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Bilateral propellers dynamic control for an underwater operated vehicle using a self-synchronization practical tracking controller

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ABSTRACT

This paper proposes the station-keeping control for an underwater vehicle keeping balance motions and performing accurate manipulations in underwater inspections. In order to control position and maintain bilateral balance in deep water, a controller is designed with a Sprott system-based self-synchronization error formulation and a bisection approach algorithm to enhance the performances of brushless dc motors. A sufficiently high but not exceeding metacentric height (GM) is designed for the proposed underwater vehicle. Depth control with a pressure sensor is carried out depth gauge to determine the operated voltages. Using the voltage control mode, the practical tracking controller can maintain the same dynamics for bilateral propellers. Uncertainty dynamic parameters cannot be precisely modeled in a vehicle, and another one can track the pre-specified dynamic responses of a reference model. It keeps the bilateral propeller balancing operations by close-loop controlling the duty ratios of a buck-boost converter. In contrast with the incremental conductance based controller and PID controller, the proposed bilateral propellers controller is used to demonstrate the superior performances in depth and station-keeping tests, operating with armature voltages of 0–30 VDC and rotor speeds of 0–900 rpm in 0–3 m diving depth.

1. Introduction

Recently, underwater vehicles are widely used for oceanographic research, commercial tasks, and military missions, including hull and harbor inspection, pollution surveillance, underwater salvage and autonomous navigation. Observation class vehicles with specific sensors, such as autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs), can dive into a deep-sea environment to make detailed maps of the seafloor, measure the concentration of various compounds and capture images using an underwater camera (Miller et al., 2010; Bingham, 2008; He et al., 2011). If the underwater vehicle has a station-keeping function, it can maintain balance motion, navigate accurately, and perform accurate manipulations for underwater inspections (Miller et al., 2010; Donovan, 2012). An important issue, in a marine propulsion system is a propeller that generates thrust and overcomes water resistance. In addition, its motion will be affected by current forces, hydrodynamics and pressure. A vehicle swing frequency is affected by the separation distance between the center of gravity (G) and the center of buoyancy (B). Any rotational motion around the center of B immediately sets up a restoring moment arm (The fleet type submarine-Chapter 5). The restoring moment is proportional to distance GM, i.e. the distance between the G of the vehicle and its metacenter (M), which is called the metacentric height (MH). Each vehicle was designed with a large MH to ensure safety against the overturning of a floating body. The MH is a measurement of a floating body's initial static stability. A sufficient distance that does not exceed GM was determined for the design of the underwater vehicle. For an underwater vehicle or a submarine, the surrounding tank is submerged and stable. The stable equilibrium always has the G below the B and both are in the same vertical line, as shown in Fig. 1(a). This study aims to design a vision servo vehicle to enable underwater station-keeping stability for applications such as sea pipeline exploration, geological exploration, and reservoir investigation. The proposed underwater vehicle is employed with respect to the desired distance measurement. In addition, the voltage and thrust

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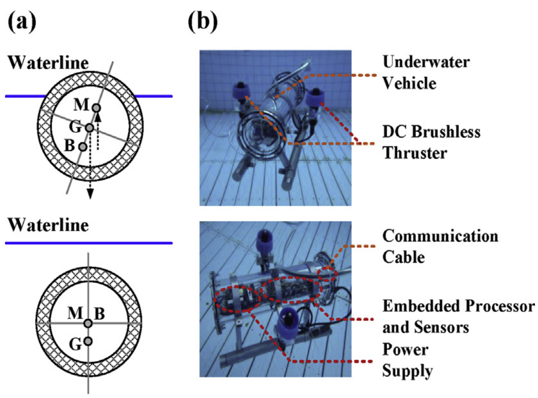

Fig. 1. Metacentric height (MH) and configuration of proposed underwater vehicle. (a) Change of the center of gravity (G), the center of buoyancy (B), and metacenter (M) during submergence, (b) The proposed prototype model of an underwater vehicle with two dc brushless thrusters (top and side view).

characteristics of each thruster in a thruster pair will not be identical as they operate over time. Therefore, a pressure sensing system and a close-loop control algorithm were used to mitigate thrust imbalance effects in an uncertain marine environment.

An underwater vehicle consists of several components: a vehicle hull, thrusters, a camera, lights, sensors (depth, gyroscope, and accelerometer), a power source (AC/DC and DC/DC converter), and a control system (Blue Ray Team; ROV Team, 2012), as shown in Fig. 1(b). The laptop communicates with the control system via an Ethernet protocol and a wireless router. The propulsion system comprises two dc brushless thrusters (Model 260, Tecnadyne, Inc.) that are arranged vertically to allow for diving, and depth and motion controls. A pressure transducer (P51, SSI Technologies, Inc.) is used to measure the depth under the waterline. A brushless type motor is commonly used. To enhance the performance of the motor, a gearbox reduces the rotational speed, improves torque and significantly reduces power consumption (Blue Ray Team). The gear train consists of a planetary gear, with a reduction gearbox ratio fitted directly to the output end of the motor. Previous studies (Fossen, 1994; Thor et al., 2000) have proposed different methods to control a dc motor, such as voltage control, current control, or torque control. Therefore, a high efficiency motor controller is used to regulate the armature voltage, depending on the output loading.

The propulsion components of electric vehicles, such as brushless dc motors (BDCM), perform better than brushed dc motors and induction motors and are widely used in industrial applications, because of their simple structure, fast response, high power density, high reliability and low maintenance requirements (Pan and Luo, 2005; Wang et al., 2011). To achieve good performance, a Proportional-Integral-Differential (PID) controller is commonly used for this application (Wang et al., 2011; Singhal and Padhee, 2012). Artificial intelligence (AI) methods, such as fuzzy controllers (Cao and Cao, 2009), artificial neural networks (ANN) based controllers (Pan and Luo, 2005; Wlas et al., 2005; Bose, 2007), differential-geometric-based non-linear controllers (Huang et al., 2009) and sliding mode controllers (Haddoun et al., 2006), are also employed in electric vehicles. The Fuzzy and ANN methods (Cao and Cao, 2009; Wlas et al., 2005; Bose, 2007) have high computational capability for the controller. However, it is essential to consider the various uncertainty conditions to design an adaptive model-based controller with improved performance.

When proposing a station-keeping control, the proposed self-synchronized practical tracking controller tracks the dynamic responses of a reference model. A chaotic system (CS) such as the Sprott system comprising a master system (MS) and a slave system (SS) (Kuo, 2007; Chen et al., 2007, 2013; Pisarchik and Ruiz-Oliveras, 2010; Kuo et al., 2013) is a simple structure to design a self-synchronization error formulation. A coupling dynamic variable is used so that the response of the SS can automatically track the response of the MS to trace the BDCM voltage changes in real-time signals. This is represented using straightforward mathematical formulations, and it provides rapid solutions in deep water. Self-synchronized practical tracking maintains the same dynamics for bilateral propellers. Then, the bisection approach algorithm is employed to control the duty ratios of a buck-boost converter (BBC) under step-up and step-down conditions. The proposed controller can quickly regulate the control signal to switch the duty ratio of the BBC. For an estimated operating point, its manipulation can eliminate the chattering phenomenon and allow for good station-keeping and steady motion for deep-water tasks. For an active vehicle, the proposed controller needs to utilize a digital signal processor (DSP), a field-programmable gate array (FPGA), a chip, or an application-specific integrated circuit chip (Bose, 2007), which provides control procedures to achieve good performance. At present, high-level chips have advanced VLSI technology and its support built-in functions have improved the execution speed. In this study, the Sprott—CS—based self-synchronization error formulation and bisection approach algorithm were designed as a microcomputer-based controller in an embedded system. The intelligent mobile vehicle could track the pre-specified dynamic responses of a reference model and maintain the same dynamics for bilateral propellers.

In a simulation model of an underwater vehicle, the dynamic tests show that the proposed method has good computational efficiency. This paper is organized as follows: Section 2 describes the electromechanical propulsion system and Section 3 describes the implementation of a practical tracking controller. In Sections 4 and 5, the experimental results and conclusions are given, to show the efficiency of the proposed controller.

2. An electromechanical system for an underwater vehicle

2.1. DC electromechanical system

A DC electromechanical system comprises electrical and mechanical components, as shown in Fig. 2. It can be used for robotic controls, computer taps and disk-drive position controls, propeller controls, and underwater vehicle control. A magnetic field is produced by stationary permanent magnets (PM) or a stationary electromagnet. In servo applications, the dc motor is used in the linear range of the magnetization curve. Therefore, the field flux, Φ, is proportional to the field current, i_f: that is $\Phi \propto i_f$. The torque, T_m, of the motor is proportional to the armature current, i_a, and its back electromotive force (emf) is also proportional to speed (Nise, 2004). The relation between the armature current i_a, applied armature voltage e_a, and back emf v_b is found using a loop equation around the Laplace transformed armature circuit:

$$R_a I_a(s) + L_a s I_a(s) + V_b(s) = E_a(s) \tag{1}$$

$$T_m(s) = K_m I_a(s), \quad V_b(s) = K_b s\theta_m(s) \tag{2}$$

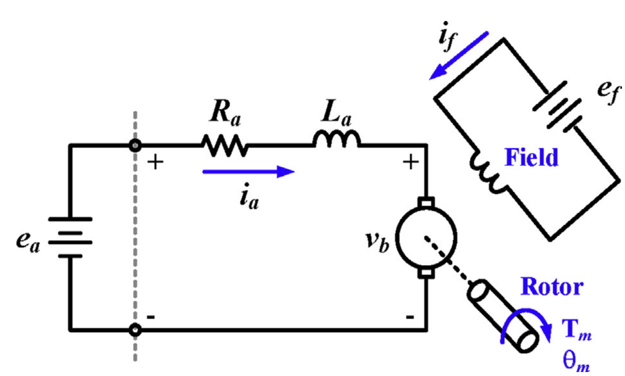

Fig. 2. The diagram of dc electromechanical system.