Ocean Engineering 125 (2016) 103–112

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Nonlinear heading control of an autonomous underwater vehicle with internal actuators

Bo Li, Tsung-Chow Su *

Department of Ocean and Mechanical Engineering, Florida Atlantic University, Boca Raton, FL 33431, USA

ARTICLE INFO

Article history:
Received 17 March 2016
Received in revised form
18 June 2016
Accepted 7 August 2016

Keywords:
Autonomous underwater vehicle
Backstepping
Nonlinear dynamics
Internal actuator

ABSTRACT

Designs of hybrid autonomous underwater vehicles (AUVs), which use internal actuators instead of control surfaces to steer, have emerged recently in the ocean engineering community. This paper focuses on the heading autopilot design for a REMUS AUV by using an internal moving mass. A nonlinear dynamical system is first derived which describes the horizontal-plane motion of the vehicle coupled with an internal moving mass. It is shown that a displacement of the internal mass in the sway direction can affect the flow of the dynamical system in phase space. Using displacement as the system input, a LQR controller is designed to stabilize the heading angle of the vehicle by taking advantage of the position and inertia of the internal moving mass. The linear controller cannot deal with large perturbations due to the constraints on the maximum displacement and movement speed of the internal moving mass. Consequently, a tunnel thruster is added to the design in order to address the problem. A nonlinear full-state feedback law is derived based on backstepping and Lyapunov redesign technique to control the displacement of the internal mass and the force exerted by the tunnel thruster. Simulation results demonstrate the effectiveness of the proposed design.

1. Introduction

New applications of streamlined autonomous underwater vehicles (AUVs) require them to be capable of operating at low speeds or in harsh ocean environments featuring strong currents (Wynn et al., 2014). Unfortunately, conventional AUVs generally steer using control surfaces, whose performances are dependent on their relative velocities with respect to the fluid. Therefore, they will become ineffective in those circumstances. Many solutions have been proposed in the literature to enhance the maneuverability of streamlined AUVs. Equipping AUVs with more hydrodynamic surfaces can provide a larger control force to the vehicles (Meneses et al., 2014); however, the relative flow around the control surfaces must be accurately measured in order to obtain the desired control force. Some underwater vehicles are externally mounted with azimuth thrusters, which can allow them more maneuverability (Yoshida et al., 2012), and the capability of performing tasks that require dynamic station keeping (Santhakumar and Asokan, 2013). Tunnel thrusters or jet pumps have also been studied in some designs of AUVs to serve the same purposes (Saunders and Nahon, 2002; Palmer et al., 2008; Steenson et al., 2011). Instead of control fins, the Typhoon AUVs use two vertical and two lateral tunnel thrusters to directly control their pitch and yaw angles, respectively (Allotta et al., 2014, 2016). Azimuth and tunnel thrusters are able to produce forces almost independent of the relative flow around the vehicle. However, they have the disadvantages of large power consumption and compromise hull integrity.

As an alternative steering method for underwater vehicles, the concept and application of internal actuators has emerged through the development of underwater gliders. Unlike thruster-driven AUVs, typical underwater gliders use internal actuators, including electrically or thermally driven buoyancy propulsion system and an internal moving mass, to travel by gliding upwards and downwards through water columns. The dynamics and linear control of the sawtooth motion using a ballast chamber and moving mass was established by Leonard and Graver (2001), which was explained in detail in Graver (2005). Existing underwater gliders such as Seaglider (Eriksen et al., 2001), Spray (Sherman et al., 2001), and Slocum (Webb et al., 2001) have demonstrated features of low energy consumption and high endurance. However, underwater gliders typically move at a speed of about 0.3 m/s compared with 1.5–2.0 m/s of thruster-driven AUVs, thus making them unsuitable to operate in harsh ocean environments.

Recently, designs of hybrid underwater vehicles have been proposed, which combine the characteristics of conventional AUVs and underwater gliders. On the one hand, propeller units of AUVs

---

* Corresponding author.
E-mail address: su@fau.edu (T.-C. Su).

http://dx.doi.org/10.1016/j.oceaneng.2016.08.010
0029-8018/© 2016 Elsevier Ltd. All rights reserved.

can be combined into underwater gliders to increase their forward speeds, thus overcoming ocean currents (Wang et al., 2011; Claus and Bachmayer, 2012; Isa et al., 2014). For example, the Slocum G2 hybrid glider is an evolution of the Slocum glider, which is equipped with a collapsible propeller that folds when not being used (Claus et al., 2012; Jones et al., 2014). The hybrid capability allows the vehicle to pass through strong ocean currents and shallow waters with great efficiency. On the other hand, internal actuators can be used in conventional AUVs to take place of control surfaces. For instance, the Fòlaga III (Alvarez et al., 2009) and its latest evolution eFòlaga (Caffaz et al., 2012) are streamlined vehicles driven by a stern jet pumps, but unlike conventional AUVs, Fòlaga vehicles do not have control surfaces. Their maneuverability is achieved by using glider-like actuation for pitch and heave, and using jet pumps at the bow and the stern for yaw. A ballast chamber controls the vehicle buoyancy, while internal displacement of the battery pack is actuated along the surge axis for pitch control. A hybrid AUV was proposed in Li et al. (2008), which uses an internal point mass and a rear thruster to steer in the vertical plane. Its controller for the vertical trajectory tracking is based on backstepping technique. A sliding mode controller was proposed in Zhao and Song (2012) for the moving mass control system to steer an AUV's vertical motion. Aside from an internal mass, stabilizing AUVs motion using internal rotors was investigated based on geometric control theory in Woolsey (2001) and Woolsey and Leonard (2002). The use of control moment gyros (CMGs) as internal actuators for energy storage and three-axis attitude control can be found in Thornton et al. (2007, 2008).

Although internal actuators have been successfully applied to diving control for AUVs and underwater gliders, a comprehensive study on its use for the heading control is rare in the literature. It is a well-known fact that the roll motion of an underwater vehicle can have a great effect on its heading angle. Accordingly, conventional AUVs need to be properly trimmed so that the yaw-roll coupling can be suppressed as much as possible. Besides, a tail-cone was specially designed by Panish (2009), whose stators are angled to counteract the roll torque induced by the propeller. Conversely, roll motion could also be deliberately produced to control the heading angle of an AUV. An internal moving mass can adjust the gravity center of a vehicle, thus generating a roll torque on the vehicle to induce the desired roll angles.

This paper addresses the topic of controlling an AUV's heading angle by taking advantage of its roll-yaw coupling. First, we derive the nonlinear equations of motion of a REMUS AUV with the coupling between the vehicle and an internal moving mass. Subsequently, the effect of the moving mass on the horizontal-plane motion of the vehicle is investigated. Assuming that the fins of the vehicle are fixed, we design a linear feedback law to stabilize its heading angle by controlling the position of the internal moving mass inside the vehicle. Simulation results are presented to demonstrate the effectiveness of the internal actuator design. Furthermore, a control strategy including a tunnel thruster along the sway direction is proposed in order to improve the performance of the internal moving mass. A nonlinear control law is derived based on backstepping technique and Lyapunov redesign to control the displacement of the moving mass and the thrust by the tunnel thruster.

2. AUV dynamics with an internal moving mass

Throughout the paper, we illustrate our results based on the model of a REMUS 100 AUV due to its extensive use in ocean engineering. The main geometries of the AUV are listed in Table 1 (Prestero, 2001).

Table 1
Main geometric parameters of a REMUS 100 AUV.

Parameter	Value	Units	Description
l	1.330	m	Vehicle total length
d	0.191	m	Maximum hull diameter
A_f	0.029	m^2	Hull front area
A_p	0.226	m^2	Hull projected area
S_w	0.709	m^2	Hull wetted surface area
∇	0.032	m^3	Estimated hull volume

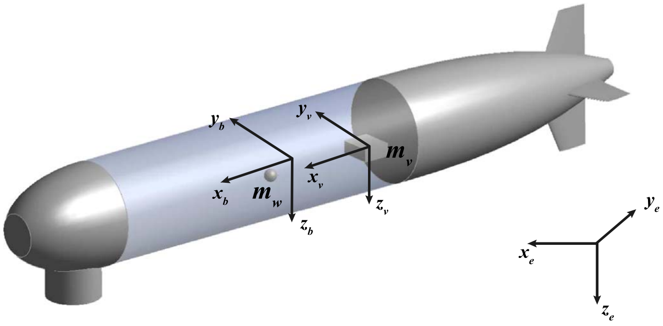

Fig. 1. A REMUS AUV with an internal moving mass.

The kinematics and dynamics of an AUV can be established using an earth-fixed reference frame and a body-fixed reference frame as shown in Fig. 1.

The earth-fixed reference frame is a North-East-Down (NED) coordinate system (Fossen, 2011), and the origin of the body-fixed reference frame is at the center of buoyancy of the vehicle. A local reference frame is fixed to the internal moving mass, whose origin is at the center of gravity (CG) of the mass. The position of the internal moving mass can only be shifted along the y_v-axis. The total mass of the vehicle is given by $m = m_w + m_v$, where m_w and m_v stand for the fixed point mass of the vehicle and the internal moving mass, respectively. Denoting the gravity centers of the vehicle, the fixed mass and the internal moving mass as $\boldsymbol{r}_g = [0, y_g, z_g]^T$ $\boldsymbol{r}_w = [x_w, 0, z_g]^T$ and $\boldsymbol{r}_v = [x_v, y_v, z_g]^T$, respectively, in the body-fixed reference frame, the lateral position of the vehicle's CG is given by

$$y_g = \frac{m_v}{m} y_v \tag{1}$$

2.1. Equations of motion in 3D

In the body-fixed reference frame, the linear and angular velocities of the AUV are denoted as $\boldsymbol{u} = [u, v, w]^T$ and $\boldsymbol{\omega} = [p, q, r]^T$, respectively.

The momenta $(\boldsymbol{p}_v, \boldsymbol{\pi}_v)$ of the internal moving mass are given by:

$$\boldsymbol{p}_v = m_v(\boldsymbol{u} + \dot{\boldsymbol{r}}_v + \boldsymbol{\omega} \times \boldsymbol{r}_v) \tag{2}$$

$$\boldsymbol{\pi}_v = \boldsymbol{r}_v \times \boldsymbol{p}_v + \boldsymbol{I}_v \boldsymbol{\omega} \tag{3}$$

where $\boldsymbol{I}_v$ is the moment of inertia of the moving mass about its local reference frame. The total momenta of the vehicle-fluid system are $\boldsymbol{p} = \boldsymbol{p}_w + \boldsymbol{p}_v$ and $\boldsymbol{\pi}_0 = \boldsymbol{\pi}_w + \boldsymbol{\pi}_v$, where $\boldsymbol{p}_w$ and $\boldsymbol{\pi}_w$ denote the linear and angular momenta of the vehicle-fluid system without the internal moving mass, respectively. The equations of motion of an AUV moving in a calm fluid can thus be written as (Leonard, 1997):