1. AUV with reference frames

The positions and orientations of the vehicle are expressed in relation to the inertial reference frame while the linear and angular velocities described in relation to the body's coordinates system (4). We use the following vectors to represent the movement of the AUV:

To transform the velocity of the AUV to the inertial reference we use the transform matrix in Eq.1:

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_1) & 0_{3x3} \\ 0_{3x3} & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \quad (1)$$

Where the values of $J_1(\eta_1)$ and $J_2(\eta_2)$ are determined by Eq. 2 and Eq. 3:

$$J_1(\eta_1) = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi c\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\psi s\theta c\phi & -c\psi s\phi + s\psi s\theta c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \quad (2)$$

$$J_2(\eta_2) = \begin{bmatrix} 1 & s\phi t\theta & s\psi c\phi + c\psi c\phi s\theta \\ 0 & c\phi & -c\psi s\phi + s\psi s\theta c\phi \\ 0 & \frac{s\phi}{c\theta} & \frac{s\phi}{s\theta} \end{bmatrix} \quad (3)$$

So, the Kinematic modeling of the AUV is determined by Eq. 4:

$$\dot{\eta} = J(\eta)v \quad (4)$$

The Dynamic modeling is developed in the body's reference using the principles of Newtonian and Lagrangian mechanics (4). It was shown that the dynamics of the AUV is nonlinear with the 6 DOF completely coupled and its considered that the AUV is exposed to forces and moments of the dam's environment, such as waves, wind and currents.

In this work it was used Fossen proposal of Dynamics as can be seen in Eq. 5:

$$M\dot{v_r} + C(v_r)v_r + D(v_r)v_r + g(\eta) = \tau \quad (5)$$

In the equation above, M is the inertial matrix including added mass, C is the matrix of Coriolis and Centripetal, D is the matrix of hydrodynamic damps, G is the vector of gravitational forces and moments, τ is the vector of resultant forces and moments.

However, its necessary to consider that the environment also have its own velocity, so it was used the relative velocity to model the dynamics of the AUV (1) in Eq. 6

$$v_r = v - J(\eta)^{-1}v_c \quad (6)$$

Thus, the dynamics is represented by equation Eq. 7:

$$M\dot{v_r} + C(v_r)v_r + D(v_r)v_r + g(\eta) = \tau \quad (7)$$

The thrusters are responsible for the movement of the AUV, it is active by electric motors or hydraulic motors. in the BA-1 they are disposed as four in the horizontal plane and two in vertical plane According to (3,4) the thrust and torque of each thruster can be expressed by Eq. 8 and Eq. 9:

$$F_{pi} = C_T(\sigma)\frac{\rho}{8}\left[v_w{}^2 + (0{,}7 + \pi n_{pi}D)^2\right]\pi D^2 \quad (8)$$

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$$M_{pi} = C_Q(\sigma)\frac{\rho}{8}\left[v_w{}^2 + (0,7 + \pi n_{pi} D)^2\right]\pi D^3 \tag{9}$$

The coefficients C_T and C_Q are functions of the advance angle and obtained by consulting the thruster's characteristic curve. (3,4). The entering water's velocity on the thruster is considered equal to the AUV's relative velocity parallel to the thruster's action line. However, the contribution of the entering water's velocity is minimal to the motion of the vehicle when compared to the thruster's motion.

According to (3) the electric and mechanic dynamic of a DC motor is described by Eq. 10 and Eq. 11:

$$L_a \frac{di_a}{dt} = -R_a i_a - 2\pi K_m n + V_a \tag{10}$$

$$2\pi J_p \frac{dn}{dt} = T_m - Q \tag{11}$$

Where i_a is the current in the motor's armature, Va is the tension applied to the motor, Ra and La are respectively the armor's resistance and inductance, Km is the motor's electromagnetic constant, Jp is the sum of the inertia's moments of the motor and the thruster. Tm is the motor's torque and Q is the resistant torque. We use 2π to express the motor's angular speed in radians per second. We can despise the $L\frac{di_a}{dt}$ term so Eq. 10 becomes Eq. 14:

$$-R_a i_a - 2\pi K_m n + V_a = 0 \tag{12}$$

Finally, the thrusters' dynamics is described by Eq. 13:

$$V_a = \left[2\pi \dot{n} J_p + 2\pi \frac{K_m^2}{R_a} n + Q_{|n||n|}|n||n|\right]\frac{R_a}{K_m} \tag{13}$$

Thruster Configuration Matrix: Using the information of the vehicle's thruster position it's possible to describe the torques and moments provided to the AUV. Despite the fact of the vehicle has six degrees of freedom we prefer to use only five, according to (1) distance between the center of mass and the center of buoyancy automatically stabilizes the roll motion, so it's unnecessary to spend computational strength with it. Our thruster model is shown as in Figure 3:

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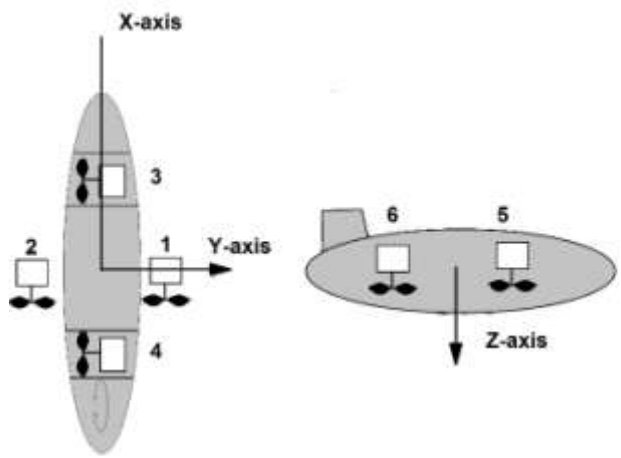

Figure 2: AUV's thruster configuration

Let $\tau \in \Re^5$ be the resultant forces and moments applied to the AUV, $B \in \Re^{5x6}$ be the thruster configuration matrix and $T \in \Re^6$ be the thrusters' forces, we have the relation of τ and T in Eq. 14

$$\tau = Bu \tag{14}$$

However, the B matrix's elements are determined by the geometrical configuration of thrusters, and also, it's possible to express τ and T in their horizontal and vertical components so our Eq. 14 can be rewritten as Eq. 15:

$$\begin{bmatrix} \tau_H \\ \tau_V \end{bmatrix} = \begin{bmatrix} B_H & 0_{3x2} \\ 0_{2x4} & B_V \end{bmatrix} \begin{bmatrix} T_H \\ T_V \end{bmatrix} \tag{15}$$

Where the terms T_H, T_V, τ_H and τ_V are explained in Eq. 16:

$$T_H = (T_1, T_2, T_3, T_4)^T \in \Re^4; T_V = (T_5, T_6)^T \in \Re^2; \tau_H = (F_x, F_y, M_z)^T \in \Re^3; \\ \tau_V = (F_z, M_y)^T \in \Re^2 \tag{16}$$

As said by (4) Fx, Fy, Fz and Mz are the resultant forces and moments acting along the x-, y-, and z-axis of the body frame attached at the AUV. Also, the thrusters' configuration matrixes � and � depends on the configuration of horizontal and vertical thrusters, being described as in Eq. 17:

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$$B_H = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ -a & a & b & -b \end{bmatrix}; B_V = \begin{bmatrix} 1 & 1 \\ -c & c \end{bmatrix} \quad (17)$$

Fault Tolerant Control using Takagi-Sugeno:

For this work, its considered that the system can easily recognize the fault of the propeller, due to the consume of electric current consumed by the motor during the mission. Our AUV doesn't have a complete fault of its thrusters, only a partial development of propulsion, so it's not used any isolation method for this work. As mentioned by (5), the fact of the AUV has four horizontal and two vertical propellers implies that the target AUV intrinsically has a fault-tolerant capability for horizontal motions. It happens because this system has 4 thrusters in the same plane of action (1).

According to (1), it is possible to apply the Levi-Civita connection to perform the distribution of forces and moments of the propellers, in this way, in the event of lack of a propeller, one can isolate the lack of the same or still, if the lack of it is partial, distribute the force of that propeller to one of the other non-missing, needing to calculate the amount of force to be distributed. Assuming a partial lack in the horizontal thruster 1 (T_1) and a failure in the thruster 4 (T_4) would have the following vector of horizontal forces of the vehicle in Eq. 18

$$T_H = [\tilde{T}_1, (\tilde{T}_1 + T_2), (T_3 + \tilde{T}_4), 0] \quad (18)$$

Where, $\tilde{T}_1$ is force of the propeller 1 with partial lack and $\tilde{T}_4$ it is the additional force must be added to the propeller 3 aiming to compensate for the lack in the propeller 4.

Fuzzy Logic: The fuzzy logic extends the classical logic by using intermediate truth values between one and zero applying fuzzy sets and rules (6). So, the fuzzy control provides a formal methodology for implementing, manipulating and representing the human's knowledge about how to control a system (7). In the rule-based systems the rules are expressed in a form such as "If a is X then b is Y", where X and Y are fuzzy sets, a is the domain of X and b is the domain of Y. The principal benefit is to approximate system behavior where analytic functions do not exist, such as complex and uncertainty systems (7).

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Takagi-Sugeno-Kang Fuzzy Control design: The Takagi-Sugeno (TS) fuzzy logic is able to model dynamic nonlinear systems using linear, locally valid dynamic systems. Considering an entry ($x_1, x_2, \ldots, x_n$), the output is given by Eq. 19:

$$y = \frac{\sum_{i=1}^{n} w_i f(x_1, x_2, \ldots, x_n)}{\sum_{i=1}^{n} w_i} \tag{19}$$

Where w_i is the activation weight of each Fuzzy rule.

By adopting the parameters of missing torque and the derivative of the missing torque in the time domain, it was possible to create a set of Fuzzy rules to find the gains for the values of partial and total faults seen in Eq. 18.

Results. It was used the values of the BA-1 such as (2) so (0, 0, 0.15) m is the center of mass, (0, 0, -0.15) m is the center of buoyancy. The maximum thruster's force is ±100N, because the maximum voltage supported is ±24V, also it's considered that in there were no faulty thrusters in the beginning of the AUV's mission. Two simulations were performed to analyze the control strategy developed, which can be seen in Figures 3 (a) and 3 (b). In the first case, there was a lack of 30% in thruster 1 and 50% in thruster 4 and, in the second case, there was a lack of 60% for both thrusters 1 and 4.

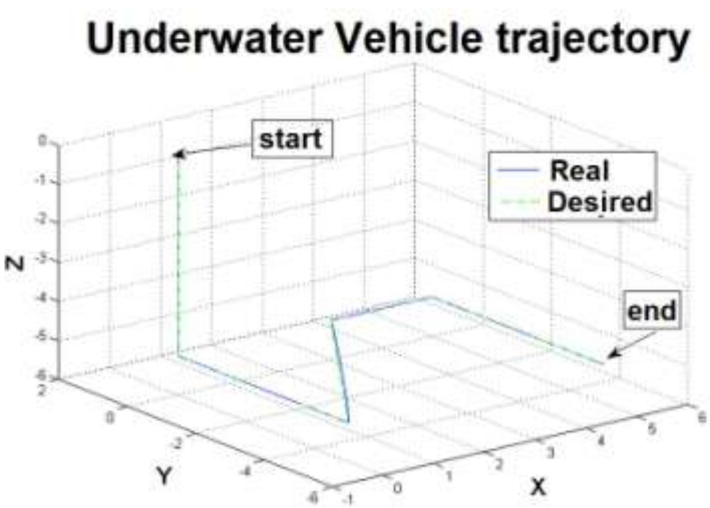

Figure 3(a). Results of first case

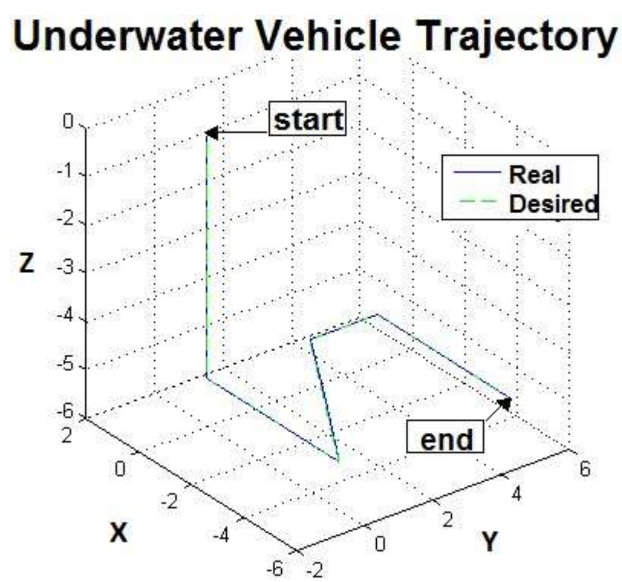

Figure 3(b). Results of second case

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Conclusion. The FTC developed showed satisfactory results for both cases proposed, with the maximum error of 5 cm in the x-axis in the first and 12cm in the second, despite of the partial faults. The suggestion for future works is to use the Levi-Civita connection with other control laws and test the fault in the vertical thrusters.

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