Linear control of the yaw and rudder limitations for Cormoran AUV

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***Abstract*—This work presents a detailed situation about the linear control design for the yaw in the Cormoran autonomous underwater vehicle (AUV). The development includes the physical limitations of the rudder that involve more constraints for the control that has a limited action and implies to reduce the gain loop of the controller. The whole system is simulated in simulink and three different controls (P, PD, PID) are compared.**

Keywords—AUV; cormoran; linear control; rudder limitations

I. Introduction

The Cormoran is a low cost oceanic observation vehicle developed by Mediterranean Institute for Advanced Studies (IMEDEA), which combines the characteristics of the ASVs and AUVs because its principle of motion (see fig. 1). This principle is based on the navigation at the surface level, where the vehicle has to follow a predefined path in the mission. The path is defined by a series of waypoints, in which the vehicles stops, dives and emerge vertically in order to obtain a profile of a water column [1].

This task leads to the need of a control system for the yaw which be fast and stable. Our previous work has dealt this issue [2], but this work focus in the problem of physical constraint of the rudder that has a limited action and implies to reduce the gain loop of the controller. This work addresses this control using different linear controls (P, PD and PID) and comparing them with a root locus analysis that includes these constraints.

For this, it is organized as follows: section II shows a dynamic model of the vehicle in 3 degrees of freedom with the rudder limitations; section III shows its linearization around a constant velocity; section IV presents the linear control designs and their implications according to the constraints; finally, section V shows the results and conclusions.

Fig. 1. Cormoran AUV.

II. Dynamic Model

The dynamic model has been derived from the Fossen equations [3], and it was simplified to 3 degrees of freedom due to its principle of movement to navigate over the surface. These degrees are surge (x), sway (y) and yaw (ψ). Following the representation of Fossen, the dynamics of the vehicle can be modeled as:

$$(M_{RB}+M_A)\dot{\nu}+(C_{RB}+C_A)\nu+(D_n+D_f)\nu=\tau \quad (1)$$

Where $\nu=[u,v,r]^T$ is the velocity vector in 3 DoF, M_{RB} the rigid body matrix, M_A the hydrodynamic inertia matrix, C_{RB} the rigid body coriolis and centripetal matrix, C_A the hydrodynamic coriolis and centripetal matrix, D_n the nonlinear damping matrix, D_f the fin lift matrix and τ the propulsion vector.

Particularly, this work stand out the action of the fin lift matrix D_f (see equation 2), that leaves to two terms that influences the turns, which are $Y_{uuf}u^2\delta_r$ and $N_{uuf}u^2\delta_r$, in where δ_r represents the action of the rudder, and its action is limited in the range +/-20º. The reader can consult in [2] a detailed mathematical description.

$$D_f=\begin{bmatrix}0 & 0 & 0\\ -Y_{uuf}u\delta_r & -Y_{uvf}u & -Y_{urf}u\\ -N_{uuf}u\delta_r & -N_{uvf}u & -N_{urf}u\end{bmatrix} \quad (2)$$

III. Linearization

In order to design a control system of the yaw it is necessary to obtain a linearization of the dynamic model. This linearization assumes that the surge velocity (u) is bigger compared with the other sway (v) and yaw (r) velocities that are smaller and taken zero. Consequently, the point of work is $(u,v,r)=(u_0,0,0)$.

Applying Taylor series approximations and Jacobian matrices, the resulting transfer function of the yaw (ψ) respect the rudder (δ_r) after a simplification of poles and zeros has the form [2]: G(s)= -b/(s(s+a)), where $a,b\in\mathbb{R}^+$ and depend in the velocity of linearization u_0.

Two linearizations will be used for the following study: at 0.3m/s and 3.3m/s. The corresponding transfer functions are:

$$\frac{\Psi(s)}{\delta_r(s)}=\frac{-0.444}{s(s+0.9878)} \qquad u_0=0.3m/s \quad (3)$$

$$\frac{\Psi(s)}{\delta_r(s)}=\frac{-53.72}{s(s+10.866)} \qquad u_0=3.3m/s \quad (4)$$

IV. LINEAR CONTROL DESIGN

The closed loop consist in a feedback of the transfer function G(s) with a control C(s) (see figure 2), which can be expressed as:

$$G_{loop}(s) = \frac{\Psi(s)}{\Psi_{ref}(s)} = \frac{C(s)G(s)}{1 + C(s)G(s)} \quad (5)$$

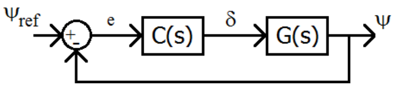

Fig. 2. Closed loop for the control of the yaw

The design of a linear control implies to find a C(s) that leads the poles to a region as negative as possible, and at the same time don't demand excessive values to the rudder, which can be expressed as:

$$\frac{\delta_r(s)}{\Psi_{ref}(s)} = \frac{C(s)}{1 + C(s)G(s)} \quad (6)$$

This work compares several C(s) using different root locus for $G_{loop}(s)$, and computing the step response for δ_r/ψ_{ref} as one way to determine the exigencies required in the rudder and its maximum values. The condition used is to accept the controls that don't be bigger than 0.35 radians in the rudder, i.e. 20º.

Since it is possible to saturate the rudder when the control uses big values, this action provokes a non-linearity in the model which is not contemplated here.

Figure 3 shows a root locus for a P-control in where the gain loop has been limited to 0.35. It shows that while the gain kp grew up the dominant pole is more negative which implies a better stability for both velocities. It also shows an extension of the root locus if it is used a higher value for the control (dash line up to -1.35) where the rudder cannot follow it due its physical constraint. In this case, the best option is to take for both speeds:

$$C(s) = -0.35 \quad (7)$$

It should be noted that the high speed 3.3m/s leads the poles to a region more negative in the real axis compared with the low speed 0.3m/s using the same control.

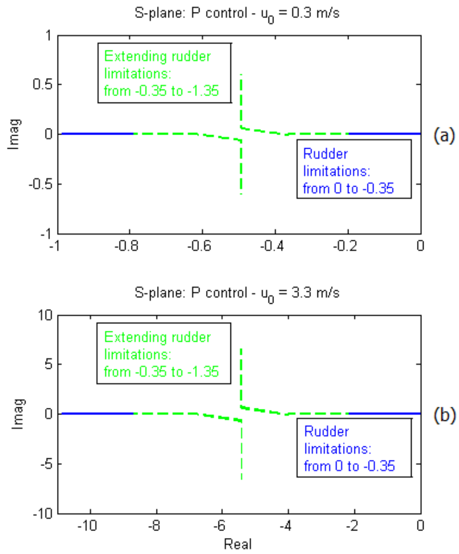

Fig. 3. Root locus for P-control design for a) u_0=0.3m/s and b) u_0=3.3m/s.

When it is used a PD control the results are very close. The control selected for both speeds is:

$$C(s) = -0.3259 - 0.0002s \quad (8)$$

It was used the maximum constant *kd* for each case in order not to exceed the 0.35 radians. However, the *kd* is very sensitive to the step response using the derivative filter and for this reason this component is very small. Figure 4 shows its root locus.

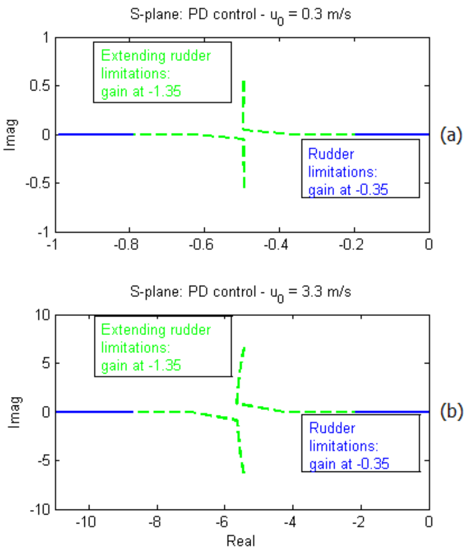

Fig. 4. Root locus for PD-control design for a) u_0=0.3m/s and b) u_0=3.3m/s.

Finally, the root locus for a PID control is showed in the figure 5. In this case, the integral action adds one pole to the system and there are more possibilities to design the linear control. The figure shows the root locus for different values of *ki* and varying the *kp* and *kd* as the previous controls. It also shows that while the *ki* grew up there are fewer margins to move the poles due the rudder constraints.

In this case, there has taken different controls for the two speeds since the low velocity is sensitive with the *ki* value. The equations (9) and (10) show the selected controls for 0.3 m/s and 3.3 m/s respectively.

$$C(s) = -0.2414 - 0.03\frac{1}{s} - 0.0011s \qquad u_0 = 0.3m/s \quad (9)$$

$$C(s) = -0.2172 - 0.3\frac{1}{s} - 0.0013s \qquad u_0 = 3.3m/s \quad (10)$$

Likewise, in the PID control the high speed the poles are more negative than the low speed, which implies more stability and speed reaction.

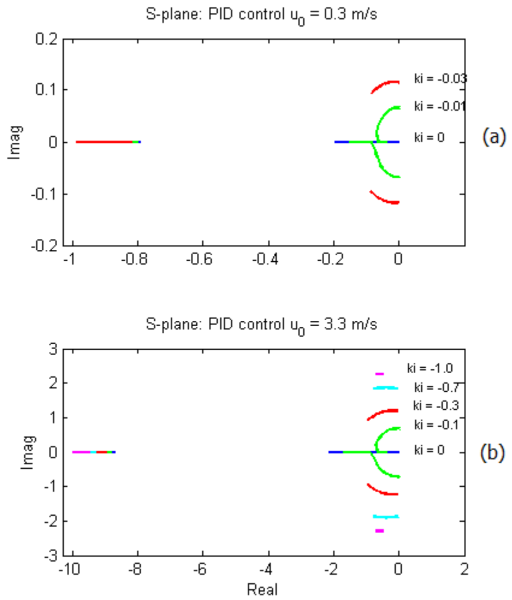

Fig. 5. Root locus for PD-control design for a) u_0=0.3m/s and b) u_0=3.3m/s.

V. RESULTS

The dynamic model was simulated using Matlab. All of the controls designed in the section IV were tested simulating the step response and showing the rudder action at all times.

The step response for the P-control can be shown in the figure 6. It shows an over damped behavior for both speeds. Regarding the establishment time, the vehicle needs 12.33 s for the low speed (0.3m/s) and 1.24 s for the high speed (3.3m/s). It should be noted that for both speeds the rudder (green line) used its maximum possible value.

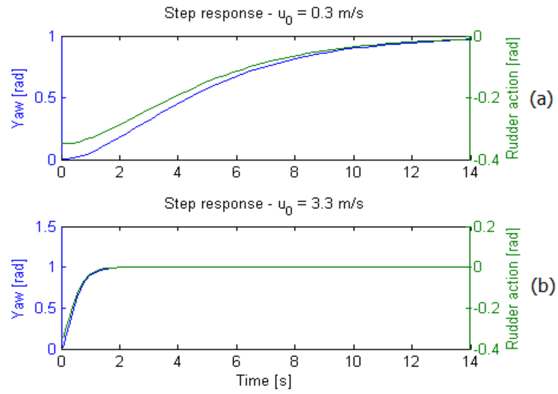

Fig. 6. Step response for P-control for a) u_0=0.3m/s and b) u_0=3.3m/s.

The figure 7 shows the step response for the PD-control designed. In this case, the results are very similar compared with the P-control. The establishment times are 13.69s and 1.37s for the low speed and high speed respectivelly.

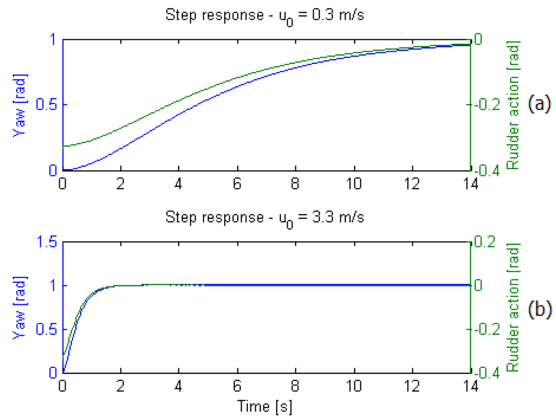

Fig. 7. Step response for PD-control for a) u_0=0.3m/s and b) u_0=3.3m/s.

Finally, the figure 8 shows the step response for the PID-control designed. As the previous controls, it also use the maximum possible value for the rudder. The establishment times are 52.58s and 5.36s for the low speed and high speed respectively. In the other hand, it has a under damped behavior for both velocities. The low speed (0.3m/s) presents an overshoot of 38% and the high speed (3.3m/s) presents an overshoot of 40%. These characteristics are larges compared with the previous controls due the *ki* value implies an overshoot in the system and the constraints are limited for a robust control. However, this PID-control can be useful for a ramp input since it can eliminate the velocity error while the previous controls don't.

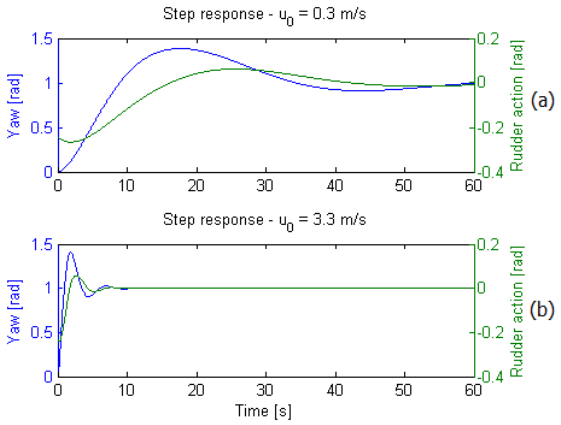

Fig. 8. Step response for PID-control for a) u_0=0.3m/s and b) u_0=3.3m/s.

VI. Conclusions and Future Work

The cormoran AUV has its physical limitations due the rudder constraints. The work showed that the control design is very limited since the margin to move the poles are conditioned with the rudder.

In the other hand, the control for the high speed works better than the control for the low speed. The same control for both speeds showed a better performance and establishment time for the high speed. This is because the poles for the high speed are more negative than the low speed and therefore more stable. For this reason, the vehicle has its own time responses depending of the forward velocity.

As future work will be studied this design regarding different step sizes in order to have more margin with the gain loop, as well as combine several linear controls in a fuzzy control as handler control in order to jump from a control to other depending the situation and the forward velocity.

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