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IFAC-PapersOnLine 49-23 (2016) 008–013

Sliding mode reference conditioning for path following applied to an AUV. ⋆

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Abstract: This work presents a dynamic model for an autonomous underwater vehicle (AUV), a validation of this model together with the simulator obtained from its application and an implementation of sliding mode reference conditioning (SMRC). This last technique is proposed in order to follow a path at maximum speed with bounded errors in a dynamical framework, taking care of the saturation in systems actuators, resulting in an improvement of the path tracking time.

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

1. INTRODUCTION

Path tracking is a normal duty in robotics, from industrial applications to mobile robots. The objective is to follow a path with accuracy and as fast as possible, between these contradictory purposes arises the main issues of control tuning. Several problems emerge from this, for instance if a path with tight curves is considered or if a short time is desired to complete the path, it will generate actuator saturations. In these applications, we can remark that 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 error 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 experimentally tested. This idea was presented in Garelli et al. (2010) for a cinematic model, and we expand this to a dynamic model. For the demonstration, the methodology is applied to the AUV Ciscrea, showed in fig. 6 as their specifications details in Table 1. This kind of robot is usually designed to operate in the ocean environment, for this, their hydrodynamic model naturally suffers from numerous uncertainties. Due to these identification and modeling problems, this is an interesting plant to model an test control laws, as has been done in Yang et al. (2015a).

This works 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 experimental results, and finally in section 5 some conclusions are given.

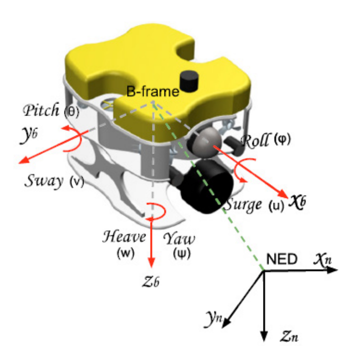

Fig. 1. B-frame and NED-frame of Underwater Vehicles

⋆ This research is partially supported by EIFFEL scholarship from France Government, by CONICET (PIP0361 and 0237), MINCYT(PICT2394) and UNLP(I164), Argentina.

10.1016/j.ifacol.2016.10.314

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 an robust control design. Modeling of underwater vehicles involves two parts of study: kinematics and dynamics. In this work is used the modeling ideas of Fossen (2002) and numerical values obtained in Yang et al. (2015b). Based on 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 see in figure 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:

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

According to Fossen (2002), rigid-body hydrodynamic forces and moments can be linearly superimposed. Furthermore, the overall non-linear underwater model is characterized by two parts, the rigid-body dynamic (eq. 2) and hydrodynamic formulations (eq. 3) (hydrostatics included). Parameter definitions are given in Table 2.

$$M_{RB}\dot{\nu} + C_{RB}(\nu)\nu = \tau_{env} + \tau_{hydro} + \tau_{pro} \tag{2}$$

$$\tau_{hydro} = -M_A\dot{\nu} - C_A(\nu)\nu - D(|\nu|)\nu - g(\eta) \tag{3}$$

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

Table 2. Nomenclature of AUV Model

In the present application M_{RB} is obtained from Yang et al. (2015b), in addition as the vehicle speed is low C_{RB} and C_A are neglected, $C(\nu) \approx 0$. The restoring forces and moments vector $g(\eta)$ is composed of the forces and torque produced by the weight and the buoyancy forces. It can be expressed as in eq. 4 where $BG = [BG_x, BG_y, BG_z]^T$ is the distance from the center of gravity (CG) to the buoyancy center (CB), ρ is the fluid density, vol is the displaced fluid volume, g is the gravity acceleration and m is the AUV mass.

$$g(\eta) = \begin{bmatrix} -(m-\rho vol)g\sin\theta \\ (m-\rho vol)g\cos\theta\sin\phi \\ (m-\rho vol)g\cos\theta\cos\phi \\ -BG_y mg\cos\theta\cos\phi + BG_z mg\cos\theta\sin\phi \\ -BG_z mg\sin\theta + BG_x mg\cos\theta\sin\phi \\ -BG_x mg\cos\theta\sin\phi - BG_y mg\sin\theta \end{bmatrix} \tag{4}$$

For Ciscrea robot, CB and CG are really close so it is possible to consider them in the same place and in the geometrical center of the robot. The marine disturbances, such as wind, waves and current contribute to τ_{env}. But for an underwater vehicle, only current is considered since wind and waves have negligible effects on AUV during underwater operations.

In order to transform the model in B-frame to a NED-frame, a transformation $J(\Theta)$ is made in eq. 5, according to eq. 2 and 3. This transformation matrix can be consulted in Yang et al. (2015b).

$$M^*\ddot{\eta} + D^*(|\nu|)(\dot{\eta}) + g^*(\eta) = \tau_{pro} + \tau_{env} \tag{5}$$

with:

$$\begin{array}{c} M^* = J^{-T}(\Theta)(M_{RB} + M_A)J^{-1}(\Theta), \\ D^*(|\nu|) = J^{-T}D^(|\nu|)J^{-1}(\Theta), \\ g^*(\eta) = J^{-T}g^(\eta), \quad \Theta = [\phi, \theta, \psi]^T. \end{array}$$

From this transformation two hydrodynamic parameters have to be precised:

- $M_A \in \Re^{6\times 6}$: 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.
- $D(|\nu|) \in \Re^{6\times 6}$: 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, and the others could be approximated by a linear and a quadratic matrices, D_L and D_N respectively, as is shown in eq. 6 (Yang et al. (2015b), Fossen (2002)).

$$D(|\nu|) = D_L + D_N|\nu|\nu \tag{6}$$

The final model used in the simulator can be represented by eq. 7, where torque of propellers are affected by a transformation from each propeller frame to the B-frame, and extra cross relations between equations due to the angular momentum are considered. Moreover some additional notations have to be introduced:

- T_i is the i-thruster of the robot for which ϕ_{t_i} θ_{t_i},ψ_{t_i} denote respectively the roll, pitch and heading of it in B-frame expressed with respect to B-frame.
- D_{Ni} is the non linear damping coefficient for i-direction.
- D_{Li} is the linear damping coefficient for i-direction.

2.2 Simulator and model validation

The proposed model is used for the implementation of a simulator in the Matlab Simulink software, the numerical values of the model related to the hydrodynamic effects were recuperated from the work Yang et al. (2015b) and the mechanical values were taken from measures realized over the robot and data provided by the manufacturer.

Two additional effects were considered in the simulator: