The general design of a seafloor surveying AUV system

Hongwei Zhang, Liang Hao, Yanhui Wang*, Yuhong Liu, Zhiliang Wu, Shuxin Wang, Shuai Shao, Dongjie Wei
Key Laboratory of Mechanism Theory and Equipment Design of Ministry of Education,
School of Mechanical Engineering, Tianjin University
Tianjin 300072, China
*Email: yanhuiwang@tju.edu.cn

Wei Hou
Tianjin Navigation Instruments Research Institute
Tianjin 300313, China

***Abstract*—Owing to the exceptional ability of obtaining maximum data quality by bringing advanced payload sensors close to the seafloor, AUVs have been widely applied to seafloor survey task in recent years. Tianjin University developed a seafloor mapping AUV in 2010. In this paper, the energy consumption and endurance of the seafloor mapping AUV are predicted. To optimize the maneuverability at the early design stage, the hydrodynamic characteristics of the vehicle are calculated and evaluated. A propeller-gear-motor combination thruster is developed to ensure maneuverability and realize high resolution trajectory tracing at a low speed. An aided inertial navigation system integrating a number of surface and subsea navigation sensors is mounted on the vehicle to achieve better surveying data quality. Several trials were conducted and the general design of the whole system is verified.**

Keywords—general design; seafloor surveying; AUV; maneuverability

I. INTRODUCTION

With the exceptional ability of obtaining maximum data quality by bringing advanced payload sensors close to seafloor, AUVs have been widely applied to hydrographic surveying tasks in recent years. There are several AUVs that have completed sufficient sea trial and achieved stage success in high resolution mapping, such as Hugin [1,2], Explorer[3,4], Autosub [5,6], Remus 6000 [7] and Bluefin-21 [8]. Some of these AUVs have been put into commercial operation. However, the AUV technology is far from complete maturity, and there are several challenges for achieving higher performance. Further research on unit technologies, such as hydrodynamic performance, intelligent control technology, energy storage, navigation and communication technology, is still in progress.

In 2010, a new project of developing seafloor mapping AUV was launched by Tianjin University. At the initial stage of developing this AUV, the seafloor mapping AUV is expected to possess three main characteristics, which are a low drag shape, excellent maneuverability, and a high resolution navigation system.

In a typical seafloor mapping operation, AUVs are expected to have long endurance and cursing range in a single voyage. According to current research achievements of low drag hull, a streamlined shape of the vehicle is designed using CFD calculation.

Generally, when carrying out a seafloor surveying task, the AUV is operating at a constant altitude of approximately 20-50 meters above the seabed, providing good swath coverage by using side scan sonar and multibeam echo sonar to yield highly accurate and cost-effective geophysical information. That is to say that the AUV should avert its depth in accordance with the terrain of seafloor. So the vehicle should have a good maneuverability and stability at low or high speeds in the underwater environment. To ensure maneuverability and realize high resolution trajectory tracing at low speeds, a vectored thruster is adopted and rudders are abolished to decrease water resistance. Moreover, to achieve better surveying data quality, the navigation and positioning system should provide adequate precision to meet the requirement of seabed mapping.

At the light of this philosophy, efforts have been made to research on related aspects in recent years. In the paper, the general design of this AUV is presented (Fig. 1).

Fig. 1.The seafloor surveying AUV

In January 2012, the underwater trial of seafloor mapping AUV was conducted at Fuxian lake, Yunnan, China. This trial

978-0-933957-40-4 ©2013 MTS

verified the general design of the whole system and indicated the direction of improvement in the future.

II. General Design

The seafloor survey AUV is a modular open system, consisting of mechanical, control, battery, sensor subsystems and system integration. The main parameters and specifications of the vehicle are shown in Table I.

TABLE I. The Specifications Of Seafloor Surveying AUV

Displacement	2200 kg
Length	7.8 merters
Diameter	0.8 meter
Depth rating	2000 meters
Velocity	3-5 knots
Power	1.1 kW (4 knots), 0.62kW (3 knots)
Endurance	22.5 hours (4 knots, 162 km); 37.5 hours (3 knots, 202 km)
Power	Li polymer battery, 35kWh
Navigation	Ixsea PHINS and Linkquest DVL
Positioning	Ixsea GAPS system
Communication	Surface: GPS/Iridium/Wi-Fi Underwater: Acoustic modem
Payload	MultiBeam Echo Sounder: EM2040 Subbottom Profiler and Side Scan Sonar: 2200M, CTD: Sea bird

The vehicle hull is a free flooding type, which allows greater freedom in vehicle configuration. The hull of the vehicle is made of glass reinforced plastic and the frame is made of stainless iron. High performance syntactic foam is used as the buoyancy material to provide buoyancy for the vehicle. The frame and hull provide a stiff structure for sensor installation with precise alignment accuracy. The design provides an open internal structure for installation of instrument containers, battery and transducers. To keep the streamline form of the hull, the buoyancy material is machined accordingly. Figure 2 illustrates the general internal layout of the vehicle.

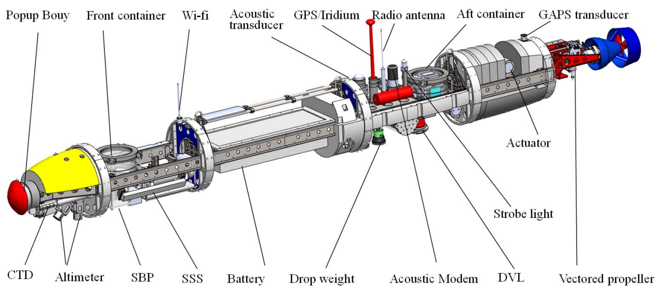

Fig. 2. General internal layout of the seafloor surveying AUV

Due to the remarkable viscous and additional inertial effect of water, more than 70% of the whole energy storage is consumed by the propulsion system. In order to decrease the drag force significantly, the seafloor mapping AUV adopts the Granville streamlined shape. The flow structure of the streamline is simulated by the commercial CFD software FLUENT and the drag force at the working speed is predicted. The drag forces at different speeds are shown in Table II and the drag coefficient of the whole body of the AUV with appendage parts is 0.31. The drag force, energy consumption and endurance of the propulsion system are presented in Table II.

TABLE II. Energy Storage and Endurance

Speed (knot)	3	3.5	4	5
Drag (N)	184	207	225	293
Effective power (W)	284	372	463	753
Consumed power	685	899	1118	1820
Current (A)	3	3.45	4.3	7
Endurance (hr)	37.5	25	22.5	13

III. Energy storage and Propulsion

A. Energy storage

The electric power for the whole vehicle is provided by a set of pressure tolerant lithium polymer rechargeable batteries, as shown in Fig. 3. The maximum power consumption of the propulsion system is presumed to be 2.5 thousand watts. In order to decrease the requirement of overload capacity of electronic devices, 260 voltage is adopted to decrease electric current.

Fig. 3. Battery

B. Power consumption and propulsion system

To protect the propeller and increase the thrust force, a ducted propeller is adopted and the diameter of the duct is 400 mm. The propulsion efficiency of the ducted propeller is presupposed to be 60% according to the special design diagram. According to the diagram, when running at a speed of 3.5 knots, the turning speed of the propeller is 500 rpm and the torque acted on the shaft of propeller is 12 N·m.

To ensure the transform efficiency from electric energy to mechanical energy, the oil compensated motor was tested by a dynamometer at 12 N·m and 500 rpm, as shown in Fig. 4.

The test results show that the energy transform efficiency of the motor at the cruise speed of 3.5 knots is 69%. So the whole efficiency of the propulsion system is 41.4%.

It is also shown that at a cruise speed of 3.5 knots, the effective power of the thrust motor is 620 watts and the working current is 3.45 A. According to this, when the capacity of the 260 V battery pack is 90 Ah, the endurance of the AUV at 3.5 knots is 25 hours and 160 kilometers. Both the cruise speed and the endurance can meet the demands of the typical survey tasks.

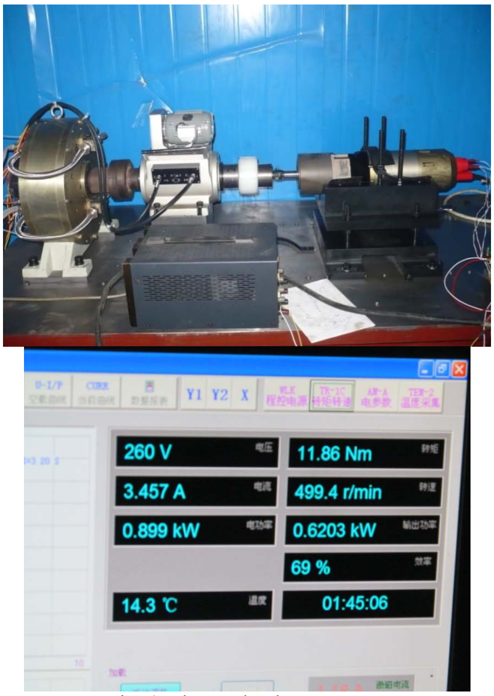

Fig. 4. The test by dynamometer

C. *The Vectored Thruster*

A new kind of vectored thruster system is designed with reference to several existing designs. The vectored thruster can provide approving control force and achieve better maneuverability for the vehicle even at a very low speed. Moreover, the ducted propeller has the advantage of providing higher thrust force at low speeds. The novel vectored thruster is shown in Fig. 5.

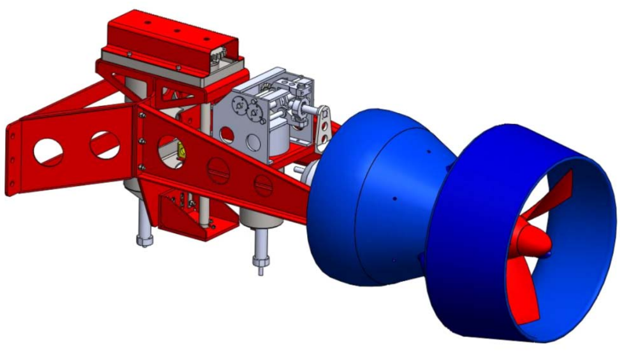

Fig. 5. The axonometric drawing of the vectored thruster

The construction principle of the thruster is a propeller-gear-motor combination, surrounded by a duct which is used as the control surface for the AUV. The entire assembly is attached to a frame via a gimbal that permits actuation in the horizontal and vertical planes. Linear drive actuators perform the control and maneuvering functions of the unit. All these three cabins are pressure compensated with oil.

The thruster design is optimal for operations at a speed of 3-4 knots and has the following characteristics, as shown in Table III.

TABLE III. THE BASIC PARAMETERS OF VECTORED THRUSTER

Motor and power consumption	DC brushless motor, 260 V, 2500W
Actuator	DC brushless servo motor, 48V, 240 W
Depth rating	3000 meters
Duct speed	5° / sec
Elevator and rudder range	±15°

IV. THE MANEUVERABILITY IN VERTICAL PLANE AND HORIZONTAL PLAN

A seafloor survey AUV should have a good attitude-holding capability and a favorable trajectory-tracking performance both in the vertical plane and the horizontal plane. Besides, manual operation is often needed when the AUV is navigating on or under the water surface. According to previous trial experience, the general AUV may have a good performance in the autopilot mode, but the manual manipulation from water surface tends to be difficult due to repeated overshoot caused by lag in dynamic response.

To optimize maneuverability of the vehicle, at the early design stage, the hydrodynamic coefficients related to the hydrodynamic force and moment on the main hull are calculated and motion stability theory is used to analyze dynamic stability and maneuverability of the system. The dynamic stability depends on the ability of original state restoration under disturbance, while the maneuverability depends on the ability of rapid response and the convergence speed.

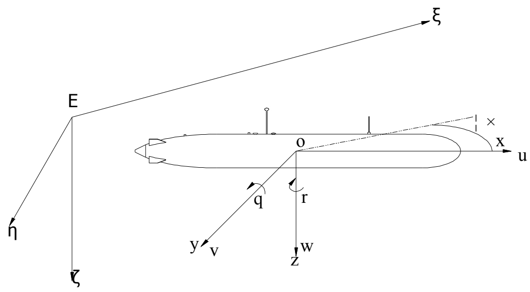

Fig. 6. ITTC coordinate system

In order to investigate the dynamics of the vehicle, International Towing Tank Conference (ITTC) coordinate system is adopted in this paper, as illustrated in Fig. 6. Notations used for the formulation are as follows. $E-\xi\eta\zeta$ denotes the earth-fixed coordinate system with the ζ axis in the direction of gravity. The $o-xyz$ coordinate is the body-fixed coordinate. The decoupled linear maneuvering model of horizontal plane can be denoted as:

$$\begin{cases}(m'-Y'_{\dot{v}})\dot{v}-Y'_{v}v+Y'_{\dot{r}}\dot{r}+(m'-Y'_{r})r=T'\sin(\delta_{r})\\(I'_{z}-N'_{\dot{r}})\dot{r}-N'_{r}r-N'_{\dot{v}}\dot{v}-N'_{v}v=T'l'_{ot}\sin(\delta_{r})\end{cases} \tag{1}$$

where m is the mass of the vehicle, I_z is the moments of inertial about the z axis, T is the propeller thrust, δ_r is the angle between the oxz plane and T, l_{ot} is the distance between the center of propulsion and the fixed point o, $Y_{\dot{v}},Y_{\dot{r}},N_{\dot{r}},N_{\dot{v}}$ are the added mass coefficients, and Y_v,Y_r,N_r,N_v are the velocity dependent hydrodynamic derivatives.

Considering $\Delta\psi(t)$ as the time integral of the yaw angular velocity r, the differential equation for the uncontrolled disturbance of r can be written as the following equation by eliminating the sway velocity v in Eq. (1).

$$T_1T_2\Delta\ddot{r}+(T_1+T_2)\Delta\dot{r}+\Delta r=0 \tag{2}$$

where

$$T_1T_2=(\frac{L}{V})^2\frac{(I'_z-N'_{\dot{r}})(m'-Y'_{\dot{v}})}{C_H}$$

$$T_1+T_2=(\frac{L}{V})^2\frac{[-(I'_z-N'_{\dot{r}})Y'_v-N'_v(m'-Y'_{\dot{v}})]}{C_H}$$

$$C_H=N'_rY'_v+N'_v(m'-Y'_r)$$

The general solution for Eq. (2) is:

$$\Delta r(t)=C_1e^{\lambda_1 t}+C_2e^{\lambda_2 t}$$

where $\lambda_1=-\frac{1}{T_1},\lambda_2=-\frac{1}{T_2}$

Therefore,

$$\Delta\psi(t)=\int_0^t\Delta r(t)dt \quad =\int_0^t(C_1e^{\lambda_1 t}+C_2e^{\lambda_2 t})dt=\frac{1}{\lambda_1}C_1e^{\lambda_1 t}+\frac{1}{\lambda_2}C_2e^{\lambda_2 t}+C_0$$

The vehicle is said to be directionally stable if the real part of the roots to Eq. (2) are all negative, which means that $\Delta r\to 0,\Delta\psi\to C_0$ as $t\to\infty$, where C_0 is a constant. And the imaginary part represents the oscillatory behavior of r and ψ in time.

Considering that the hydrodynamic coefficients $N'_{\dot{r}},Y'_{\dot{v}},N'_r,Y'_v$ are all negative and m',I'_z are positive constants, after a further analysis, the discriminant of the stability can be obtained as:

$$C_H=N'_rY'_v+N'_v(m'-Y'_r)>0$$

In order to facilitate the analysis, the C_H can be rewritten as:

$$C_H=[1+\frac{N'_v(m'-Y'_r)}{N'_rY'_v}]>0$$

The AUV has good dynamic stability in the horizontal plane when $C_H>0$. A larger C_H indicates that the vehicle has the merits of faster system response and better dynamic performance. Generally, submarines have good manual manipulation performance, where C_H is recommended to be 0.2~0.4 according to Submarine design tutorial [9].

Similarly, the discriminant of dynamic stability in the vertical plane can be obtained as:

$$C_v=[1-\frac{M'_w(m'+Z'_q)}{M'_qZ'_w}]>0$$

After substituting the hydrodynamic parameters we can get C_H of this vehicle is 0.248, which demonstrates that the AUV is in accordance with the requirement of manual operation. And C_v is 0.743, which indicates that the AUV has good attitude-holding capability when carrying out a seafloor surveying task above seabed.

V. SEA TRIALS

Four sea trials were carried out from 2012 to 2013. Figure 7 shows an 80-meter-deep voyage. A typical "mower" type of trajectory was set for surveying and mapping, with five routes whose length is 2 kilometers. The tracking error of the vehicle was less than 5 meters. In manual operation trial on the water surface, the AUV exhibited fast response and short delay in steering. When the vehicle was running on the water surface under manual control, it could adjust its position and orientation reliably.

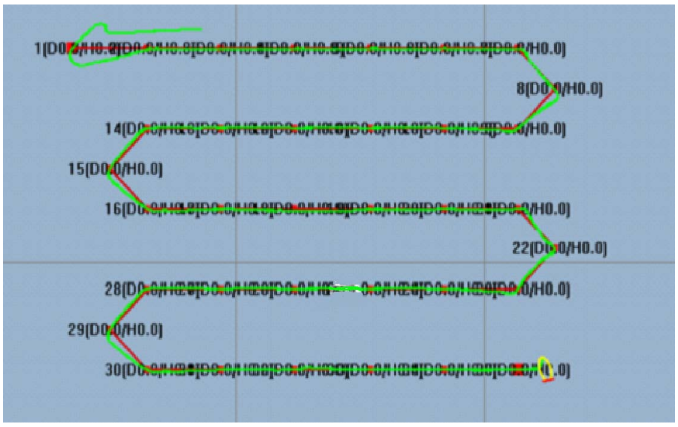

Fig. 7.The saw tooth trajectory of the vehicle

Figure 8 shows the result of an 11-meter-deep voyage carried out in shallow sea. During navigation, adjustment of the attitude and the depth is an asymptotic convergence process without oscillation and overshoot. The pitch angle has a minor fluctuation and the depth error is small. These trials demonstrate that the vehicle could meet the requirement of maneuverability and dynamic stability during surveying and mapping tasks. In future trials, we will validate the ability of fixed high navigation and the obstacle avoidance ability of the vehicle.

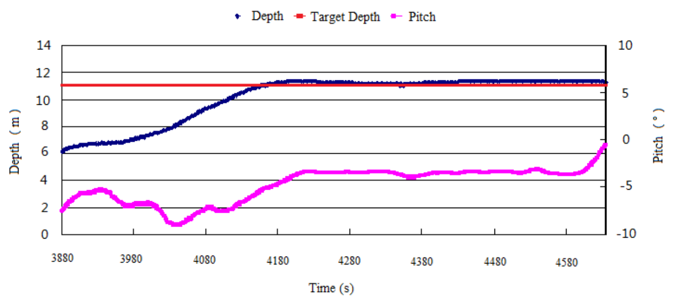

Fig. 8. The pitch angle of the 11 meters voyaging

VI. CONCLUSIONS

Copmared with traditional surveying methods, the seafloor survey AUV has an advantage of maximum data quality that can be achieved by bringing advanced payload sensors close to the seabed and operating them from an autonomous stable platform with low noise.

In the paper, the overall sensor layout for the seabed mapping AUV is presented according to the task demands and the maneuverability and dynamic stability in the horizontal and the vertical plane are analyzed. The preliminary sea trials have demostrated that the AUV is in accordance with the expected design specifications. These tests also lay a foundation for future systematic optimization and practical applications.

References

[1] R. Marthiniussen, K. Vestgard, R.A. Klepaker, N. Storkersen, "HUGIN-AUV concept and operational experiences to date," in *Oceans '04 MTS/IEEE Techno-Ocean '04*, vol. 2, pp. 846-850, nov. 2004, .Kobe, Japan.

[2] M.S. Wiig, T.R. Krogstad, O. Midtgaard, "Autonomous identification planning for mine countermeasures," in *IEEE/OES Autonomous Underwater Vehicles (AUV 2012)*, pp. 8, 2012, Setp. Southampton, UK.

[3] R. Lewis, S.Adams, N. Bose, J. Anderson,"Explorer AUV missions in coastal Newfoundland Royal Institution of Naval Architects - International Maritime Conference," pp. 408-414, 2008, Sydney, NSW, Australia.

[4] V. Riqaud, J.L. Michel, J.S. Ferguson, J.M. Laframboise, T. Crees, P. Leon, J. Opderbecke, Y. Chardard, "First steps in ifremer's Autonomous Underwater Vehicle Program- A 3000m depth operational survey AUV for environmental monitoring," in *Proceedings of the International Offshore and Polar Engineering Conference*, pp. 203-208, 2004, Toulon, France.

[5] Furlong, M.E., D. Paxton, P.Stevenson, M. Pebody, S.D. McPhail, J. Perrett, "Autosub Long Range: A Long Range Deep Diving AUV for Ocean Monitoring," 2012 IEEE/OES Autonomous Underwater Vehicles , pp. 7, 2012, Southampton, UK.

[6] S. McPhail,M. Furlong, V. Huvenne and P. Stevenson, "Autosub6000: Results of its Engineering Trials and first Science Missions,"Journal of Bionic Engineering, vol.6, pp.55-62, March 2009.

[7] M. Purcell, D. Gallo, G. Packard, M. Dennett, M. Rothenbeck, A. Sherrell, S. Pascaud, "Use of REMUS 6000 AUVs in the search for the Air France Flight 447," OCEANS 2011, pp. 7 , sept. 2011, Waikoloa, HI, USA.

[8] R. Henthorn, D.W. Caress, H. Thomas, R. McEwen, W.J. Kirkwood, C.K. Paull, R. Keaten, "High-resolution multibeam and subbottom surveys of submarine canyons, deep-sea fan channels, and gas seeps using the MBARI Mapping AUV," in *OCEANS 2006*, pp. 6, Setp. 2006, Boston, MA, USA.

[9] Shengda Shi, submarine manoeuvrability, Beijing: National Defense Industry Press, 1995.(In Chinese)

.