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Study on docking guidance algorithm for hybrid underwater glider in currents

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ABSTRACT

The development of a novel type of hybrid underwater glider (HUG) that combines the advantages of buoyancy-driven underwater glider and propeller-driven autonomous underwater vehicle (AUV) has recently received considerable interest. HUG is designed with a rotatable thruster to ensure the enough maneuverability of the vehicle for underwater docking. Unlike the fixed funnel-type dock, the dock proposed here can rotate actively to allow the vehicle to approach the docking station from most range of directions providing better accessibility for the vehicle. Considering that the ocean current may have a significant impact on the HUG, a pursuit guidance algorithm with current compensation is presented. The performance of the guidance algorithm is compared with other existing guidance algorithms, such as pure pursuit guidance and proportional navigation guidance by simulation based on the dynamic model of HUG. Moreover, underwater docking experiments are conducted to validate the feasibility of the docking system and the effectiveness of the proposed guidance algorithm. The experimental results indicate that the proposed algorithm compensates well for the current disturbances on HUG docking mission and the HUG can dock with the rotatable dock entrance successfully.

1. Introduction

Underwater gliders are highly efficient, winged underwater vehicles that propel themselves by modulating their buoyancy and attitude (Mahmoudian and Woolsey, 2008). These gliders are widely used in oceanographic research because of their low cost, long range, and high endurance. However, the low-speed capability presents with significant problems when operating in areas with strong water currents that exceed the glider's maximum forward speed (Claus et al., 2010). Moreover, gliders have limited applications because they do not have horizontal flight capabilities. By contrast, conventional propeller-driven autonomous underwater vehicles (AUVs) have high maneuverability, but their endurance time usually ranges from hours to days, which is much less than underwater gliders.

A novel type of hybrid underwater glider (HUG) that combines the advantages and features of gliders and AUVs is proposed (Bachmayer et al., 2004; Jenkins et al., 2003). Several types of HUG have already been developed in previous studies. Alvarez et al. (2009) and Caffaz et al. (2010) fabricated a HUG called Folaga. Claus et al. (2010) developed a low-power, propeller-based propulsion module to augment the buoyancy engine of a 200 m Slocum electric glider. Wang et al. (2010, 2011) developed a HUG called PETREL. Isa and Arshad (2013) and Isa et al. (2014) presented a mathematical model and analysis of the motion control for a USM (Universiti Sains Malaysia) hybrid-driven underwater glider, which has independently controllable wings and a rudder. A concept of a gliding robotic fish that combines gliding and fin-actuation mechanisms has also been presented (Feitian et al., 2014; Tan, 2011; Zhang et al., 2012). However, few studies have considered a HUG with docking capability. If a HUG can dock with an underwater station with enough maneuverability for battery recharging and data communication, vehicle endurance can be enhanced a lot. We can then expand glider applications, for example, oceanographic scientists who aim to monitor long-term change of the ocean, can benefit from the long-term deployment of HUGs instead of recovering the vehicles and replacing the batteries after each mission. Furthermore, if the docking station is connected to a cabled ocean observatory (Chen et al., 2012a, 2012b, 2013), the HUGs can be considered as additional mobile

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nodes for three-dimensional ocean observation. Considering the benefits described above, Zhejiang University is developing a HUG for underwater docking (Peng et al., 2014). In this paper, a small-scaled hybrid underwater glider called Mini-HUG, is developed for the validation of docking scheme and guidance algorithm, considering its convenience for deployment and operation. For a vehicle to perform underwater docking, horizontal flight capability and high maneuverability are obviously necessary, which are two important features of the vehicle to realize underwater docking. Typically, underwater gliders are driven by a buoyancy engine and do not have horizontal flight capability to perform underwater docking. Moreover, the low maneuverability of underwater gliders also adds the challenge for potential docking. Therefore, for underwater gliders, docking is a more difficult and possibly different problem. In our case, by the concept of ‘hybrid’, the HUG has horizontal flight capability. However, given the low speed of our HUG, a key technical challenge in vehicle design is how to obtain high maneuverability at low speeds for underwater docking (Peng et al., 2013). As conventional AUVs use control fins to control the yaw and pitch, and their steering capability is strongly coupled with their velocities, they have to reach a minimum speed to maintain control authority and counteract the positive buoyancy (Morel, 2002; Woolsey, 2005). Although the minimum speed may differ depending on vehicle configuration, Thivierge et al. (2005) showed that most control fins are effective as long as the vehicle's velocity is 1 m/s (two knots) or faster. Given that the speed of our glider is low, the traditional fin-steering method is unsuitable for our case. We thus attempt to design a HUG whose yaw is controlled by the rotation of the thruster and whose pitch is controlled by a longitudinal moving mass.

In terms of the dock, there are two most common dock designs for flying vehicles: one is a pole type (Singh et al., 2001); another is a funnel type (Allen et al., 2006; McEwen et al., 2008; Park et al., 2009). As we will discuss latter, each type has its own pros and cons. To integrate the advantages of both types, this paper introduces a rotatable funnel-shaped dock, which can rotate around its vertical axis actively. The dock proposed here can rotate actively to allow the vehicle to approach the docking station from most range of directions providing better accessibility for the vehicle, thus reducing the complexity of the docking algorithm.

With regard to the underwater docking, the docking guidance algorithms are of vital importance. McEwen et al. (2008) presented a cross-track-error based docking control algorithm for a unidirectional docking system. Park et al. (2009) introduced a vision-guidance docking algorithm with PID controllers for the vertical and horizontal plane. Kim (2007) derived a linear terminal guidance (LTG) controller in the framework of optimal control for AUV docking. Because the LTG controller does not consider the effect of ocean currents, a modified LTG is addressed by Park et al. (2011a, 2011b) for unidirectional docking compensating the effect of currents. Teo et al. (2012, 2015) gave a fuzzy docking guidance that can handle unknown currents. However, few studies have been conducted on the docking algorithms of funnel-shaped rotatable docking system. This paper aims to develop a docking guidance algorithm for the rotatable docking system; the effect of ocean currents is also taken into consideration.

The paper is organized as follows. Section 2 presents the details of the docking system developed by Zhejiang University. A novel type of HUG with a rotatable thruster is first proposed. Since HUG is an underactuated vehicle, an underwater station with a rotatable dock entrance is designed to assist the vehicle for docking. In Section 3, the dynamic model of HUG is derived briefly, which is the basis of numerical simulation for motion prediction and algorithm validation. Considering that the ocean current may have a significant impact on the motion of HUG, a pursuit guidance algorithm with current compensation is proposed in Section 4, whose performance is compared with the existing guidance algorithm by simulation. Section 5 gives the results of underwater docking experiments which are conducted to validate the feasibility of the docking system and the effectiveness of the proposed guidance algorithm. Section 6 summarizes the main contributions and describes some additional avenues for continuing research.

2. Docking system

For long-term sustainability, an AUV or HUG should be able to autonomously perform its mission and dock at a deployed underwater docking station for data downloads, battery recharging, and new mission script upload for the next mission operation. According to the functions of the docking system, it can be divided into three main parts: the autonomous vehicle, which is a HUG in our case; the mechanical system of a docking station with navigation and guidance accessories, such as the acoustic transducer and the light source, and so on; and the power and data transmission system. More details on our docking system are presented as follows.

2.1. Hybrid underwater glider

A small-scaled hybrid underwater glider called Mini-HUG, is developed for the validation of the docking scheme and guidance algorithm, motivated by its convenience for deployment and operation. The main specifications of Mini-HUG are shown in Table 1. For a vehicle to perform underwater docking, horizontal flight capability and high maneuverability are obviously necessary, which are two important features of the vehicle to realize underwater docking. Given the low speed of our HUG, a key technical challenge in vehicle design is how to obtain high maneuverability at low speeds for underwater docking. Due to this, a rotatable thruster and a longitudinal moving mass are adopted to control the yaw and the pitch movements, respectively.

2.1.1. Mini-HUG design overview

As shown in Fig. 1, Mini-HUG can be divided into four sections: Bow Section, Main Section, Electronic Section, and Thruster Section. Specifically, the Bow Section is a flood section, which holds a camera and the flooding part of the ballast system. The Main Section contains the attitude control system and the sealed part of the ballast system. The attitude control system regulates the pitch angles of the vehicle by moving an internal mass. The ballast system changes the net weight of the vehicle by pumping water inside or outside the vehicle. The Main Section also contains the control and signal processing boards, the navigation devices as well as the battery. The GPS and communication terminals together with the antennas are all fixed in the Electronic Section. In the Thruster Section, there is a thruster which can rotate around

Table 1
Main specifications of Mini-HUG.

Feature	Description
Length	1 m
Diameter	130 mm
Weight in air	7.85 kg
Operating depth	$0 \sim 10$ m
Deflection angle of thruster	$\pm 45^\circ$
Ballast system	Piston-cylinder
Communications	Radio
Sensors	TCM5, depth sensor, camera, GPS receiver
Battery	Lithium battery
Operating in glider mode	0.2–0.4 m/s
Operating in AUV mode	0.2–0.6 m/s