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Dynamic Control Design LQR PI Vectorial of Remotely Operated Underwater Vehicle.

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***Abstract*—This Document shows the control LQR (Linear quadratic Regulator) PI (Proportional Integral)Vectorial design, which is developed to control the dynamic of a remote operated underwater vehicle ROV, to allow that the vehicle follow a horizontal trajectory autonomously . The results are showed through simulations of following the trajectory of ROV obtaining satisfactory results and complying with the objective to control the dynamic while follow a trajectory.**

I. INTRODUCTION

Activities under water are very important today, such activities are performed and used in various applications and because it present different levels of difficulty for men whether access or risk developed in a hostile ambient [1] Accuracy in the process [2]. Develop of new technology has been implemented to reduce directly man intervention, vehicles submerged remote control operated or ROV [3],[4].
ROV has many applications such exploration of hydrothermal sources [5],[6]. Pipes inspection [7]. Boat hull inspection [8]. Marine platforms Construction and installation, exploration and study of marine habitats [9],[10]. Military operations [11]. And many others. This is a I don't understand the importance of knowing this kind of vehicles that has been developing around the world by industrialized countries and is been introduce in the country lately.
The main objective of this document is design a LQR Control PI Vectorial , which it is developed to control the dynamics of a subaquatic vehicle remote controlled and it allow to follow an autonomy trajectory leaving room for the operator to focus in another tasks , giving the vehicle free operation in a normal conditions and also regain control if an error occurred in the process.
In order to design the system control we need a mathematical model which will describe the dynamic for the ROV. This control system could be acquired by an experimental or theory form in this case we opted for a theory model due to a lack of ROV. However, a theoretical model can provide a close approximation to the actual dynamic behavior of such vehicles and that is why they are used in many papers related topic.
To implement the model, we must have particular ROV parameters as mass, center of gravity, inertia and other particular characteristics of the vehicle, in addition to that we must know the hydrodynamic coefficient that occur in the interaction between the vehicle and the fluid . These parameters are taken from a study in CFD software to an underwater vehicle because as mentioned above we do not have a prototype ROV further the main objective of the paper is focused on the design of the control system.
Given the above, in the development of this paper we are presented initially the dynamic model of the vehicle, where we give a brief explanation of the governing equations the motion of the ROV and the particular parameters used are shown.
Following this we proceed to show the proposed design to control the horizontal movement of ROV giving a brief explanation of the control system used and obtaining the Q and R matrices (which determine the relative importance of error and cost of the energy) used for the design and realization of LQR PI Vectorial control. Finally, we show the results in graphical form of the state variables to be controlled in addition to a random path for the vehicle following it. All results are obtained through simulations.

II. DYNAMIC MODEL OF ROV

Taking into account previous studies [12] with respect to the dynamics of underwater vehicles the following equations that describe the movement of the ROV are established.

$$\begin{aligned}
X &= m(\dot{u} - vr + wq + x_G(q^2 + r^2) + y_G(pq - \dot{r}) \\
&\quad + z_G(pr + \dot{q})) \\
Y &= m(\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{q}) \\
&\quad + x_G(qp + \dot{r})) \\
Z &= m(\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) \\
&\quad + y_G(rq + \dot{p})) \\
K &= I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + \\
&\quad (pr - \dot{q})I_{xy} + m[y_G(\dot{w} - uq + vp) \\
&\quad - z_G(\dot{v} - wp + ur)] \\
M &= I_y\dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{yzx} + \\
&\quad (qp - \dot{r})I_{yz} + m[z_G(\dot{u} - vr + wq) \\
&\quad - x_G(\dot{w} - uq + vp)] \\
N &= I_z\dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + \\
&\quad (rq - \dot{p})I_{zx} + m[x_G(\dot{v} - wp + ur) \\
&\quad - y_G(\dot{u} - vr + wq)] \qquad (1)
\end{aligned}$$

Where u, v and w are the linear velocities, p, q and r are the rotational speed X, Y and Z are the external forces, K, M and

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N are the external moments and xG, yG and zG represents the position of center of gravity the body with respect to a inertial reference frame fixed to ground.

Equations describing the dynamic behavior of ROV (1) are nonlinear, which makes it necessary linearize the model, because the control theory intended to be used is only valid for linear models.

To further simplify the model, the following assumptions are considered: the vehicle is moving at low speeds, the ROV has three planes of symmetry, and the tank in which is contained the fluid, where the vehicle moves is sufficiently large so that the walls will not interfere with the dynamics of the ROV.

When making the simplifications described above and replacing the characteristic parameters taken from [13], the equations governing the dynamics of the vehicle are:

$$\begin{aligned}
\dot{u} &= 0.087u(|u_0| + u_0 sen(u_0) - 1) - 0.061r_0 v \\
&\quad -0.061v_0 r - 2.082(10^{-4})(f1 + f2 - f3 - f4) \\
\dot{v} &= 16.27r_0 u + 7.08v(1 - v_0 sen(v_0 - |v_0|) \\
&\quad +16.27u_0 r - 3.39(10^{-3})(f1 - f2 - f3 + f4) \\
\dot{r} &= -0.28v_0 u + 0.86r(1 - r_0 sen(r_0) - |r_0|) \\
&\quad -0.28u_0 v + 5.43(10^{-5})(f1 - f2 + f3 - f4) \\
\dot{x} &= ucos(\psi_0) - vsen(\psi_0) - \psi(v_0 cos\psi_0 + u_0 sen(\psi_0)) \\
\dot{y} &= usen(\psi_0) - vcos(\psi_0) + \psi(u_0 cos\psi_0 + v_0 sen(\psi_0)) \\
\dot{\psi} &= r
\end{aligned} \tag{2}$$

Characteristic parameters, which depend on the design of the ROV, were taken from [13], in this work contemplations design are specified and obtaining the parameters using CFD are explained. Finally, taking as balance point zero for all state variables is obtained:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \\ \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.0876 & 0 & 0 & 0 & 0 & 0 \\ 0 & 7.0793 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.8601 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \\ x \\ y \\ \psi \end{bmatrix}$$

$$+ \begin{bmatrix} -2.082e-4 & -2.082e-4 & 2.082e-4 & 2.082e-4 \\ -3.387e-3 & 3.387e-3 & 3.387e-3 & -3.387e-3 \\ 5.435e-5 & -5.435e-5 & 5.435e-5 & -5.435e-5 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{3}$$

III. LQR PI Vectorial Control

To tackle the problem of LQR control, the variables state equations are presented of the form:

$$\dot{x} = Ax + Bu \tag{4}$$
$$y = Cx$$

And a control signal defined as:

$$U = -Kx \tag{6}$$

Where the objective is to find the feedback K matrix to minimize the cost function [14]:

$$J = \int_0^\infty (x * Qx + u * Ru)dt \tag{7}$$

Where Q and R matrices define the importance of the error and the cost of energy [14],[15]. During the control design the objective is to find the Q and R matrices, which define the value of the K matrix, it is fed back to the states, changing the dynamics of the ROV with the aim of control it. In this type of control is necessary to use a pre-compensator, this helps reduce the steady-state error, but in turn creates a dependency in that no variation in the model, this can generate problems in a real implementation of control system. Given the above, it is proposed to introduce an integral action which eliminates the error steady state and break the dependency of model variation. At the time of adding an integrator in closed loop control, a variation occurs in the matrices of state variables that define the model. These are defined as:

$$A = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} B = \begin{bmatrix} B \\ 0 \end{bmatrix} \tag{8}$$

Defined the new matrices A and B, the values of the matrices Q and R are set, this is done without reference to any criterion, because there is no methodology or stepwise to obtain such matrices. Then the change of the behavior of dynamic ROV is observed, ie, settling time, steady-state error, overshoot, and values of the control signal as they are entered values to the Q and R matrices iteratively until the time when the variables determining the horizontal movement of the underwater vehicle are controlled. The Q and R matrices used are shown below:

$$Q=10^6 diag\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 0.07 & 0.3 & 0.01 \end{bmatrix}$$
$$R = diag\begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix} \tag{9}$$

And with this, the compensator K, which consists of the state vector feedback Kc compensator and the integrator Ki gain, is obtained.

$$K= \begin{bmatrix} Kc & Ki \end{bmatrix}$$

$$Kc=10^2 \begin{bmatrix} -2.69 & -2.29 & 10.08 & -2.20 & -2.36 & 2.11 \\ -2.69 & 2.29 & -10.08 & -2.20 & 2.36 & -2.11 \\ 2.69 & 2.29 & 10.08 & 2.2 & 2.36 & 2.11 \\ 2.69 & -2.29 & -10.08 & 2.20 & -2.36 & -2.11 \end{bmatrix}$$

$$Ki = \begin{bmatrix} -418.33 & -866.0254 & 158.1139 \\ -418.33 & 866.0254 & -158.1139 \\ 418.33 & 866.0254 & 158.1139 \\ -418.33 & -866.0254 & -158.1139 \end{bmatrix} \tag{10}$$

IV. RESULTS

Here the response to a unit step input for the state variables to be controlled to perform a horizontal movement of the vehicle, ie the position in x, y, and the orientation angle of the vehicle are shown.

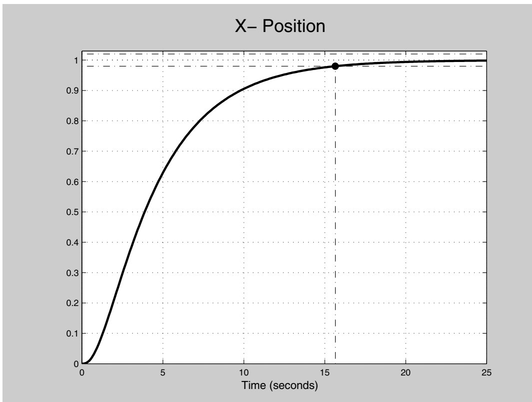

Fig. 1. X-Position

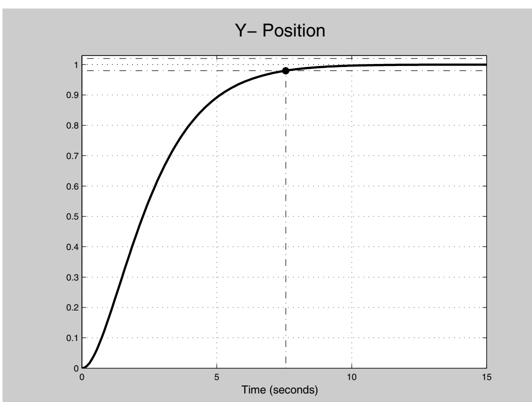

Fig. 2. Y-Position

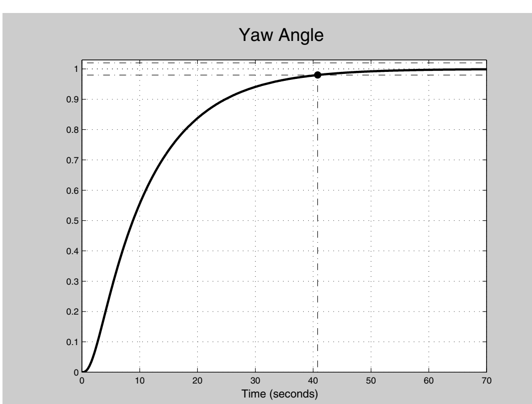

Fig. 3. Yaw Angle

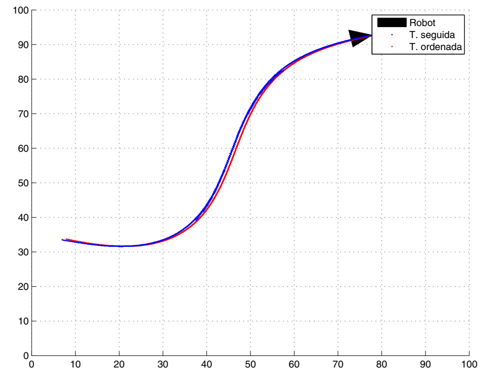

Fig. 4. Path-following

In Figures 1, 2 and 3 shows that the state variables are successfully controlled without overshoot and an error is achieved at steady state equal to zero due to the integral action, plus it does not show ripple in the signal, which shows that there is no need for a derivative action.

Settling times are 16, 7.46, and 41.8 seconds for x, y and fhi respectively, are acceptable considering that the movement of these vehicles occurs at low speeds.

As for the path-following, simulations where different points are set on the coordinate plane generating a trajectory which the ROV must follow autonomously are performed .

In Figure 4 shows that the vehicle achieved path-following through all the set points.

V. CONCLUSIONS

The LQR control system can achieve different results in the change of vehicle dynamics, ie you can have different values in dynamic characteristics such as settling time, overshoot, control signal etc. The results shown are those the author considers satisfactory after performing the simulation method iteratively analyzing the dynamic characteristics mentioned above, at each iteration.

The settling times were 16, 7.46, and 41.8 seconds for each of the three analyzed variables what is considered acceptable at the discretion of the author, considering that the movement of these vehicles occurs at low speeds.

As shown In Figure 4 the vehicle achieved path-following through all the set points. This statement is taking into account Figure 4, but the evaluation of the full autonomy of ROV must be done experimentally with a prototype of the vehicle, where can cause interference and obstacles from the path not taken into account in this work.

The LQR PI Vectorial Control proves suitable for these applications because it is a robust control. Addition to reducing and optimizing the control signal, its design requires different tests to obtain the proper compensators which depends on the Q and R matrices for the design conditions as required.

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