Proceedings of the 32nd Chinese Control Conference
July 26-28, 2013, Xi'an, China

Control System of a Novel Underwater Vehicle for Global Ocean Science to the Deepest Ocean

WANG Biao, WU Chao, GE Tong

School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: biaowang@sjtu.edu.cn

Abstract: A new remotely operated underwater vehicle-a hybrid ROV capable of working to the full depth of the ocean (11000m) has been developed. The battery powered vehicle operates in two modes. Basically, the vehicle is predominately operated fully remotely and video controlled via a light fiber optic cable. In a critical situation the fiber optic cable will be disconnected and the vehicle should switch automatically into the autonomous mode, returning to surface for recovery. If appropriate, the vehicle can also be used as a pre-programmed AUV for broad area survey from beginning. This paper presents the control system architecture of the vehicle including hardware and software. Also the lake trial and the full ocean depth simulation test are reported for verification of the effectiveness of the whole system.
Key Words: hybrid ROV, control system, full ocean depth, distributed, redundant

1 Introduction

The ocean covers about two-thirds of the earth and its abundant living and non-living resources are yet to be utilized on a large scale. For example, it is estimated that there are about 2,000 billion tons of manganese nodules on the floor of the Pacific Ocean near the Hawaiian Islands. Various kinds of underwater vehicles have been developed for human being to explore the ocean over the past 50 years -e.g. the 4,500 m Alvin human occupied submersible[1], the 4,500 m ABE AUV[2]. Only a few currently operational vehicles are capable of diving to between 6,000 m and 7,000 m-e.g. the 6,500 m Jason II ROV[3] and the 7,000 m Kaiko 7000[4]. Progress in deep sea research between 7,000 m and 11,000 m has been hindered by the absence of suitable cost-effective vehicles capable of operating at these depths although two vehicles have reached the deepest place on the earth-Challenger Deep of the Marianas Trench at 11:22'N, 142:25'E in the Western Pacific Ocean near the island of Guam[5-6]. Until recently, field trials of the U.S. Nereus hybrid underwater robotic vehicle in the depth of 10,903m were reported[7]. Given the national and international need for exploration to the full ocean depth, we proposed to build a novel underwater vehicle-a hybrid ROV that combines the function of ROV and AUV. Its battery powered and controlled via a light fiber optic cable with two operation modes, AUV mode and ROV mode, similar to some other vehicles of a hybrid type[6][8-10]. The intended depth rating of the vehicle is 11000m.

This paper presents the control system of a hybrid ROV. The remainder of the paper is organized as follows. An overview of the vehicle is introduced in Section 2. The architecture of both hardware and software is introduced in Section 3 and 4. And experiments results are reported in Section 5. Finally a summary is given in Section 6.

2 Overview of the Vehicle

The vehicle employs twin free-flooded hulls, as shown in Fig.1. Aluminum frames accommodate all on-board instruments. Internal electronics and sensors are housed in four titanium alloy pressure housings of sphere shape developed specially for this project. Cameras, LED lamps, acoustic modem and other external electronics are housed separately in pressure housings specially designed. The power source is rechargeable lithium polymer battery. Pressure-balanced, oil-filled junction boxes and hoses provide vehicle electrical and optical-interconnect. The vehicle has five thrusters driven by D.C. brush-less motors. Two horizontal thrusters laid aft are used for cruising and heading control, other one lateral thruster is used for side movement. The vertical thrusters are used for depth control. The manipulator, battery pack pan&tilt unit and thrusters are all pressure-balanced and oil-filled. Five pressure compensators are added for oil compensation. The vehicle navigation system is described later in the paper. Additional buoyancy are provided by buoyancy foam and lightweight, hollow ceramic buoyancy spheres[11]. The vehicle's large metacentric height provides passive stability in roll and pitch. Fixed vertical tails provide passive hydrodynamic stability in heading.

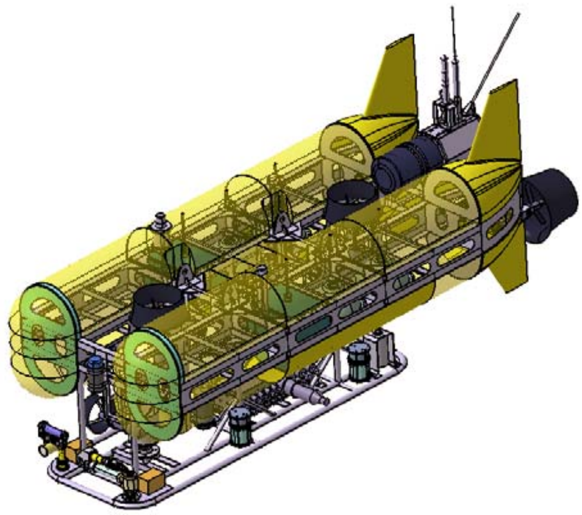

Fig. 1: 3D view of the vehicle

3 Hardware Architecture

The vehicle control system has distributed architecture, as shown in Fig.2. To enhance the reliability and fault tolerant capability of the control system, redundant communication bus and power bus are adopted. Two main battery banks of total 13.2kWh, one on port side and one on starboard side of the vehicle, provide power for the vehicle. Four sub systems are connected via CAN (Controller Area Network) bus. Each of them has a suite of PC/104 boards including CPU board, communication board and data acquisition board. The CUP board uses Pentium M CPU as the main processor with its main frequency being 1GHz. It works at 5VDC and has one net-work port and two serial ports. Compact Flash card is used to replace other external memory. The communication board is fixed with 4 optical isolation asynchronous serial interfaces, 2 optical isolation CAN bus interfaces and 24 DIO channels. The data acquisition board provides 32 16-bit ADC channels, 8 14-bit DAC channels and 32 DIO channels. The three boards are connected through 104 bus. More details will be given in the following paragraph.

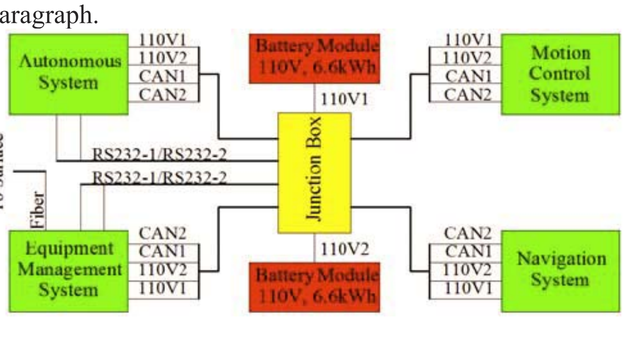

Fig. 2: Block diagram of the vehicle control system

3.1 Autonomous System

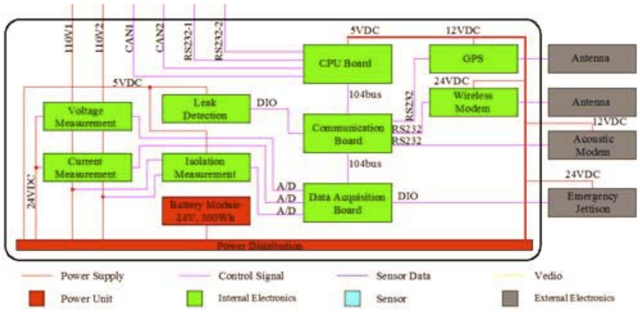

Fig. 3: Schematic of autonomous system

The autonomous system acts as brain of the control system. It receives commands from the surface control system and transmits the vehicle status to surface in real-time. Commands are decoded under the communication protocol before they are sent to the other three sub systems. Meanwhile, information from the other sub systems including sensor data, system health status and actuators feedback are gathered and transmitted to surface by the autonomous system. High level control strategies are embedded in the CPU board of the autonomous system to implement complicated tasks autonomously. The emergency jettison system is controlled directly by the autonomous computer to ensure the vehicle0s safety. Acoustic modem, wireless modem and GPS receiver are integrated for multi-channel communication. A separate battery of 24V is used to provide power for low voltage electronics and sensors when the main power down. The health monitor system consists of leak detection, isolation measurement, voltage measurement and current measurement. The same health monitor system also exists in the other three sub systems. Fault diagnosis and tolerant strategies are developed based on system health status.

3.2 Motion Control System

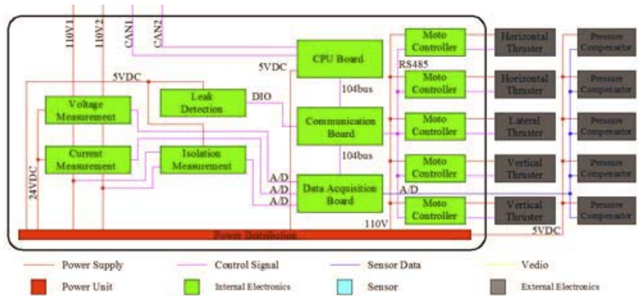

Fig. 4: Schematic of motion control system

This system is responsible for basic control of the vehicle. Low level control strategies are embedded in the PC/104 computer. Auto-Heading, Auto-Depth and Auto-Altitude are implemented with the sensor data from navigation system. The thrusters can also be manually operated from surface by joysticks. A thrust allocation matrix ensures that every thruster outputs the proper thrust. The maximum output of a thruster is 600W with a supply voltage of 110V. All of the thrusters are oil-filled and pressure-balanced. PC/104 computer sends control signals to motors drivers and gets feedback from them about thruster speed and fault status via RS485 communication port. Five pressure compensators (two for thruster, two for junction box and the other one for battery module) make sure all the oil-filled instruments work under a balanced pressure equal to environment. Pressure signals with a range of 0-5VDC are acquired in real time.

3.3 Navigation System

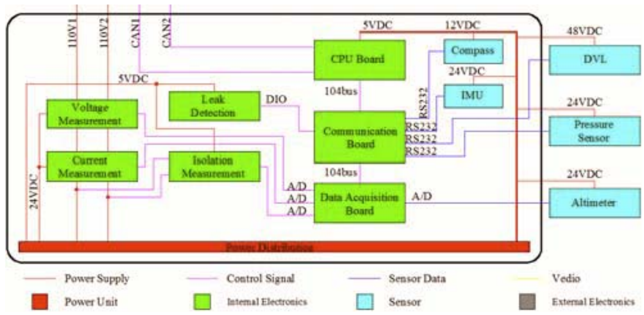

Fig. 5: Schematic of navigation system

The navigation system is an integrated system including a Teledyne-RD Instruments Doppler velocity log (DVL), an IXSEA Phins IMU, a Honeywell digital compass, a pressure sensor and an altimeter. The DVL provides 3-axis, bottom-lock, vehicle velocity with respect to the sea floor at up to 200 m altitude. The IMU contains a 3-axis, North-seeking, fiber optic gyrocompass providing attitude and heading at 0.01 ° accuracy. Obviously, sensor redundancy makes a good promise for vehicle navigation. For example, it is possible for the vehicle to switch navigation from the digital compass readings to DVL attitude readings in case of digital compass failure. Navigation sensor data is received by navigation computer. Then the navigation process provides the best estimate of position, velocity, and attitude by combining information from these instruments.

3.4 Equipment Management System

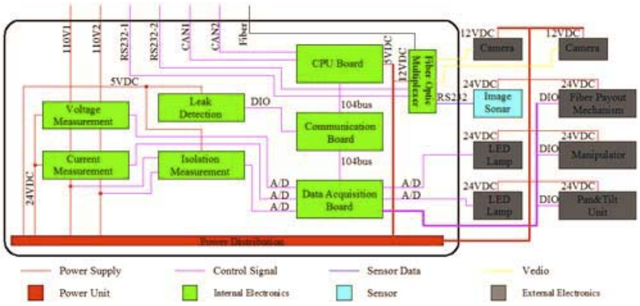

Fig. 6: Schematic of equipment management system

The equipment management system supports a range of equipment. The pan&tilt unit moves in 2 degree of freedom. Two LED lamps and two cameras are separated into two packs. One is fixed to the pan&tilt unit. The other is fixed to the vehicle frame. A 2-function oil-filled pressure balanced manipulator is designed for sampling. A multi-function manipulator will be designed in the future work. A commercial available fiber optic multiplexer provides digital fiber transmission for 3 high quality video and 6 data channels. The image sonar communication port is connected directly to one RS232 serial data channel of the fiber optic multiplexer. The fiber payout mechanism payouts fiber from vehicle as needed during mission and disconnects fiber before ascent.

4 Software Architecture

The software architecture has a modular, flexible structure for any modification or additions. With the open architecture, it is possible to use any vendor's hardware. Each module can be controlled with minimum interface with others. Thus, almost all of the software modules can be easily rebuilt or replaced for upgrading or testing like hardware components. Each module follows its own specification to maintain the specific software/control architecture. The software architecture consists of three layers, device layer, user layer and application layer, as shown in Fig.7.

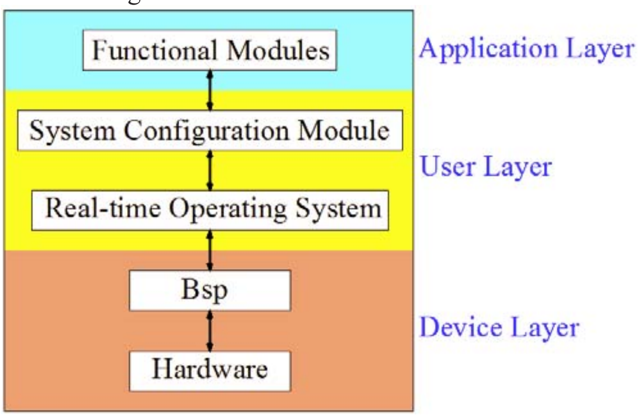

Fig. 7: Hierarchical control architecture for software

The device layer is the only hardware dependent part. The board support package (BSP) implements specific support code for a given board that conforms to a given operating system. It is commonly built with a boot loader that contains the minimal device support to load the operating system and device drivers for all the devices on the board.

The user layer consists of a real-time operating system and a system configuration module. The main role of a system configuration module is providing a hardware-independent interface for the application layer. A block diagram of the system configuration module is shown in Fig.8. MainEntry is the entrance of the whole program. TargetInit finishes configuration of hardware resources such as DIO, ADC, CAN etc. ParaInit sets initial value of global variables used for data sharing between tasks. SemInit creats semaphores for tasks scheduling. UsrTaskInit creats user tasks. WDInit sets software watchdog on.

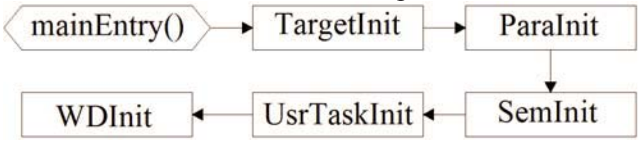

Fig. 8: Block diagram of the system configuration module

The application layer is user-oriented and can be transplanted to other control systems without modification. It has no relation with hardware and operating system. The actual functional modules such as sensor data sampling, equipment control, actuator control etc. are embedded in different tasks of the application layer. The semaphores are in charge of communication and scheduling between tasks. The functional modules are different with respect to the specific application.

For implementation of the software architecture, VxWorks real-time operating system is embedded in the PC/104 computer. Duo to the consistency of hardware, the sub systems have the same device layer. Although there exist some differences according to actual resources utilized in each sub system, they have a similar user layer of the architecture shown in Fig.8. The differences in application layer between sub systems are evident. Fig.9 shows the detailed task diagram of each sub system.

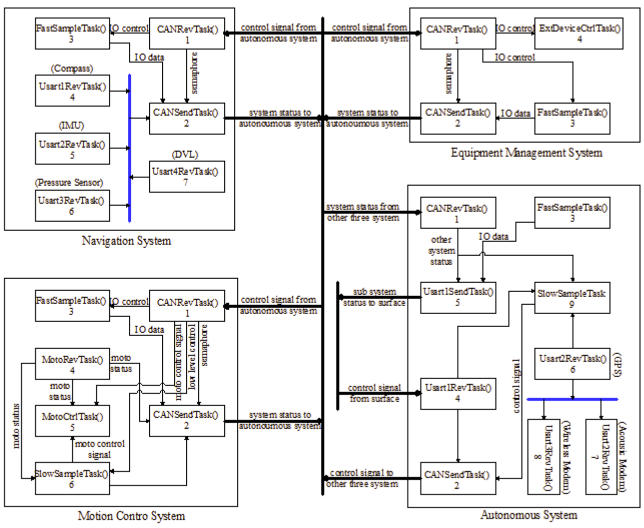

Fig. 9: Detailed task diagram (number in the block means priority)

5 Experiment

5.1 Lake Trial

We have carried a lake trial in December 2011. The principle engineering objective of the lake trial was to test the vehicles mechanical, electrical, and optical subsystems in a real-world environment. Several dives were made in ten days to test the vehicles function completely. In the last dive, the vehicle was operated to 1 kilometer away from the support vessel in ROV mode and returned by itself in AUV mode. Pictures of the lake trial are shown in Fig.10 and Fig.11.

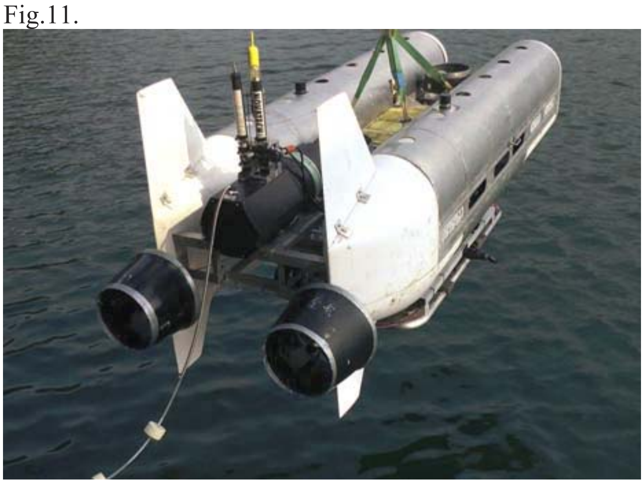

Fig. 10: A picture of lake trial (deployment)

Fig. 11: A picture of lake trial (underwater)

5.2 Full ocean depth simulation test

We have carried a full ocean depth simulation test in January 2012. The goal of the test was to test the vehicles mechanical, electrical and optical subsystems at a full ocean depth pressure. Although every vehicle component was individually pressure tested multiple times during development, this test was the first opportunity to test them as a complete vehicle system. The deep ocean environment simulator is designed to have a maximum pressure of 160Mpa (about 16000m). A steel frame was designed to accommodate all the components as shown in Fig.12. The whole system worked well during a two hour test at a pressure of 119Mpa.

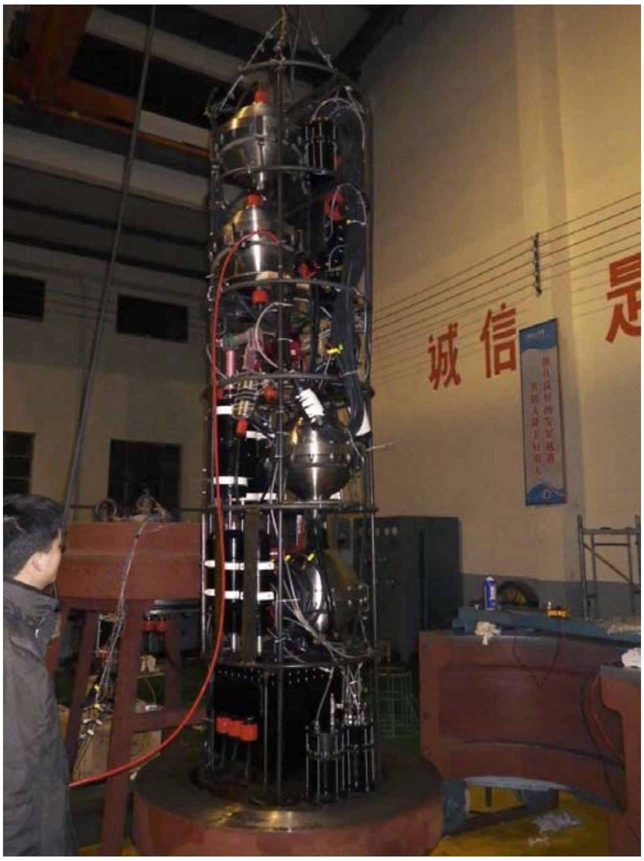

Fig. 12: A picture of simulation test

6 Conclusion

A hybrid ROV has been developed for global ocean science to 11000m. The vehicle provides a platform for research of key techniques in deep ocean vehicles. As one of the key techniques, control system architecture is presented. Lake trial and full ocean depth test have demonstrated basic functionality of capabilities in titanium alloy pressure housings, fiber-optic tether systems, manipulators, cameras and lighting, navigation, control, and acoustic telemetry necessary for AUV mode autonomous survey missions and ROV mode sampling missions in a single vehicle package. The improvement of the vehicle has been scheduled. Finally, it is expected that the vehicle will dive to the deepest depth, Mariana Trench in the near future.

References

[1] Victoria A. Kaharl, *Water Baby: The Story of Alvin,* New York: Oxford University Press, 1990.

[2] D.R. Yoerger, A.M. Bradley, B.B. Walden, H. Singh, and R. Bachmeier, Surveying a subsea lava flow using the Au tonomous Benthic Explorer (ABE), *International Journal of Systems Science*, 29(10): 1031-1044, 1998.

[3] L. L. Whitcomb, J. Kinsey, D. Yoerger, C. Taylor, A. Bowen,B. Walden, and D. Fornari, Navigation upgrades to the National Deep Submergence Facility vehicles D.S.V. Alvin, Jason 2, and the DSL-120A, in *American Geophysical Union, Fall Meeting 2003,* 2003: 225-231.

[4] T. Murashima, H. Nakajoh, H. Yoshida, J. N. Yamauchi, and H. Sezoko, 7000 m class ROV KAIKO7000, In *Proceedings of IEEE/MTS OCEANS*, 2004: 812-817.

[5] P. Fryer, N. Becker, B. Appelgate, F. Martinez, M. Edwards, and G. Fryer, Why is the Challenger Deep so deep, *Earth and Planetary Science Letters*, 211(3): 259-269, 2003.

[6] Andrew D. Bowen, The Nereus hybrid underwater robotic vehicle for global ocean science operations to 11,000m depth, in *Proceedings of IEEE/MTS OCEANS*, 2008: 1-10.

[7] Andrew D. Bowen, Field trials of the Nereus hybrid under water robotic vehicle in the Challenger Deep of the Mariana Trench, in *Proceedings of IEEE/MTS OCEANS,* 2009: 1-10.

[8] Andrew D. Bowen, Exploring the deepest depths: preliminary design of a novel light-tethered hybrid ROV for global science in extreme environments, *Marine Technology Society*, 38(2): 92-101, 2004.

[9] Gerrit Meinecke, Volker Ratmeyer, Jens Renken, Development of a new underwater vehicle for high-risk areas, in *Proceedings of IEEE/MTS OCEANS*, 2011: 1-6.

[10] Li Yi-Ping, Li Shuo, Zhang Ai-Qun, Recent research and development of ARV in SIA, in *Sixth International Symposium on Underwater Technology*, 2009: 87-90.

[11] S. Weston, J. Stachiw, R. Merewether, M. Olsson, and G. Jemmott, Alumina ceramic 3.6 in otation spheres for 11 km ROV/AUV systems, in *Proceedings of IEEE/MTS OCEANS,* 2005: 172-177.