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A Heterogeneous Glider System with Underwater Acoustic Communication and Positioning

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ABSTRACT

Autonomous underwater vehicles are increasingly frequently used in the fields of ocean observation, data collection, and tactical surveillance. Underwater navigation and near real-time communication are the most important factors limiting the performance of these vehicles. In this article, an underwater acoustic communication and positioning system (UACPS) based on heterogeneous gliders is presented. The system consists of an acoustic wave glider and an acoustic underwater glider, and includes an ultrashort baseline and an acoustic modem. The program and communication protocol of the communication and positioning algorithm are independently developed, and the hardware circuit design of the communication and ultra-short baseline positioning, as well as the embedded surface wave gliders and gliders are independently implemented. Sea trial results indicate that the communication distance of the system is more than 3 km and the positioning error is less than 5%. With the further improvement of system performance, the low cost, long time, long distance and near real-time communication characteristics of our UACPS can be used to integrate multiple autonomous unmanned platforms as part of intelligent surveillance robot networks.

Keywords: acoustic wave glider (AWG), acoustic underwater glider (AUG), heterogeneous, communication and positioning

INTRODUCTION

Over the last decade, there has been significant interest in the acquisition of marine environmental data due to an increasing interest in marine resources. Numerous ocean observation networks have therefore been established based on underwater unmanned platforms for data collection, disaster monitoring, navigation and even battlefield monitoring [1-3]. These systems can record underwater data for long periods, and can transmit the collected information to a data processing centre [4,5]. However, although they are stable, they are not flexible and cannot be used for mobile observation, nor do they have navigation and positioning functions [6].

Research based on underwater unmanned platforms (such as underwater gliders and surface wave gliders) has been intensifying [7,8]. The use of autonomous underwater vehicles (AUVs) with sensors makes it possible to detect resources and collect data during collaborative missions [9-11]. As part of the Seaweb project of the US Naval Research Institute, remote sonar modems have been successfully integrated into the Slocum underwater glider to enable underwater navigation, positioning, and tracking of submarines [12]. Bingham et al. [13] used wave gliders equipped with active and passive acoustic detection and positioning equipment to observe and track the marine environment, marine life, and underwater vehicles. Chen and Pompili [14] established mutual communication and coordination among multiple underwater autonomous vehicle clusters by deploying a low-power small underwater acoustic modem developed at the Woods Hole Institute of Oceanography. Lan et al. [15] proposed an acoustic positioning algorithm for multiple wave glider nodes in which wave gliders were used as nodes for underwater IoT observation. The feasibility of using wave gliders for acoustic observation was verified through simulation and sea experiments.

A heterogeneous glider communication system effectively exploits the advantages of both underwater and surface wave gliders while using underwater acoustic communication and positioning technology [16,17]. This integration has led to the construction of a three-dimensional mobile observation and detection system that can operate underwater and above water [18,19], acting as a cross-media information transmission link that spans the underwater, surface, space-based, and short-range fields. This innovative method solves the limitations of previous single glider systems and greatly expands the detection range. In addition, the system successfully overcomes the shortcomings of traditional underwater gliders, such as poor real-time performance and inflexible communication information capabilities [20]. It is characterised by strong concealment, low energy consumption, and a high level of controllability, and can be deployed for long periods over vast sea areas, allowing it to play an important role in marine environmental monitoring, seabed detection, and covert detection.

This paper focuses on the development of a heterogeneous communication and positioning system in which an acoustic wave glider (AWG) is used as an information transmission relay. This AWG is tasked in formation with one or more acoustic underwater gliders (AUGs). Our architecture is stable, and can be used to build a three-dimensional mobile observation and detection system in the deep sea. The system can ensure near-real-time transmission of environmental data, position acquisition and navigation control of the AUGs. Firstly, the hardware systems including surface wave gliders and underwater gliders are introduced. Then two main software structures are introduced from communication system and location algorithm. In addition, the data transmission protocol and transmission process of the whole link are introduced. Finally, the effectiveness and stability of the algorithm are verified by sea experiments.

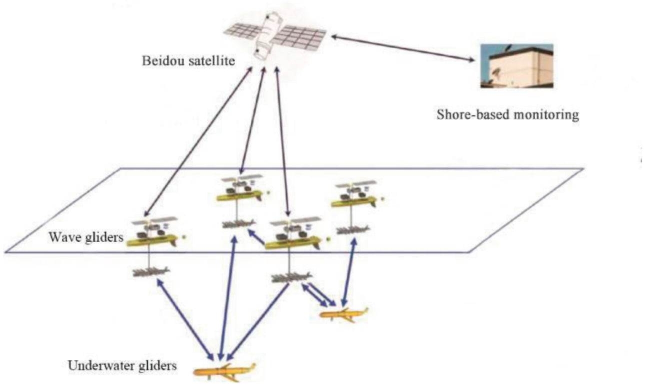

Fig. 1. Proposed heterogeneous glider system.

SYSTEM ARCHITECTURE

Underwater navigation has been one of the most intensely researched topics in recent years, and although many methods and configurations have emerged, a combination of an ultra-short baseline (USBL) with an AWG has shown particular promise for small mobile platforms in the deep ocean. An AWG is a new type of marine equipment, and its most important feature is that it can rely on the wave energy of the ocean to provide power, thus providing long-term endurance.

SURFACE WAVE GLIDER SYSTEM

The AWG considered in this paper was provided by the Ocean University of China, and consisted of three parts: a surface mother ship, an underwater tractor and a flexible armoured cable. The surface mother ship, with dimensions of 2.6×0.6×0.3 m, was constructed from ethylene-vinyl acetate (EVA) float material, to ensure buoyancy with a minimum of mass. Four solar panels were installed on the surface to supply energy to the system, providing a total output power of 200 W. The flexible communication cable was mainly composed of multi-core armoured cable and universal joints, was 7 m long, and could take a load of 1 ton. The dimensions of the underwater tractor were 1.92×1.1× 0.35 m. It was mainly driven by wave energy, and the maximum driving speed was greater than 0.5 m/s.

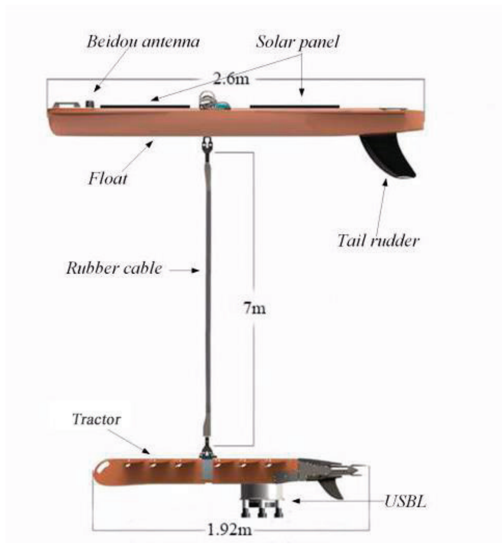

Fig. 2. Proposed acoustic wave glider system.

We designed an USBL to be fixed under the tractor, with a size of Ø170×133 mm, consisting of one transducer and four hydrophones with a cross-array structure. Test results indicated that the maximum source level of the transducer was 190 dB, with optimal frequencies ranging from 9 to 15 kHz, and the sensitivity of the hydrophone was –185 dB (0 dB @ 1 V/μPa). Several methods were applied to reduce the error, such as mounting an attitude sensor, optimising the installation process and using a precision structural design.

UNDERWATER ACOUSTIC GLIDER SYSTEM

An AUG is a type of energy-efficient propeller-less AUV that can operate over months, as it uses battery-powered hydraulic pumps to change the buoyancy, which can power forward gliding along a sawtooth trajectory. The AUG used in this paper is a cylinder 2.6 m long and 0.23 m in diameter, provided by Tianjin University, with a speed of 2 knots and a maximum depth of more than 1 km. It is a very mature platform, and is equipped with an acoustic modem that operates in the range 9–15 kHz, with a maximum nominal range of 10 km, and speed of 200 bps, which is used for transmitting data to and from the AWG.

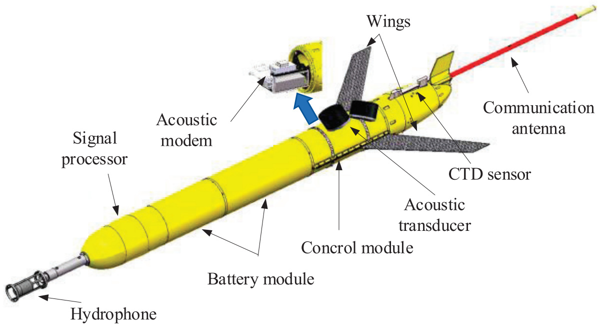

Fig. 3. Proposed acoustic underwater glider system.

SOFTWARE DESIGN

In order to ensure that the energy radiation angle of the transducer does not fluctuate greatly after a change in the attitude of the underwater glider, a dual transducer design is adopted in which the two transducers are tilted at a certain angle to the vertical line of gravity. By controlling the heading angle, one transducer can be set to a vertical upward state during the diving process of the floating cargo, thus achieving optimal energy radiation.

COMMUNICATION SYSTEM

Multi-frequency shift keying (MFSK) provides a compatible solution with both stability and reliable quality, and can effectively overcome the issues associated with multipath mobile platforms, which are susceptible to Doppler shift and require a high signal-to-noise ratio (SNR) for reception. The use of cyclic prefixes to reduce inter-code interference can successfully maintain a regionally acceptable communication rate without affecting stability, making this a particularly suitable choice for communication between heterogeneous gliders.

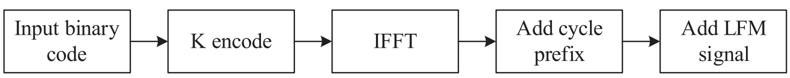

Fig. 4. Flow chart for MFSK modulation

The MFSK modulation mode is shown in Fig. 4. Unlike traditional MFSK modulation, our communication system includes synchronisation sequences and protection intervals at both the front-end and back-end of the communication data. In this system, the selected synchronous signal is a linear frequency modulation (LFM) signal, which exhibits good autocorrelation characteristics and is not sensitive to Doppler effects. Both the descending and the ascending LFM serve as synchronisation heads before the data frame, and a further ascending LFM is added after the data frame as the signal as the signal for ultra short baseline positioning.

LOCATION MODEL AND ALGORITHM

The three-dimensional five-element array proposed in this article is shown in Fig. 5. Sensor element S1 is located at the origin of the coordinator, while the other four elements are at positions S2 to S5, respectively. The spherical coordinates of the underwater target T are (R, θ, φ), where R is the distance between the target and the origin of coordinates, θ is the elevation angle, and φ is the horizontal azimuth angle.

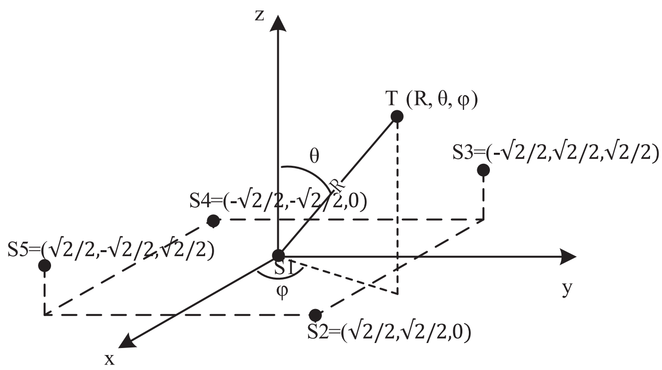

Fig. 5. Stereoscopic five-element matrix for the USBL

Using S1 as a reference element, we see that the difference in the sound path between the signals propagating to *Si* and *S1* is d_{i1} $(2 \le i \le 5)$, with a delay of τ_{i1}, where the sound velocity in seawater is *c*. The distance between the target and the coordinate origin is much greater than the distances between the array components, meaning that the signal can be regarded as far-field plane wave propagation with a sound path difference of d_{i1} :

$$d_{21} = -\frac{\sqrt{2}}{2} d \sin\theta \cos\varphi - \frac{\sqrt{2}}{2} d \sin\theta \sin\varphi \tag{1}$$

$$d_{31} = \frac{\sqrt{2}}{2} d \sin\theta \cos\varphi - \frac{\sqrt{2}}{2} d \sin\theta \sin\varphi - \frac{\sqrt{2}}{2} d \cos\theta \tag{2}$$

$$d_{41} = \frac{\sqrt{2}}{2} d \sin\theta \cos\varphi + \frac{\sqrt{2}}{2} d \sin\theta \sin\varphi \tag{3}$$

$$d_{51} = -\frac{\sqrt{2}}{2} d \sin\theta \cos\varphi + \frac{\sqrt{2}}{2} d \sin\theta \sin\varphi - \frac{\sqrt{2}}{2} d \cos\theta \tag{4}$$

In Eqs. (1)–(4), the azimuth and pitch angle are as follows:

$$\varphi = \arctan\left(\frac{d_{41}-d_{21}+d_{51}-d_{31}}{d_{41}-d_{21}+d_{31}-d_{51}}\right) \quad (5)$$

$$\theta = \frac{\sqrt{(d_{41}-d_{21}+d_{51}-d_{31})^2+(d_{41}-d_{21}+d_{31}-d_{51})^2}}{2(d_{41}+d_{21}-d_{51}-d_{31})} \quad (6)$$

The USBL positioning system uses a responder to send infrared signals to the transducer array of underwater targets. After receiving the signal, the responder responds to the positioning signal. The transducer array measures the phase difference or delay difference between the array components to determine the target orientation, and measures the round-trip time between the query signal and the positioning signal to determine the distance between the measured target and the transducer array, thereby completing underwater target positioning.

DATA FLOW

The architecture of the UACPS is shown in Fig. 6. We design two communication modes, called uplink and downlink communication, which can perform data transmission and navigation control of the underwater gliders. In the first scenario (i.e. passive data transmission), the AUG returns data according to the task settings, and the data are sent from the AUG to the acoustic modem through a serial port. In the second scenario (i.e. active transmission of data and instructions), real-time data transmission and instruction control can be carried out as needed, achieving reverse data flow from the shore-based monitoring centre to the AUG. Both modes can be used for control over the transmission of instructions and status information. The system completes the information exchange across media, thus laying the foundation for the formation network control of an unmanned platform.

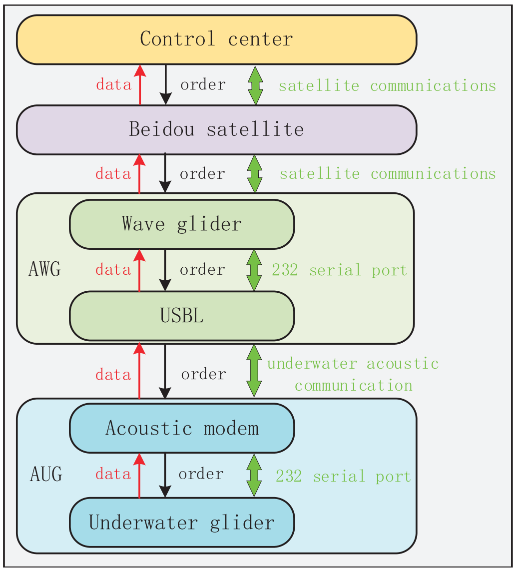

Fig. 6. Architecture of the heterogeneous glider for control and communication

SEA TRIAL EXPERIMENTS

TRIAL DESCRIPTION

Tests of our unmanned platform communication positioning system based on a heterogeneous architecture were conducted in the South China Sea during May of 2021. The average depth of the test area was greater than 1300 m, and the sea conditions were good during the test. The overall test process was divided into two stages. In the first stage, a performance verification test was carried out using an AWG system and a subsurface buoy system composed of five acoustic modems. In the second stage, an AWG and an AUG system were used to complete the collaborative communication positioning test.

Fig. 7. Sea trial area

STATIC TRIAL

Fig. 7 illustrates the location in which tests of positioning and communication from the surface mobile platform to the underwater fixed platform were carried out. The AWG navigated freely on the water surface, and the communication nodes were fixed at different depths (100, 300, 500, 800, and 1200 m) by anchor chains. The aim of this experiment was to obtain the real location of the communication node via multiple measurements using the three-point positioning method.

In practice, only nodes at a depth of 500 m were precisely located. With the passage of time, due to the influence of waves and ocean currents, each depth node undergoes a deviation in the horizontal direction, which one of the reasons for this error. The results in Fig. 8 show that the overall positioning error was less than 5% of the slope distance, meaning that our scheme can essentially meet the application requirements.

The bit error rate (BER) values measured at different depths in the experiment are shown in Table 1. At each depth, the transmitted 20 frames. All frames are decoded correctly, with a BER of zero.

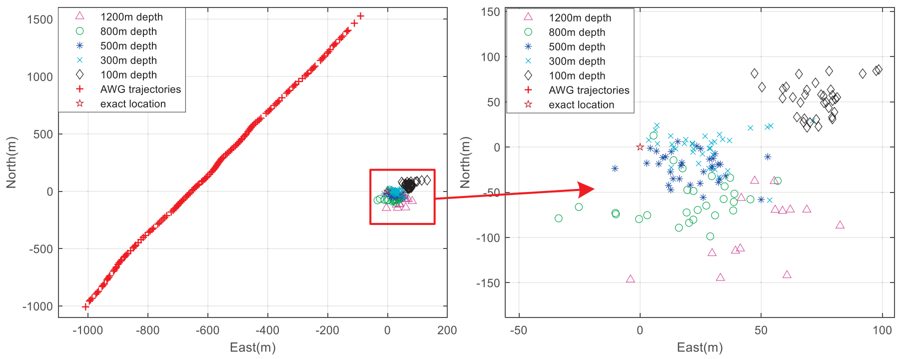

Fig. 8 Results for the communication and positioning performance of the proposed system

Table 1. BER measurements at different depths

Depth/m	Emitted frame times	Received frame times	BER
100	20	20	0%
300	20	20	0%
500	20	20	0%
800	20	20	0%
1200	20	20	0%

SOUTH CHINA SEA COLLABORATIVE TRIAL

In the second phase, the AUG and AWG were run according to preset parameters. The AUG had a maximum glide depth of 1000 m in water, and the positions of the exit and entry points were obtained through satellite positioning. During its underwater glide, the AWG sent instructions to the AUG to get its position coordinates.

In the communication process, the speed was 200 bps, and the modulation method was MFSK. The communication systems is based on a three-times response mode, which has high stability. The AUG accurately transmitted command signals and parameters (its position and depth in water) to the shore base, and the instructions (headings, surfacing or diving down) sent by the shore base could also be transmitted to the AUG via the AWG.

Fig. 9 shows the AWG tracking results for the AUG. According to the position of AUG on the water surface and the trajectory trend, the positioning results can be considered reliable. There is a delay in the communication to the AUG on the surface of the water, which will lead to a certain deviation in the position. The two types of gliders work well together. The maximum synergistic radius is over 3 km, and the AWG can communicate with and locate the AUG at any time within the operating distance. The performance of the system has enhanced space. In the future according to needs, AUG can be continuously operated underwater without exposing the surface, which would greatly improve the efficiency of the system.

CONCLUSION

In this paper, an UACPS based on unmanned platforms is designed to promote the exchange of information between these platforms. The problems of real-time data transmission of underwater mobile nodes and the observation of cooperative formation control are effectively solved, and the feasibility of the system is verified by tests in the South China Sea. The results show that the proposed system is suitable for long-term ocean observation. The next step is to change the modulation mode of the signal and improve the communication rate of

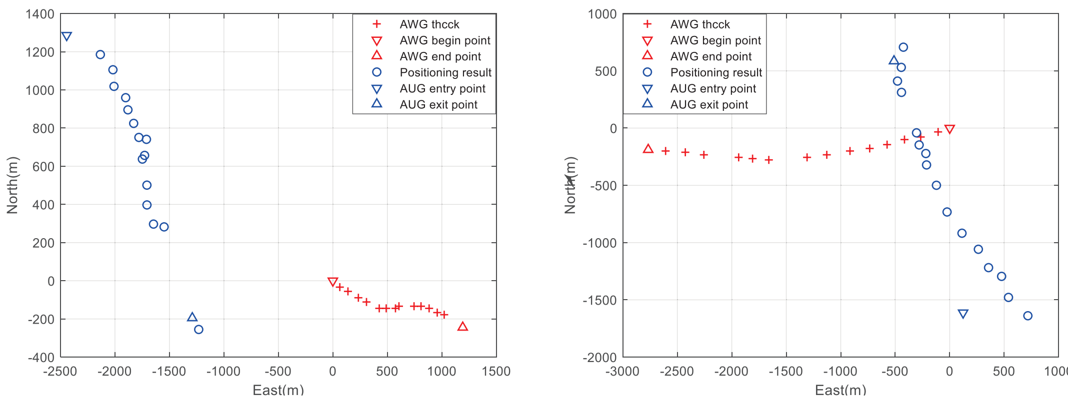

Fig. 9. Actual motion trajectories for the AUG and AWG (profiles for two voyages)

the signal. In terms of positioning, the positioning error of array hardware equipment is reduced and the positioning accuracy is improved.

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