A low-cost testbed of underwater mobile sensing network

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***Abstract*—Comprised by a swarm of acoustically linked and cooperative autonomous underwater vehicles (AUV's) with onboard sensors, an underwater mobile sensing network (UMSN) will be a complementary means to fixed observatory networks e.g. seafloor observatory networks and moored buoy arrays. It has obvious advantages over single large AUV in higher efficiency due to parallel observation, stronger robustness to vehicle failures and lower cost. Although an UMSN can be viewed as a counterpart of wireless mobile sensing networks for air and terrestrial applications, it is much more challenging due to poor performance of underwater acoustic communication, poor performance of underwater positioning and high degree of uncertainty in vehicle dynamics and underwater environment. In order to verify key technologies involved in an UMSN, e.g. cooperation of multi-AUV based on acoustic communication, a low cost testbed has been developed for experimental study. The design of both hardware and software is introduced in this paper. Also the results of functional test for verification of the effectiveness of the testbed are presented.**

Keywords-underwater mobile sensing network (UMSN); autonomous underwater vehicle (AUV); testbed; coordination and cooperation control

I. INTRODUCTION

In the near future, an underwater mobile sensing network (UMSN) will be a new tool for fast ocean exploration, for example, it can be used as a complementary means to fixed observatory networks e.g. seafloor observatory networks and moored buoy arrays in the Ocean Observatories Initiative (OOI)[1,2]. An UMSN is composed of a swarm of acoustically linked autonomous underwater vehicles (AUV's). By equipping AUV's with specific sensors, an UMSN can conduct mobile sensing missions. It has obvious advantages over single large AUV in higher efficiency due to parallel observation, higher accuracy due to redundant measurement, stronger robustness to vehicle failures and lower cost as well.

Although an UMSN can be viewed as a counterpart of wireless mobile sensing networks for air and terrestrial applications, it is much more complicated due to poor performance of underwater communication [3], poor performance of underwater positioning and high degree of uncertainty in vehicle dynamics and underwater environment. In our opinion, cooperation of multiple AUV's based upon acoustic communication is a key technology for an UMSN to achieve a self-organized mobile sensing. Although some studies on coordination and cooperation control (CCC) of multiple AUV's, e.g. coverage control and formation control[4-9], have been reported in the literature, few have been verified via field tests[10]. The main reason for this lies in high cost of construction of a real UMSN.

The construction of a low cost testbed for experimental study of UMSN's is introduced in this paper. The remainder of the paper is organized as follows. An overview of the testbed is introduced in Section 2. The design of both hardware and software is introduced in Section 3. And functional tests are presented in Section 4, and finally a summary is given in Section 5.

II. AN OVERVIEW OF THE TESTBED

As illustrated in Fig.1, the testbed comprises a surface (laptop) computer, three AUV's and a RF modem-based communication system to mimic underwater acoustic communication. It will be seen that this testbed can verify the coordination and cooperation control of a two dimensional UMSN.

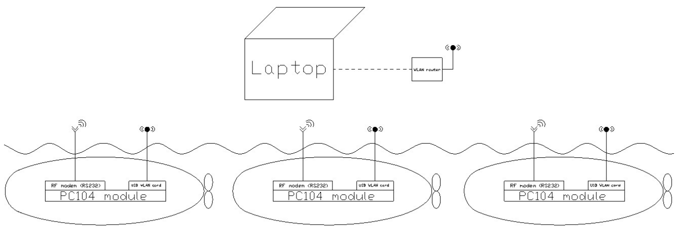

Fig.1 Architecture of the testbed

A. Surface computer and remote control

Similar to remote control of a single AUV, the inclusion of a surface computer in a UMSN is also essential during its deployment and recovery phases when each AUV needs to be controlled independently by a human operator. Moreover, it is also a preferable means for data exchange between the surface computer and the AUV's, i.e. download of mission parameter prior to missions and upload of collected data after missions.

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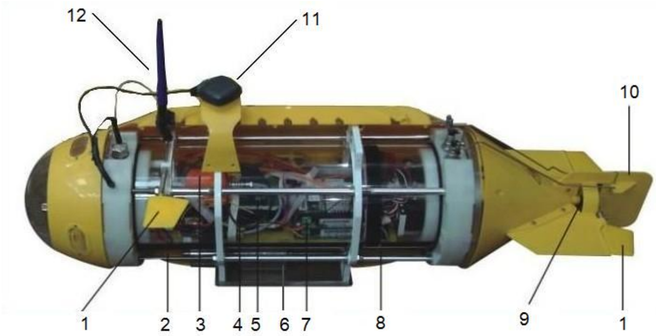
The surface computer provides a graphical user interface (GUI) for a human operator to remotely control the AUV's via wireless local area network (WLAN) within which each AUV is allocated an independent and fixed IP address.

Both open loop and closed loop control are enabled. While the maneuvering commands e.g. propeller speed and rudder deflection are sent to individual AUV's under open loop mode, the motion demands e.g. forward speed and heading are sent to individual AUV's under closed loop mode. The closed mode depends on the feedback information from sensors onboard AUV's.

B. Low-cost AUV

As shown in Fig. 2, the AUV is developed by reconstructing a radio controlled toy submarine NEPTUNE SB-1, which is produced by Thunder Tiger. Its specific parameters are listed in Table I.



1-Stern-plane; 2-12V Li battery; 3-IMU/GPS; 4-RF modem; 5-Digital compass; 6-Ballast blocks; 7-PC104 module; 8-Depth sensor and WLAN card; 9-Propulsion motor and screw propeller; 10-Rudder; 11-GPS antenna; 12-RF modem antenna;

Fig.2 A picture of the AUV

TABLE I. AUV'S SPECIFIC PARAMETERS

Overall length	774 mm
Beam	290 mm
Height	285 mm
Draft	200 mm
Displacement	7.7 kg(surface) 7.95 kg(submerged)
Propeller	3 blade OD 40mm pitch 41mm
Speed	1.45 knots(surface) 1.08 knots(submerged)
Diving depth	10 m(mechanical limit)

To achieve autonomy, both control and communication systems of the toy submarine are reconstructed. While the enhancement of communication systems involves a replacement of single way RF controller with a WLAN adaptor, the upgrade of control system is achieved by introducing both motion sensors and a PC104-compatible computer.

C. Simulation of Underwater acoustic communication system

By equipping each AUV with an acoustic modem, an underwater communication system can be built. It enables an AUV to communicate with its neighbors within the communication range. Based upon this local communication, each AUV can know the positions of its one hop neighbors, and adjust its positions accordingly and the swarm of AUV's will adopt a cooperative collective motion e.g. mobile sensing with a specified geometric pattern.

However, the underwater communication system is currently replaced by radio frequency (RF) modems. The reason for this simplification comes from two aspects. The first reason is the lower cost of RF modems compared to acoustic modems. The second reason is the immaturity of underwater acoustic communication network. The development of an underwater acoustic communication network encounters many challenges [3]. Although they have been being a very popular research topic, reliable and low cost network protocols for an UMSN are still unavailable to the best of our knowledge.

Although current implementation of the underwater communication system is based upon RF modems, we argue that it can still simulate underwater acoustic communication to some extent for coordination and cooperation control purposes. For example, the transportation delay of acoustic channel, which is a critical factor affecting stability of control systems, can be simulated by degrading the RF channel according to the distance between the adjacent AUV's.

Obviously all the AUV's must move near the surface to ensure the effectiveness of the RF modems that mimic the underwater communication system. Therefore the testbed can only be applied to verify a UMSN of two dimensions, which moves in horizontal plane.

III. DEVELOPMENT OF THE LOW-COST AUV

A. AUV's hardware

The AUV's hardware diagram is shown in Fig. 3

1) Control computer: The AUV's control computer is the core component of all the control hardware, and has heavy processing tasks to complete, so it needs to have a good performance. Considering that the inner space of the pressure shell is limited, so its size should be small and it preferably can support PWM signals output. A PC104 embedded computer with a Vortex86DX-800MHz CPU, 256MB DDR2 onboard system memory and 4GB flash disk is chosen. It can output16 channel PWM (Pulse Width Modulation) signals to drive the DC motor (for the thruster) and the servomotors (for control fins). It also provides four RS232, one RS485, two USB and one Ethernet ports for interfacing with motion sensors, USB WLAN card and RF modem.

2) Motion sensors: The motion sensors include a digital compass, an inertial measurement unit (IMU) with GPS fixes and an intelligent pressure sensor.

The digital compass, TCM2.5 produced by PNI, is mainly used for measuring attitude and heading. It integrates 3-axis magnetic field sensing, 2-axis tilt sensing, and compass heading into a single module, and can provide accurate heading (0.8º), pitch, and roll measurements over a ±50° tilt range. Its working voltage is 5V DC, sampling frequency is 20HZ, and a RS232 serial data port is used for connection to the PC104.

The MTi-G, produced by Xsens, is a combination of a MEMS IMU, GPS and barometer, size of 58mm × 58mm × 33mm, weighs about 68g, 5VDC power supply, GPS update rate 4HZ, position accuracy 2.5m. The IMU, GPS and barometric information is blended together in Xsens' sensor fusion algorithm to estimate the most accurate speed and position possible. Its digital interface is RS-232, data output format is the type of IEEE754 single-precision.

With a range of 0-200KPa, a working voltage of 5-16VDC, and a built-in 24-bit AD Micro Controller Unit (MCU) processor, the pressure sensor can output digital signals directly to the control computer via RS232 communication.

3) Communication devices: Communication devices include a RF modem and a WLAN card.

Digi's XTend-PKG-R RF modem provides long range wireless links between devices. Simply feed a serial data stream into one modem and the data are immediately transported to the other modems. Its built-in RS-232, RS-485 and RS-422 interface allows for rapid integration into existing data systems. Features overview as follows: size of 69.9mm × 139.7mm × 28.6mm, weight 200g, indoor / urban distance (with a 2.1dB omni-directional antenna) maximum transmission up to 900m, Outdoor / RF visual distance (with a 2.1dB omni-directional antenna) maximum transmission up to 22km, transmission power 1mW-1W, supply voltage 7-28VDC, network topology to support peer communications (no master-slave relationship), point to point, multi-point and multi-station.

The WLAN card model is VIA's VT6656 with 54M bandwidth and USB interface.

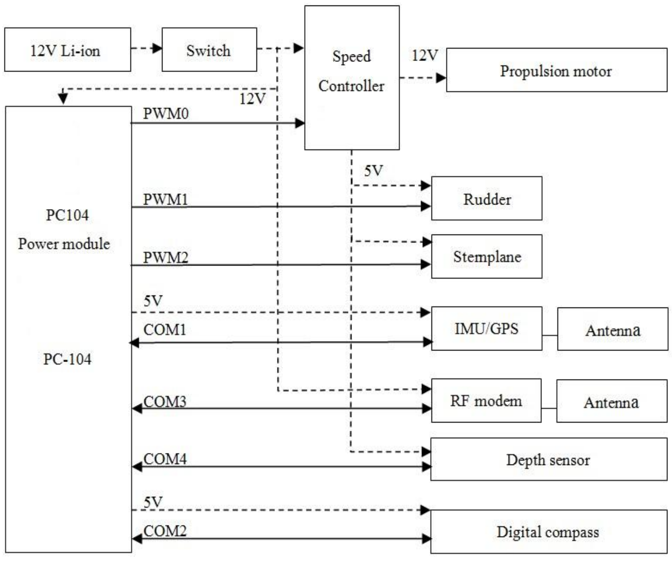


Fig.3 AUV's hardware system diagram

4) Power supply system: The AUV's power supply system can be divided into two parts, namely control circuit part and drive unit part. Control circuit part includes the PC104, motion sensors and communication devices. This part has a small power consumption, but requires a stable power supply; drive unit part includes a propeller-driven propulsion motor and two servo motors. This part has a larger power consumption and requires the capability of continuous power supply. The battery equipped on AUV itself is an energy source for its all hardware devices. What we adopt for the low-cost AUV is a 6150mAh 12V lithium battery, size of 20.5mm × 184mm × 82mm, weight 375g, with advantages of high efficiency, no memory effect and can be repeatedly charged for about hundreds of times.

B. *AUV's software design*

1) AUV's motion control algorithm

Since an UMSN is composed a swarm of AUV's, it is necessary to verify the AUV's autonomy.

As the testbed will only simulate two dimensional UMSN, and most AUV's are under-actuated flight vehicles, heading control are adequate for formation control with appropriate guidance law e.g. line of sight algorithm.

The steering controller for heading control is developed via classical PD (Proportional plus Derivative) approach. After the AUV's linearized mathematical model is extracted from its full nonlinear model, the state equation and transfer function of the heading can be obtained. On this basis, we establish the AUV's linearized simulation model under Simulink environment, as shown in Fig. 4, and use Ziegler-Nichols tuning rules to produce good values (P=8,D=12 for V=0.3m/s) for the PD parameters.

The result of the ultimate nonlinear simulations under Simulink environment is shown in Fig.5 (V=0.3m/s, P=8, D=12, desired heading angle is 30 degrees).

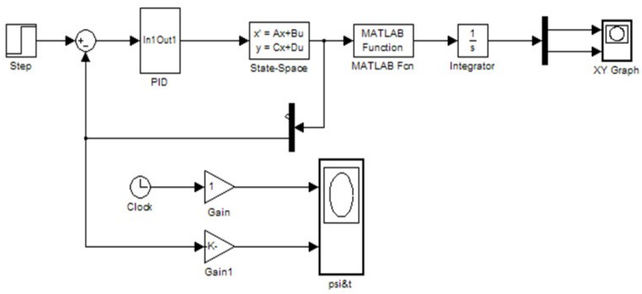


Fig.4 AUV's linearized simulation model

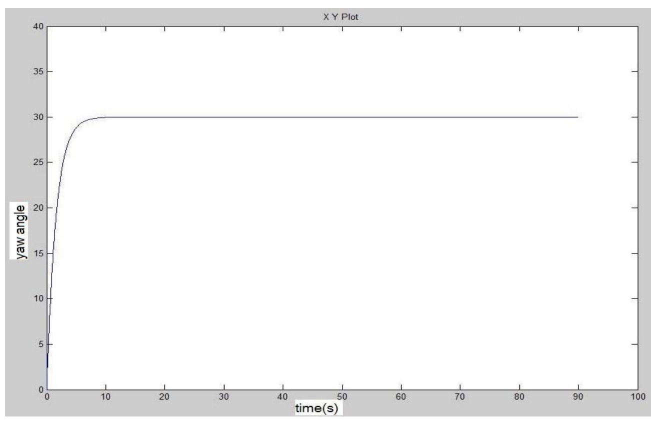


Fig.5 Result of PD controller for heading

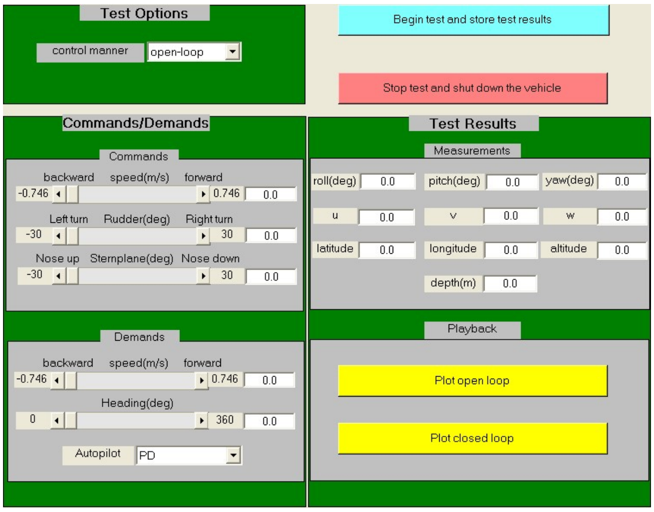
2) *GUI software for remote control*

We choose MATLAB6.5 to develop the GUI programs. Meanwhile, in order to preferably output PWM signals, we build PWM output Dynamic Link Library (DLL) files[11]. Names and functions of the DLL files are shown in Table II.

TABLE II. SPECIFICATIONS ON PWM OUTPUT DLL FILES

Name	Function
Init_WinIO.dll	Initialize WinIO function library
Set_PWM.dll	Select PWM output channels and the duty cycle
Stop_PWM.dll	Close PWM output
Shutdown_WinIO.dll	Clear WinIO function library in memory

By invoking the above DLLs, the PC104 can easily output PWM signals to control the AUV's three-dimensional motion in water conveniently. The AUV's software control interface is



shown in Fig. 6.

Fig.6 AUV's GUI

The control interface can be divided into the following four parts:

- *Test Options*: Select AUV's control manner (open-loop or closed-loop).
- *Commands/Demands*: *Commands* block is related to the open-loop control manner. *Speed*, *Rudder*, and *Sternplane* sliders control AUV's speed, rudder angle, and sternplane angle respectively; *Demands* block is related to the closed-loop control manner. *Speed* and *Heading* sliders set desired velocity and orientation, *autopilot* popup menu decides which closed-loop control method to be used. In the process of AUV's autonomous movement, test data are automatically stored as plain text files.
- *Begin test and store test results* button is used to launch AUV and start storing data under the condition of the open-loop control manner. *Stop test and shut down the vehicle* button can stop AUV movement (whether open-loop or closed-loop) and data recording. After tests, all the AUVs' test data can be automatically stored as plain text files and uploaded to the laptop through WLAN.

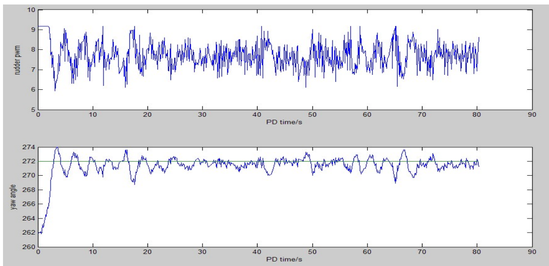
Test results: Measurements block can display AUVs' motion data just in time, this real-time display can help the operator to master AUV's navigation state conveniently. Data include roll angle, pitch angle, yaw angle, AUV's three-axis velocity, latitude, longitude, altitude, and depth; *Playback* block can draw open-loop or closed-loop data curves as long as *Plot open loop* or *Plot closed loop* button is pressed accordingly.

IV. WATER TRIALS

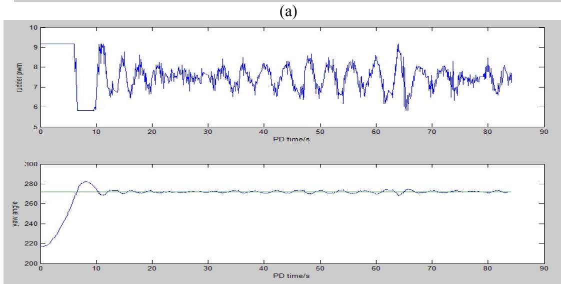
A. *Water trials of single AUV*

Heading control of single AUV was conducted in a swimming pool to verify the steering controller.Located in Xuhui Campus, Shanghai Jiao Tong University, China, the swimming pool has a size of 50m (length) by 25m (width) by 2.6m (maximal depth).

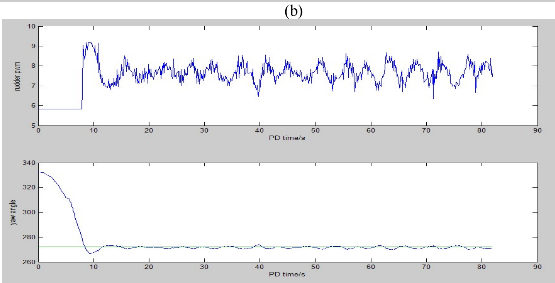
A group of test results are shown in Fig. 7 where the desired heading angle was set to 272 degrees and AUVs' speed was set to 0.3m/s. Test results for AUV1, AUV2 and AUV3 are shown in Figures 7(a), 7(b) and 7(c), respectively.



(a)



(b)



(c)

Fig.7 Test results of AUV's heading control

It can be seen from the test results that PD-based heading control system achieves acceptable performance.

B. Water trials of AUV swarm

By setting the surface laptop computer as a centralized computer, functional tests were conducted to demonstrate the effectiveness of centralized formation control.

As shown in Fig. 8, three AUV's formation was maintained by maintaining a identical heading angle which is set by the surface laptop computer during the water trial.

Fig.8 Centralized formation control of three AUV's

V. CONCLUSION

A low-cost testbed for underwater mobile sensing network has been developed. Both the hardware and software have been verified by functional tests. Water trials have been carried out to validate both the effectiveness of PD-based AUV heading control system and the centralized formation control of multiple AUV's.

It should be noted that the underwater communication system is currently simulated by the RF modems.

Future work will be focused on the implementing the underwater communication system with acoustic modems. Moreover, distributed formation control of UMSN based upon local sensing and communication will be studied.

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