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Saturation based nonlinear depth and yaw control of underwater vehicles with stability analysis and real-time experiments☆

E. Campos[b,c,d,*], A. Chemori[c], V. Creuze[c], J. Torres[a,b], R. Lozano[b]

[a] Automatic Control Department, CINVESTAV, México D.F., México
[b] UMI-LAFMIA,CINVESTAV-CNRS, México, D.F., México
[c] LIRMM, CNRS-Université Montpellier 2, Montpellier, France
[d] CONACYT-Universidad del Istmo, Tehuantepec, Oaxaca, México

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ABSTRACT

This paper deals with two nonlinear controllers based on saturation functions with varying parameters, for set-point regulation and trajectory tracking on an Underwater Vehicle. The proposed controllers combine the advantages of robust control and easy tuning in real applications. The stability of the closed-loop system with the proposed nonlinear controllers is proven by Lyapunov arguments. Experimental results for the trajectory tracking control in 2 degrees of freedom, these are the depth and yaw motion of an underwater vehicle, show the performance of the proposed control strategy.

1. Introduction

Underwater vehicles are more and more used for various types of applications, such as inspection, exploration, oceanography, biology, to name a few. They can be classified in two classes: the Autonomous Underwater Vehicles (AUVs) and the Remotely Operated Vehicles (ROVs). One of the main challenges for these types of vehicles lies in the design of the control strategy, given the nonlinear dynamics and the difficulty to accurately identify their hydrodynamic parameters [2–4]. The controller is used either to fully control the vehicle (for AUVs), or to assist the pilot (for ROVs) by providing features such as auto-depth, auto-altitude (with respect to the seabed), or auto-heading. Although many types of controllers have been studied during last decades, most of commercial underwater vehicles use PID controllers. For instance, PID control and acceleration feedback can be found in [5]; in [7] a PD controller considering the time-delay produced by the sensor has been proposed for an underwater vehicle. Nevertheless the drawback of these controllers is that they do not have a good performance when the parameters of the system change.

In practical applications, we can notice that a standard PID control design can be improved by bounding its signal. Consequently, several nonlinear PID controllers with bounded signal have been proposed in order to improve the performance of the closed-loop system. For instance, in [8] and [9] a nonlinear PD controller has been proposed for robot manipulators, where the constant proportional and derivative gains have been replaced with nonlinear functions. In [10] a nonlinear PID controller is proposed for a superconducting magnetic energy storage, where the idea was to improve the stability of the power system in a relatively wide operation range. In [11] a nonlinear PID controller was applied to a class of truck ABS (Anti-lock Brake System), where it has been shown that the nonlinear PID controller has better performance than the conventional PID controller.

In the literature there are some works about control strategies for AUVs, for example in the paper [12] the authors present a trajectory tracking control using a linear system to implement a sliding mode controller. In this case the unmodeled dynamics are consider as external perturbations. In [13] the simulation of a backstepping controller for robust diving against pitch perturbations is given. The reference [14] describes a classical algorithm of sliding mode, where the vehicle has a input/output decentralized dynamics; the main problem of this technic is the chattering. In [16] a nonlinear adaptive controller is proposed for depth and pitch control of a small underwater vehicle. The paper [17] presents a trajectory tracking control using Lagrange's operators, allowing propose a novel path-following controller for UUVs. Concerning robust controllers, one possibility is to try to reduce undesirable dynamic couplings, for instance dynamic pitch and yaw coupling suppres-

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* Corresponding author at: UMI-LAFMIA,CINVESTAV-CNRS, México, D.F., México.
E-mail addresses: camposme1a@hotmail.com, ecampos@ctrl.cinvestav.mx (E. Campos).

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Fig. 1. View of the L2ROV underwater vehicle. Its six thrusters allow precise control of its 6 degrees of freedom.

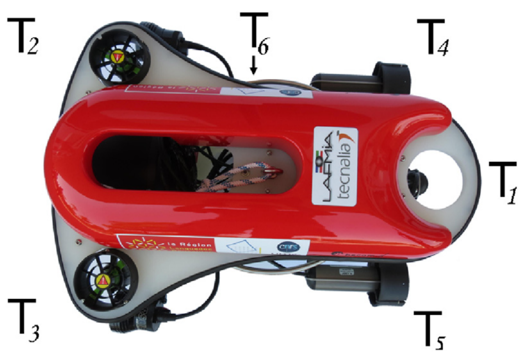

Fig. 2. L2ROV: view of forces generated by the thrusters to perform the translational and rotational motions.

sion using a robust H_∞ control technique has been considered in [18].

In the present paper, our aim is to reinforce the prominent place PD controllers have gained in a number of applications. In this vein, we propose a nonlinear PD and PD+ based on saturation function with variable parameters. Both controllers are proposed for set-point regulation as well as time varying trajectory tracking control of an Underwater Vehicle. To the best knowledge of the authors, this method has never been applied yet to control this type of vehicles. Moreover the proof of stability, based on Lyapunov arguments, is given and the control scheme is validated on a new underwater vehicle. Furthermore the experimental results presented herein have been extended to two degrees of freedom, namely depth and yaw.

The real-time experiments have been conducted using the tethered underwater vehicle L2ROV (Figs. 1 and 2) entirely designed and built at LIRMM (University Montpellier 2). One of the main advantages of this vehicle is that we can use it either as an Autonomous Underwater Vehicle (AUV) or as a Remotely Operated Vehicle (ROV), depending on the task we want to carry out. The propulsion system consists of six thrusters used to control the 6-DOF, although roll and pitch are naturally stable. This paper is organized as follows: in Section 2 we briefly describe the L2ROV prototype as well as its dynamic model. The control strategy is presented in Section 3. The obtained experimental results for trajectory tracking control are presented and discussed in Section 4. Finally, some concluding remarks and future works are given in Section 5.

2. Description and modeling of the L2ROV vehicle

This section describes the technical features of the L2ROV underwater vehicle and its dynamic model. Based on the design of the vehicle and in order to reduce further analysis, we assume that the vehicle is moving at low speeds, leading to a slightly simplified dynamics.

Table 1
The main features of the L2ROV vehicle.

Mass	28 kg
Floatability	9 N
Dimensions	75 cm(l) × 55 cm(w) × 45 cm(h)
Maximal depth	100 m
Thrusters	6 Seabotix BTD150 cont. bollard thrust = 2.2 kgf each with Devantech MD03 drivers
Power	48 V - 600 W
Light	2 × 50 W LED
Attitude sensor	Sparkfun Arduimu V3 Invensense MPU-6000 MEMS 3-axis gyro and accelerometer 3-axis I2C magnetometer HMC-5883L Atmega328 microprocessor
Camera	Pacific Corporation VPC-895A CCD1/3" PAL –25–fps
Depth sensor	Pressure Sensor Breakout-MS5803-14BA
Sampling period	50 ms
Surface computer	Dell Latitude E6230 - Intel Core i7 - 2.9 GHz Windows 7 Professional 64 bits Microsoft Visual C++ 2010
Tether length	150 m

2.1. Prototype description

The L2ROV (Figs. 1 and 2) is a tethered underwater vehicle, whose size is about 75 cm long, 55 cm width, and 45 cm height. The propulsion system of this underwater vehicle consists of six thrusters, as illustrated in Fig. 2. According to the SNAME notation [19], the translational motions are referred to as surge, sway, and heave; while the rotational motions are roll, pitch, and yaw. The surge motion is generated by the sum of the forces created by T_4 and T_5, sway movement is actuated by T_6, and heave is produced by the sum of thrusts of T_1, T_2 and T_3. The roll movement is actuated through differential force of the thrusters T_2 and T_3; the pitch motion is obtained similarly using thrusters T_1, T_2 and T_3, and the yaw motion is generated by T_4 and T_5. The experimental platform consists of a ROV driven by a laptop computer, with CPU Intel Core i7-3520M 2.9 GHz, 8GB of RAM memory. The computer runs under Windows 7 operating system and the control software is developed with Visual C++ 2010. The computer receives the data from the ROV's sensors (pressure, attitude), computes the control laws and sends input signals to the actuators. These latter are controlled by MD03 Motor Drives. The main features of this vehicle are described in Table 1.

2.2. Dynamic modeling

The dynamics of the vehicle, in the body-fixed-frame (x_b, y_b, z_b) (more details see Fig. 3), can be expressed in a compact matrix form as [20]:

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} + \boldsymbol{w}_e \tag{1}$$

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\eta)\boldsymbol{\nu} \tag{2}$$

where $\boldsymbol{M} \in \mathbb{R}^{6\times6}$ is the inertia matrix, $\boldsymbol{C}(\boldsymbol{\nu}) \in \mathbb{R}^{6\times6}$ defines the Coriolis-centripetal matrix. In our case we assume that the vehicle is moving at low speeds, then this Coriolis matrix can be neglected. $\boldsymbol{D}(\boldsymbol{\nu}) \in \mathbb{R}^{6\times6}$ represents the damping matrix, $\boldsymbol{g}(\boldsymbol{\eta}) \in \mathbb{R}^{6\times1}$ describes the vector of restoring forces and moments, $\boldsymbol{\tau} = (\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)^T = ((\tau_X, \tau_Y, \tau_Z), (\tau_K, \tau_M, \tau_N))^T \in \mathbb{R}^{6\times1}$ defines the vector of control inputs; $\boldsymbol{w}_e \in \mathbb{R}^{6\times1}$ defines the vector of disturbances; $\boldsymbol{\nu} =$