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Review

Stabilizing control and human scale simulation of a submarine ROV navigation

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ABSTRACT

This paper addresses the stabilizing control problem of a Remotely Operated Vehicle (ROV) expected for observation tasks in depth sea and marine archeology sites inspections. A stabilizing image must be ensured throughout the ROV's motion. From the kino-dynamic model we prove that the ROV fails Brockett's necessary condition. Consequently, the equilibrium cannot be stabilized using continuous pure state feedback laws. As an alternative, a continuous time-varying feedback law is proposed. In addition to basic simulation results, a human-scale visualization integrating a 3D aquatic pool environment and the ROV's 3D CAD model is introduced. The stability results imply the effectiveness of the proposed stabilizing control law.

Contents

1. Introduction

Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) have been applied in a wide variety of submarine areas. Recently, there has been a trend to use smaller autonomous underwater vehicles, both tethered and untethered in rivers, lakes and oceans. Called also underwater robots, they are an integral part of scientific equipment to explore the seas and oceans. Many examples have shown that ROVs and AUVs are useful in many fields and for a variety of applications such as inspection, mapping or bathymetry. However, we can distinguish a depth limit for different types of existing autonomous underwater vehicles. We can cite the *Hugin 3000 sensor* of Kongsberg Maritime, the *Sea Oracle* of Bluefin's Robotics and the *Alistar 3000* of ECA, which can reach depths of 3000 m, and have a high autonomy. An AUV has an important size and weight and requires significant logistics. They also use a lot of energy which may be

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constraining in some applications. However, the ROVs, as the *Phantom 500* (Folcher and Rendas, 2001), the *ALIVE vehicle* of group Cybernetix, the *ROV Triton-PR*, the *AC-ROV* (ROV sales) and the *H1000* of the Eca-Hytec, with much less autonomy, they are dedicated for inspection/observation operations in subsea and are not considered for manipulations. Underwater vehicles that use differential thrust for surge and yaw motion control have the advantage of increased maneuverability. Unfortunately, such vehicles usually do not have thrusters/actuators to control lateral movements. Hence, they fall into the underactuated vehicle category. From control point of view, which is the key problem to ensure vehicle semi-autonomy or full-autonomy, the control design becomes a challenge problem due to underactuation and high nonlinearities of the dynamic model. Thus, controlling the ROV's positions with suitable performance is so difficult due to the strong model nonlinearities and uncertainties. Several different control approaches have been studied for underwater vehicles including sliding mode control cited in Yoerger and Slotine (1991), robust control in Licea and Grimble (1994) and Han et al. (2011), adaptive control in Narasimhan and Singh (2006), fuzzy control as presented by Wang et al. (2003), neural networks of Junku (1990) and nonlinear control in Nakamura and Savant (2005). The stabilizing problem of underwater vehicles at a desired reference trajectory is an important issue in many offshore applications. This goal can be achieved by solving trajectory-tracking, path-following, path-tracking and stabilization problems (Do and Jie, 2009). Robustness of the controller with respect to non-stationary subsea environments is also a challenging problem. In Martins-Encarnacao (2002), the Lyapunov approach and the backstepping technique were combined and the control achieves the seabed monitoring. The tracking control of an AUV was limited to the horizontal plan in Lapierre and Soetanto (2007). A first order sliding mode technique was proposed by Salgado (Folcher and Rendas, 2001) for the Taipan. Work in Herman (2010) presented an adaptive control scheme of dynamic positioning of a ROV based on a variable structure model-reference adaptive control. A self-regulating fuzzy controller is designed for a small cylindrical object navigating near free-surface to minimize wave disturbance and to keep the object move in the desired depth based on the adaptive fuzzy control theory was proposed in Zhiyu et al. (2011). In Teixeira et al. (2010), a nonlinear Lyapunov-based adaptive output feedback control law is designed and shown to regulate pitch, yaw, and depth tracking errors to zero. The integrator backstepping technique is used to achieve a Lyapunov stable trajectory tracking controller in Aguiar et al. (2003). A control strategy for station keeping of underactuated flat-fish type AUVs with an addition of dedicated thrusters is proposed in Mohan and Thondiyath (2013). The stabilizing problem of ROVs systems represents a challenge for nonlinear control theory because the linearization for most of them is not controllable. In fact, as shown by Brockett (1983), for this class of systems there does not exist a smooth and pure-state control law which asymptotically stabilizes the system to an equilibrium point. As an alternative, explicit time-varying or a discontinuous laws solve the stabilizing control problem for a large underactuated autonomous systems (see Rosier, 1994; Morin and Samson, 1997; Pettersen and Nijmeijer, 2001).

Recently, virtual reality is used to study performances of 3D interaction tasks in large scale virtual environments (Ullah et al., 2009) including multimodal Human–Robot Interaction (HRI) as in Boudoin et al. (2008). Navigation is one of the fundamental tasks needed for 3D interaction with Virtual Environments. Virtual reality offer the high-end visualization and the realistic physical behavior of the ROV. Accurate simulations and graphical display of these virtual environments are being used to impart users with realistic experiences. For animation and 3D visualization of ROV behavior, virtual reality approaches are applied in many cases. In Domingues et al. (2012a), two types of Human–Robot Interface are developed for underwater robot teleoperation. The first one is a Web interface to control and teleoperate the ROV. The second (HRI) is a web interface on a special aquatic computer called DOLPHYN that simulates scuba diving (Domingues et al., 2012b). A virtual telepresence operation approach of tele-operation of underwater robots using a video camera is described in Lin and Kuo (1997).

In this paper, we study a ROV as an ultraportable submarine vehicle, which is expected for observation and exploration in subsea historical sites. The ROV is equipped by two cameras and will permit the Tele-exploration in mixed-reality sites. It is procured by the European project Digital-Ocean.[1] In order to stabilize the ROV, the submarine system should be stabilized for a given desired position and attitude under hydrodynamic effects. Based on the ROV kino-dynamic model in Adel et al. (2013), we prove that Brockett's necessary condition is not satisfied, hence a continuous linear or nonlinear pure state feedback law cannot solve the stabilizing problem. Hence, an explicit homogeneous time-varying control is elaborated. Using the virtual reality tools, we will visualize the movement of the ROV and operators could perform different manipulations.

The paper is organized as follows: In Section 2 the kinematic and dynamic model of the ROV is addressed. In Section 3, a continuous periodic time-varying feedback law is constructed. Using a virtual reality Platform the 3D simulation of the ROV navigation under the developed theoretical results are presented in Section 4. Section 5 deals with some conclusions and future works.

2. Modelling

As submarine vehicle, due to hydrodynamic forces, the ROV kino-dynamic model is highly nonlinear and coupled, however, to simplify the model most of authors introduce some assumptions (Folcher and Rendas, 2001). These assumptions concern often some coupling terms or outright neglect hydrodynamic terms. The ROV has a close frame structure (see Fig. 1). This vehicle is actuated with two reversible horizontal thrusters (F_1, O_1) and (F_2, O_2) for surge and yaw motions, and a reversible vertical thruster (F_3, O_3) for heave motion, where O_i is the center of the force F_i (see Fig. 9). A 150 m of cable provides electric power to the thrusters and enables communication between the vehicle sensors and the surface equipment (see Figs. 1 and 2), while the ROV characteristics are given in Table 1.

Note that from Table 1, the inertia product terms (I_{xy}, I_{yz}, I_{xz}) are negligible compared to the principal moments of inertia (I_{xx}, I_{yy}, I_{zz}). Then, the inertia matrix is taken diagonal.

2.1. Kinematics

An underwater vehicle model is conventionally represented by a six degrees of freedom, but with fewer control inputs which may conduct to some uncontrolled directions. Then the problem consists to find the adequate combination of control inputs that ensure the six degrees of motion. Let us consider two reference frames to describe the vehicle states, where one being the inertial frame $R_0(O, x_o, y_o, z_o)$ and the other being the local body frame R_v (C, x_B, y_B, z_B) with the origin coincident with the ROV center of buoyancy C. The center of gravity G is vertically aligned with the center of buoyancy. Surge, sway and heave directions are

[1] http://www.digitalocean.eu