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MITIGATION OF THE SATURATION EFFECT IN AUV PATH FOLLOWING APPLICATIONS.

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Abstract: The path following duties have huge importance in mobile robotics applications, especially in submarine environments where autonomous underwater vehicles (AUV) are employed. In this paper a method based on sliding mode technique is presented. The objective is to follow a prescribed path at maximum speed with bounded errors in a dynamical framework, taking care of the saturation in systems actuators. In addition, this method is compared with a traditional path following implementation resulting in an improvement of the path tracking time.

Keywords: Sliding mode, Robotics, AUV, Path following, Actuator constraints.

1. INTRODUCTION

Marine robotics (including AUV) applications include searching for an anomaly, taking position in a number of specific locations, patrolling a zone, or making scientific measures. In all of this cases the objective is to follow a path with accuracy and in a determined time. Several issues emerge from this. For instance if a path with tight curves is considered or if a short time is given to complete the path, the AUV will be forced to suffer from actuator saturations. Most of the time, for these applications, the path to follow is given as vector input that can be parametrized in terms of a motion parameter. This idea of such a parametrization has been applied in Nenchev (1995), Nechev and Uchiyama (1997), and Garelli *et al.* (2010) for manipulators.

In this kind of applications, system constraints and bounded desired errors define the maximum speed of path tracking. Considering traditional controls, three approaches can be derived:

(1) To use a fixed tracking speed, that never saturates the robot actuators.
(2) To use a fixed tracking speed but higher than the previous one, it means that at least it saturates the actuators in some point of the path followed.
(3) To use a variable tracking speed, calculated for each point of the path taking in consideration the constraints of the system.

It is clear that the first two options are not optimal: (1) does not exploit the maximum of the actuators, and (2) results in an unnecessary error in the track following. On the other hand, the (3) option looks more promising but in general the online calculation for each point is not simple.

In this paper, a simple way to implement the approach (3) is proposed and experimentally tested. The preliminary idea was originally presented in Garelli *et al.* (2011*a*) for a kinetic model, and we expand this to a dynamic model. For the demonstration, the methodology is applied to the AUV Ciscrea, showed in Fig. 1. Its specifications are detailed in Table 1. This kind of robot is usually designed to operate in an ocean environment. For this, its hydrodynamic model naturally suffers from numerous uncertainties. Due to these identification and modeling problems, this is an interesting plant to model and test control laws, as has been done in Yang *et al.* (2015*a*).

This work is organized in the following way. Section 2 proposes an AUV model for control, then section 3 gives the details for the control technique, section 4 is dedicated to simulation and experimental results, and finally in section 5 some conclusions are given.

Size	0.525m (L) 0.406m (W) 0.395m (H)
Weight in air	15.56kg (without payload and floats)
Controllable directions	Surge, Sway, Heave and Yaw
Propulsion	2 vertical and 4 horizontal propellers
Speed	2 knots (Surge) and 1 knot (Sway, Heave)
Depth Rating	50m
On-board Battery	2-4 hours

Table 1. Ciscrea characteristics

2. AUV MODELING

2.1 Modeling

The mathematical description of underwater vehicle dynamics is essential for a robust control design. Modeling of underwater vehicles involves two parts of study: kinematics and dynamics. In this work is used the model and simulator described in Rosendo *et al.* (2016), based on Fossen (2002) and numerical values obtained from Yang *et al.* (2015*b*).

According to Fossen (2002) and SNAME (1950) two coordinate systems are introduced: a NED-frame (North East Down) and a B-frame (Body fixed reference) for the localization as can be seen in Fig. 1. In this model all distances will be in meters, angles in radians and positive clockwise. The position vector η, velocity vector ν and force vector τ are defined as:

$$\begin{aligned} \eta &= [x, y, z, \phi, \theta, \psi]^T \\ \nu &= [u, v, w, p, q, r]^T \\ \tau &= [X, Y, Z, K, M, N]^T \end{aligned} \quad (1)$$

The AUV model is represented as Eq. 2 and a detail of the elements is described in Table 2.

$$(M_{RB} + M_A)\ddot{\eta} + D(|\nu|)\dot{\eta} + g(\eta) = \tau_{pro} + \tau_{env} \quad (2)$$

Where some parameters need clarification:

- $M_A \in \Re^{6\times6}$: added mass, is a virtual concept representing the hydrodynamic forces and moments. Any accelerating emerged-object would encounter this M_A due to the inertia of the fluid.

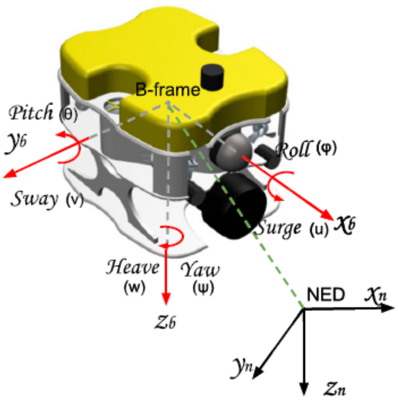

Figure 1. Ciscrea robot

Parameter	Description
M_{RB}	AUV rigid-body mass and inertia matrix
M_A	Added mass matrix
$D(\|\nu\|)$	Damping matrix
$g(\eta)$	Restoring forces and moments vector
τ_{env}	Environmental disturbances(wind,waves and currents)
τ_{pro}	Propeller forces and moments vector

Table 2. Nomenclature of AUV Model

- $D(|\nu|) \in \Re^{6\times6}$: damping in the fluid, this parameter consists of four additive parts: Potential damping, wave drift damping, skin friction, and vortex shedding damping. The first two could be dismissed in this application, whereas the others could be approximated by a linear and a quadratic matrices, D_L and D_N respectively, as is shown in Eq. 3 (Yang *et al.* (2015*b*), Fossen (2002)).

$$D(|\nu|) = D_L\nu + D_N|\nu|\nu \quad (3)$$

- τ_{env}: the marine disturbances, such as wind, waves and current contribute to this element. For an underwater vehicle, only current is considered since wind and waves have negligible effects on AUV during underwater operations.
- $g(\eta)$: as in the real robot the buoyancy is adjusted to be null, this matrix is null.

In this model the main issues of AUVs have been considered. Additionally, it is possible to work independently with each direction of the model without considering the cross relation effects, as a first approximation in the design stages. This last is possible due to the numerical values of the matrices involved, and the low coupling between the different controllable directions in the real essays.

For our particular case the path to follow is restricted to the yaw and heave direction, so it allow us to consider only these two directions in the model, giving as a simplification the Eq. 4 and Eq. 5 for heave and yaw direction respectively.

$$(M + M_{Az})\ddot{z} + D_{Lz}\dot{z} + D_{Nz}|\dot{z}|\dot{z} = \tau_z + \tau_{envz} \quad (4)$$

$$(I_\psi + M_{A\psi})\ddot{\psi} + D_{L\psi}\dot{\psi} + D_{N\psi}|\dot{\psi}|\dot{\psi} = \tau_\psi + \tau_{env\psi} \quad (5)$$

As a result from this section a model that considers the principal physical effects that involve the robot behavior is obtained, in the following is explained how the proposed method is implemented on it.

3. PATH FOLLOWING AUTO-REGULATION TECHNIQUE

The objective is to generate a variable speed tracking reference compatible with actuator limits. For this an internal variable in the system is limited, in order to assure the maximum speed over the reference path with a tolerable error in the path following.

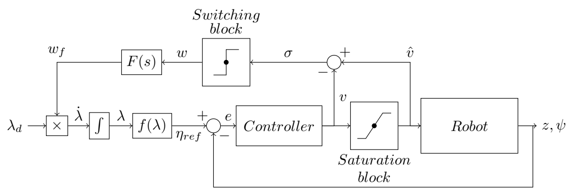

Figure 2. Proposed path following scheme

The idea is having a main closed loop with a controller implemented, an auxiliary loop is added to detect saturation over the constrained variables. This auxiliary loop generates a discontinuous signal that modifies the reference speed if saturation occurs.

Fig. 2 shows a diagram of how the method is applied to the robot, where the block "Robot" is composed of the dynamic described in Eq. 4 and Eq. 5, and the block "Controller" is a classical proportional derivative (PD) control. In addition, we also have a low pass filter $F(s)$, and the parametrization of the path, $f(\lambda)$.

Here the constrained variables are the torque applied in yaw and heave directions, in order to avoid saturation over the motors. Due to the characteristics of the robot this proposition is easily implemented because the vertical motors (used for heave direction) and horizontal motors (used for yaw direction) are independents one of each other.

The saturation detection could be established as in Eq. 6, where v_i is the controller output (here τ_z and τ_ψ) and $\tilde{v}_i$ is the actuator output.

$$\sigma(\mathbf{v}) = v_i - \tilde{v}_i \tag{6}$$

In this application the constraints are the saturation limits of the motors. When a situation of saturation is reached in any of the two torque variables, a transient sliding mode (SM) on $\sigma(v) = 0$ should be established in other to avoid it. This is the purpose of the auxiliary loop that implement the discontinuous signal w.

$$w = \begin{cases} 1 & if \quad \sigma = 0 \\ 0 & if \quad \sigma \neq 0 \end{cases} \tag{7}$$

We suppose that the path is parameterized in terms of a motion parameter λ and its first derivative is continuous. It can be expressed as follows:

$$\eta_{ref} = f(\lambda) \qquad \dot{\eta}_{ref} = \frac{\partial f}{\partial \lambda}\dot{\lambda} \tag{8}$$

Once filtered a smooth version of w is multiplied by the desired motion parameter λ_d, and subsequently integrated to generate a growing parameter λ. This parameter feeds the reference block $f(\lambda)$ producing the path reference for the controller.

When there is no saturation the switching law makes the discontinuous signal w take the value 1. In other words, while there is no saturation the auxiliary loop remains inactive and the reference speed is fixed by λ_d. When saturation occurs the signal w switches between their possible values in order to force the speed of the reference to decrease (establishing an SM). The controller could reduce the error position. Finally, when this condition is over, the auxiliary loop comes back to the inactive condition.

This configuration has several items that could be adjusted:

- λ_d: a too slow value of λ_d (that does not induce saturation anywhere along the path) would be too conservative and give a suboptimum tracking. On the other hand, a two high value of λ_d would force the auxiliary loop to be active most of the time.
- F(s): the bandwidth of the first order filter should be selected high enough to allow acceleration/deceleration of the system but sufficiently low to smooth the discontinuous signal w, in order to avoid chattering on the path reference. For a complete analysis of this problem see Garelli *et al.*, 2011*b*.
- Main controller: the controller gain should be designed similar to λ_d. A too aggressive controller would be force actuator saturation whereas a low gain controller would be suboptimum.

In conclusion, it is expected that the application of this method could get better results than traditional approaches, who suffers from the saturation effects. In order to confirm this in the next section several results are presented.

4. RESULTS

In order to evaluate the technique, a sinusoidal path in the heave and yaw direction is tested in simulation and real experiment. The parametrized path is given by:

$$yaw_{ref} = (\pi/2)\sin(\lambda) + \pi \qquad (9)$$

$$depth_{ref} = -0.65\cos(\lambda) + 1.3 \qquad (10)$$

And the initial position of the AUV is:

$$depth = 0.6 \quad (m) \qquad yaw = 1.8 \quad (rad) \qquad (11)$$

To show the results three cases are considered:

- T.1: application of the proposed technique in the robot (PD and auxiliary SM loop).
- T.2: application of a classical PD control with a constant parameter λ designed to reach the border of saturation at least once along the path.
- T.3: application of a classical PD control with a constant parameter λ that results in the same execution time as T.1.

For these three cases the same PD controllers for yaw and heave are used ($Kp_{yaw} = 25.75$, $Kd_{yaw} = 14.91$ and $Kp_{heave} = 541.43$, $Kd_{heave} = 250$). This controllers were already used by the robot operator and are considered to have an acceptable response, so from here we consider that their response is the ideal one. It is emphasized however that the design of the main controllers is outside the scope of this work.

Regarding to the tuning of the three cases only the speed reference is considered as a variable parameter. As the idea is to compare the methods, the first case adjusted was T.2 in order to get the error produced without saturation with a classical controller. Taking this in consideration then T.1 was tuned in order to get the same order of error. And finally T.3 is tuned in the way that the execution time was the same as T.1.

In the following, simulation results are presented together with real essays to verify the effectiveness of the proposal.

4.1 Simulation results

The first result that was obtained is shown in Fig. 3 where the yaw and heave evolution of the robot in time with T.1 and T.2 are presented. In this figure it is possible to see how the proposed technique completes the path 4.5 seconds faster, which represent a 10% of improvement for the same path deviation, see Fig. 4. Here it is important to remark that we are interested in the spacial result (we follow a path not a trajectory).

Moreover, Fig. 5, shows the auxiliary signals of the proposed technique that agree with the nomenclature used in Fig. 2. We can notice that there is no saturation between time 0 s and 22 s, so that the auxiliary loop is inactive $w = 1$ and the system goes at the speed fixed by λ_d. In the period 20 s to 24.3 s the robot goes into a closer part of the path where the speed imposed by λ_d can not be followed, as a result saturation occurs in actuators. Then, the auxiliary loop switches w to slow down the reference, in such a way that the positional error is reduced. This can be seen in Fig. 3 where a "bump" in the T.1 references is noticed. In this last condition the auxiliary loop makes the path reference to advance at the maximum speed that is compatible with the saturation limits (see Fig. 6). After this condition is over the auxiliary loop is inactive again until another saturation appears. Here it is important to notice that T.1 affects the reference in both directions, heave and yaw, simultaneously when a saturation is produced.

Additionally we can see in Fig. 6 how T.1 maintains the control signals in the heave direction just in the border of the saturation, while with T.3 the control signal overpasses this constraint. As a result with T.3 a larger error in the heave direction is obtained, see Fig 4.

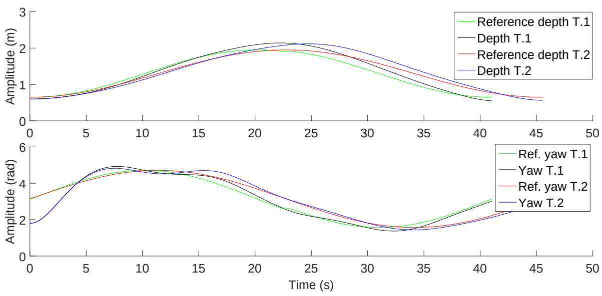

Figure 3. Evolution of heave and yaw simulation

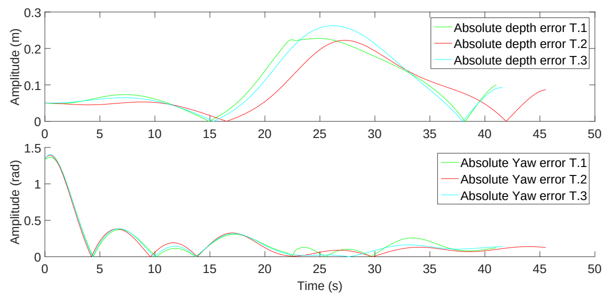

Figure 4. Evolution of absolute errors simulation

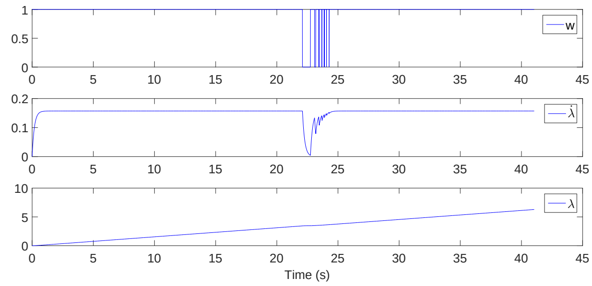

Figure 5. Evolution of auxiliary signals simulation

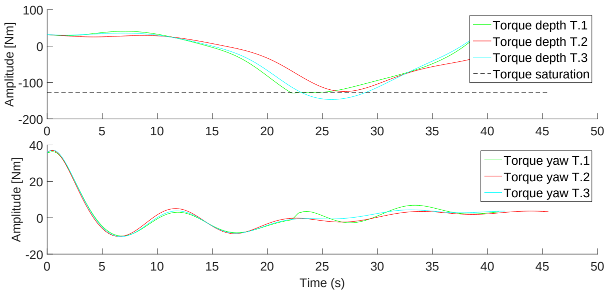

Figure 6. Evolution of torque simulation

4.2 Experimental results

The experiments were conducted in the ENSTA Bretagne pool with a setup conformed for the Ciscrea robot connected to an external computer, that stores the experimental data (see Fig. 7). The same situations as in the simulation cases were essayed, given similar results.

In Fig. 8 it is possible to see that T.1 executes the path 6 seconds faster resulting in a 15.34% of improvement, showing a similar result as in the simulation.

Moreover, in Fig. 9 is observed how T.1 preserves the robot from the saturation in contrast as T.3. where saturation has place and give as result higher error, see Fig. 10. In addition the auxiliary signals measures over the robot are displayed in Fig. 11 where a larger SM period is observed, result of the non considered dynamics over the model.

Finally, Fig. 12 show the yaw-heave plane, where the reference path as well as the ones followed in all three experiments are shown. All the experiments start in the neighborhood of point A. They evolve to reach the reference near point B, from that point the path follow the reference in the clockwise sense finishing when the point B is reached again. Note that the path T.1 is very similar to T.2 (as expected) but, as mentioned above, is completed faster. On the other hand, T.3 is performed in the same execution time as T.1 but at the cost of larger errors, particularly between points C and B.

Some additional remarks:

- The step time in the robot was 0.1 seconds. From the simulations conducted using smaller step times, the results tend to be better and the control signals more softy.
- In the experimental results a bigger oscillation is seen. This is due to an unmodeled dead-zone in the motors around the zero torque command.
- The classical controller utilized was a PD due to the nature of the system, that includes integral action.

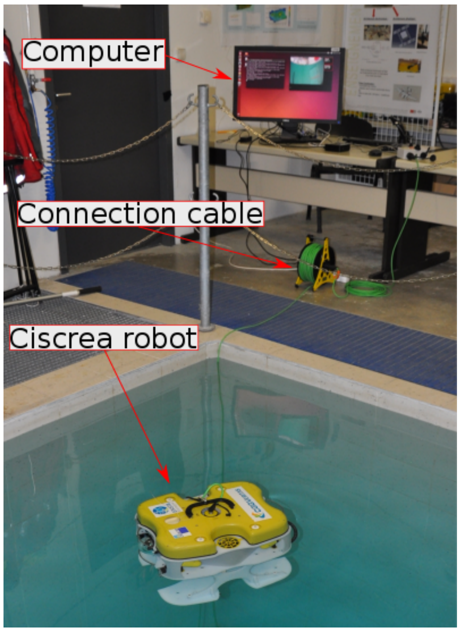

Figure 7. Ciscrea robot set up

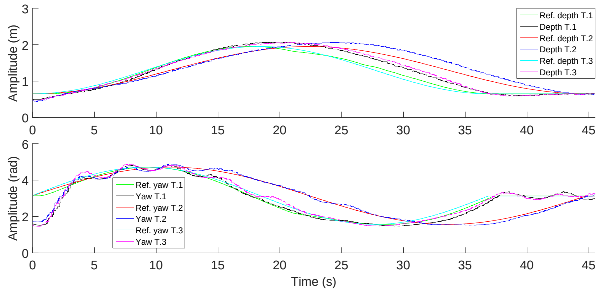

Figure 8. Evolution of heave and yaw real manipulation

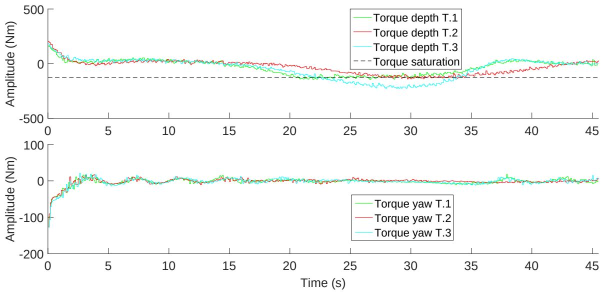

Figure 9. Evolution of torque real manipulation

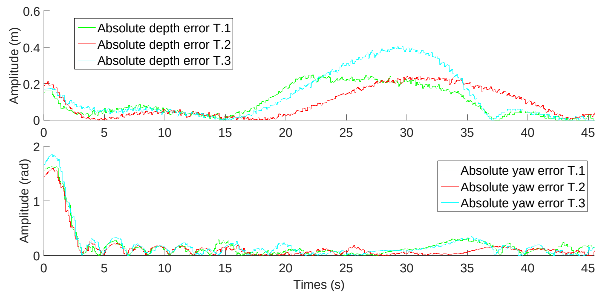

Figure 10. Evolution of errors real manipulation

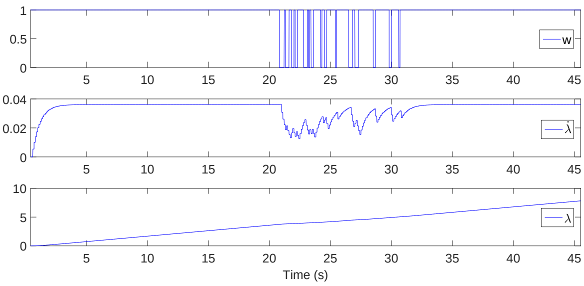

Figure 11. Evolution of auxiliary signals real manipulation

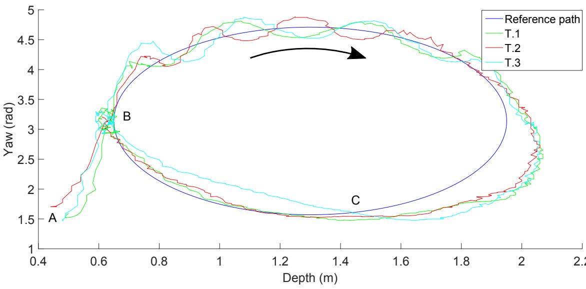

Figure 12. Path followed

5. CONCLUSION

The saturation effects on the control of path following applications has been longer studied. Several techniques used to avoid these effects, like variable gains, in general asociated to optimazing control objetives, or non linear saturation functions have aceptable results; but they usually require to consider differents points of operation and do not benefit of all the dynamic range of the actuators. In contrast, the proposed technique resolves the saturation effects and is a simple method that do not require great tuning efforts.

In this work simulation and experimental results demonstrate the feasibility of the method, showing significant improvement in execution time, and actuators saturation avoidance. An issue that arises is the way to compensate for the slow dynamics of the system, which lead to path deviations. Limitation over internal variables using the same scheme is a possible solution to explore in the future.

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