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QUUV: A quadrotor-like unmanned underwater vehicle with thrusts configured as X shape☆

Jingwei Bian, Ji Xiang*

National Laboratory of Industrial Control Technology, and College of Electrical Engineering, Zhejiang University, Hangzhou, China

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ABSTRACT

A quadrotor-like unmanned underwater vehicle (QUUV) is presented in this paper. The four fixed thrusters are configured as *X* shape through which the QUUV has vertical and horizontal movements decoupled. Its mathematical model and motion analysis are introduced accordingly. The differences with conventional underwater vehicles are also discussed to show its merits. Sliding mode control is adopted to design its controller. Various motions with the sliding mode controller are simulated, followed by an experiment test in a small pool.

1. Introduction

Nowadays, unmanned underwater vehicles have been an valuable tool for underwater exploration and operation with the growing importance of the ocean. It is an effective instrument to replace human beings in the unknown and hazardous underwater environment. In past decades many kinds of unmanned underwater vehicles (UUVs) have been designed and implemented for various applications, such as coastal oceanography [1], underwater cable examination [2], underwater archaeology [3].

There are mainly two kinds of shape configuration for UUV. One is open structure shape. Almost all remotely operated vehicles (ROV) adopt this shape configuration. The underwater vehicles with open structure are often cuboid shape. It has the advantage of large load capacity and can stay in the water for a long period with an umbilical cable to carry power from the mother-ship. The JASON ROV developed at the Woods Hole Oceanographic Institution can perform scientific tasks on the seafloor to depths of 6000 m [4]. The deep ROV Dolphin-3K is used to study colonies of giant clams, tube worms and geology of steep cliffs studies, which was manufactured by Japan Marine Science and Technology Center [5]. One disadvantage of these ROV is that its maneuverability and hydrodynamic property are not good because of its umbilical cable and cuboid shape.

The other is torpedo-like shape, which is common for autonomous underwater vehicles (AUV). It often has only a thruster at the tail and turns with the help of rudders or fins. In [6] a generation of autonomous underwater vehicle, named REMUS, is presented by the Woods Hole Oceanographic Institution; it has developed multiple series for different depth. In [7], a small AUV named ISiMI is designed to cruise the ocean engineering basin by The Korea Ocean Research and Development Institute. REMUS and ISiMI both have torpedo-like shape and have only a thruster with rudders or fins. They have to move in the horizontal direction when moving in the vertical direction, which make their motion performance not good.

There have been some multi-thruster unmanned underwater vehicles considering merits and weakness mentioned above. An advanced underwater vehicle is presented in [8,9] and adopts nearly spherical shape with eight thrusters, named omni-Directional Intelligent Navigator (ODIN). Its maneuverability and hydrodynamic property is better. In [10] thruster configurations are discussed and a better thruster configuration with six thrusters is proposed in theory. These multi-thruster underwater vehicles often have six to eight thrusters, which are relatively redundant for common motion, such as heave motion, surge motion and cruise motion. So far there are about more than 100 prototypes in the laboratories all over the world as mentioned in [11]. More kinds of underwater vehicles can refer to [12,13] and other literature.

Recently some reports about submersible unmanned aerial vehicles (UAV) have been made, which are apparently different from UUVs mentioned above. Their motivation is to offer a new kind of underwater vehicle with better performance based on UAV technology. There are two kinds of submersible UAV: submersible fixed-wing UAV and quadrotor UAV [14,15]. In [16] a submersible unmanned aerial vehicle (UAV) with fixed-wings is proposed, and its impact force with water is

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* Corresponding author.
E-mail address: jxiang@zju.edu.cn (J. Xiang).

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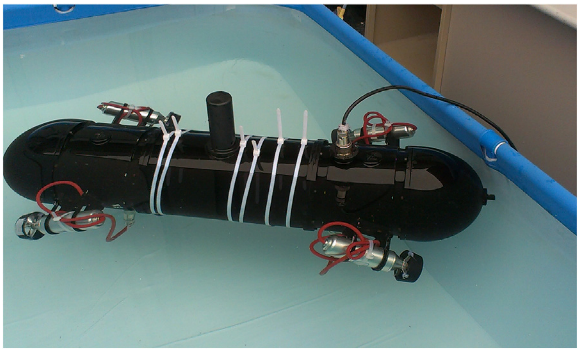

Fig. 1. The QUUV prototype.

calculated by the method of the computational fluid dynamics (CFD). In [17] a particular submersible fixed-wing UAV has been investigated and studied in detail. In addition, quadrotor UAV has become a commercial UAV because of its simple structure and flexible movement. Some researchers have studied quadrotor UAV applied in the water. In [18] a submersible quadrotor-like unmanned aerial underwater vehicle is proposed, and its kinematic and dynamic models are presented. In [19] an underwater vehicle with a quadrotor configuration is designed, and its controllers are simulated. They adopt directly thrusters configuration of the quadrotor UAV, which are upright. Their works neglect the difference between air motion and underwater motion. Thrusters configuration should be redesigned to fit with underwater situation.

This paper, as an extension of conference version [20], formally proposes a quadrotor-like unmanned underwater vehicle (QUUV). As shown in Fig. 1 the significant improvement is that four thrusters of the QUUV are inclined in this paper, which are distributed at two sides of the hull with a constant angle to form a so-called *X* shape. Moreover, controllers are designed directly to the thrust force. In comparison with underwater vehicles mentioned above, the QUUV has its special characteristics as below:

- Its motion performance is better than torpedo-like AUV. It can hover in a position and move in the vertical direction and horizontal direction independently, which cannot be achieved by torpedo-like AUV. In addition, it can yaw in a position. These good benefits attribute to the four inclined thrusters, which will be described in details in next section. Its maneuverability is better than torpedo-like AUVs because of four thrusters offering more degree of freedom for control.
- Its maneuverability and hydrodynamic property are better than conventional ROVs. In comparison with ROVs with open structure, the QUUV have a streamline shape and need not tether to the mother-ship, which make the QUUV have better maneuverability and hydrodynamic property. In addition, the QUUV with four thrusters can achieve the same flexible motion as conventional ROVs.
- Its design fits with in underwater application well. In the air, the thrusters are mainly used to overcome the gravity for the quadrotor UAV. However, the gravity of the vehicles is equal to or slightly less than the buoyancy in the water. The thrusters need to be mainly used to overcome surge resistance in the water because of large water density. The X shape of the QUUV makes the power of thrusts mainly against surge resistance.

To sum up, the QUUV avoids some aforementioned shortcomings of conventional underwater vehicles and has some advantages on maneuverability and adaptability to underwater motion. Compared to multi-thruster underwater vehicles designs, such as those in [8–10], the QUUV can achieve flexible motion with fewer thrusters, which is shown by space motion in Section 6. The QUUV is a better design considering maneuverability, hydrodynamic property and other qualities in comparison with conventional underwater vehicles.

The paper is organized as follows. Section 2 describes the design and *X* shape of the QUUV. In Section 3 the mathematical model of the QUUV is established, and some differences with conventional unmanned underwater vehicles are disclosed. The motion analysis is discussed in Section 4. The sliding mode controller design is introduced in Section 5, and various motion simulation results based on sliding mode are shown in Section 6. An experiment test is carried out based on a simple path planning in Section 7. Finally, a conclusion is drawn in Section 8.

2. System design of the QUUV

2.1. Overview of the QUUV

The QUUV addressed in this paper has a prototype shown in Fig. 1. It is composed of mechanical body, control system, communication system and power system. The mechanical body contains hull structure and four thrusters as *X* shape. The control system contains digital signal processor, sensors and other related electronic equipment. The communication system includes radio communication and acoustic communication. The power system adopts lithium battery. Table 1 shows the overall design parameters and its specification.

The control system is the most important part of the prototype. The digital signal processor is adopted in this prototype. The attitude and heading reference system (AHRS) provides information of the 3-axis angular velocities, 3-axis accelerations and 3-axis magnetic intensity to the digital signal processor. The AHRS is composed of a six-axis (gyro& accelerometer) MEMS device, a three-axis magnetometer and an ARM micro-controller. The depth information is gathered by the pressure sensor. The thrusters adopt brushless motors that are controlled by electronic speed controllers connecting with the digital signal processor. The thruster is powered by 12 V. Its maximum speed and thrust are 14,000 rpm and 4 kg, respectively.

The QUUV has two ways to communicate with the computer on land or on board. A wireless radio antenna is installed at the top of the hull, and an underwater acoustic transducer is installed at the front end of the hull. When the QUUV is on the water surface radio communication is applied. When the QUUV is underwater, acoustic communication is used because radio communication will encounter severe attenuation problems.

The lithium battery supplies all the system with power, which is arranged at the bottom of the prototype so that the center of gravity is below the center of buoyancy.

2.2. X shape

The hull size of the QUUV is constrained by the space for the instruments, and the hull shape is constrained by the hydrodynamic characteristics. The hull shape of the QUUV is designed based on the Myring hull profile equations which are known for minimizing the drag force [21]. What's more, as shown in Fig. 2, there are four thrusters symmetrically distributed at two sides of the hull. There is an angle β ($0^\circ < \beta < 90^\circ$) representing the angle between the hull and the thruster as depicted in Fig. 2, named as thruster angle. The thrusters at the right side cross the thrusters at the left side to form *X* shape, as depicted by blue line in Fig. 2. It is stated that the angle β is fixed when

Table 1
Design parameters and specifications.

Mass in air	45 kg
Total volume	45.2 dm^3
Total length	1.2 m
Diameter	25 cm
Design velocity	2 m/s