Development and Sea Trials of a Shuttle Type AUV "ALBAC"

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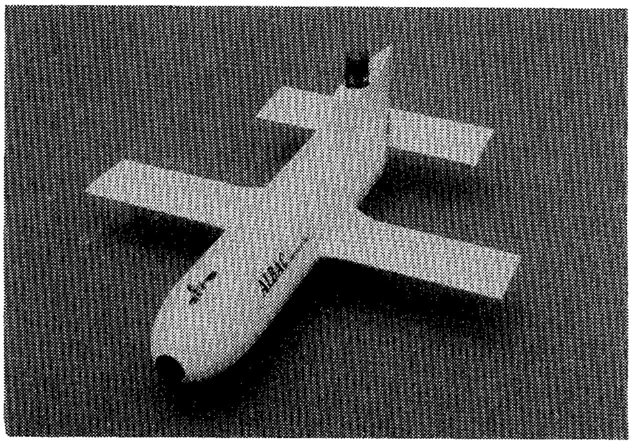
Abstract

The ALBAC, a prototype of shuttle type autonomous underwater vehicle (AUV) which was designed and constructed for oceanographic measurement of water column on the way and from seabed. The ALBAC mainly consists of a body of a cylindrical pressure hull and a pair of wings which provide large lift force. By this mean, the ALBAC can move horizontally without consuming energy of batteries by gliding up to 20 degrees down from the horizontal plane. Major equipment including control actuators are installed in one cylindrical pressure hull, which has a 3-liter dry pay load space for scientific measurement devices. To control the attitude and trajectory, an actuator system displaces the location of the center of gravity longitudinally and laterally by moving a weight. Since these apparatuses are not exposed to the sea water, the actuators are not effected by environment resulting in significantly high reliability. To ensure the total system performance, sea trials were conducted at the Suruga Bay of Japan and longitudinal and lateral motions of the vehicle were measured.

Introduction

The oceanographic measurement is generally carried out being supported by a huge research ship. Since the apparatuses are hung from the deck, the ship and researchers on deck are restricted at the site. They are obliged to spend long idle time. This procedure of measurement has not been basically changed since the beginning of the history of oceanographic measurement because of hostile underwater environment. It can be said that sophisticated AUVs without an umbilical cable should be developed for efficiency and safety of measurement. Measurement of scientific data of water column, such as temperature, conductivity, pH, etc., is suitable as a mission of AUVs. This type of vehicle which descends to a specific depth and ascends back to the surface can be called a shuttle type AUV. Since such vehicles are not deeply concerned about the seabed or obstacles, the software system for the operation can be constructed in a simple architecture taking advantage of simplicity of the mission.

Photo 1 The ALBAC



Concept of the ALBAC

A prototype of shuttle type autonomous underwater vehicle which is named ALBAC (Photo 1), was designed by the authors and constructed in 1992.

Distinctive features of the vehicle are summarized as follows: 1) The ALBAC does not have a propeller thruster but moves aside by gliding[1]. Thus, the vehicle carries only a small battery of 100 W. To get large lift force a pair of wings is fitted at the middle of the body as illustrated in Fig. 1. 2) The ALBAC controls its trajectory changing pitch angle and roll angle by displacing the center of gravity. Two actuators in a hull move a weight longitudinally and laterally. Thus the major mechanism for control is not fitted outside the hull and the actuator system is not expose to the sea water. The total hardware system, therefore, becomes highly reliable. 3) Diving depth is limited to 300 meters so that the mass is only 45 kg. 4) The vehicle does not have a communication link to the operator, so that the ALBAC can be called a fully stand alone vehicle[2]. 5) It is easy to design a vehicle which can dive deeper according to the same concept.

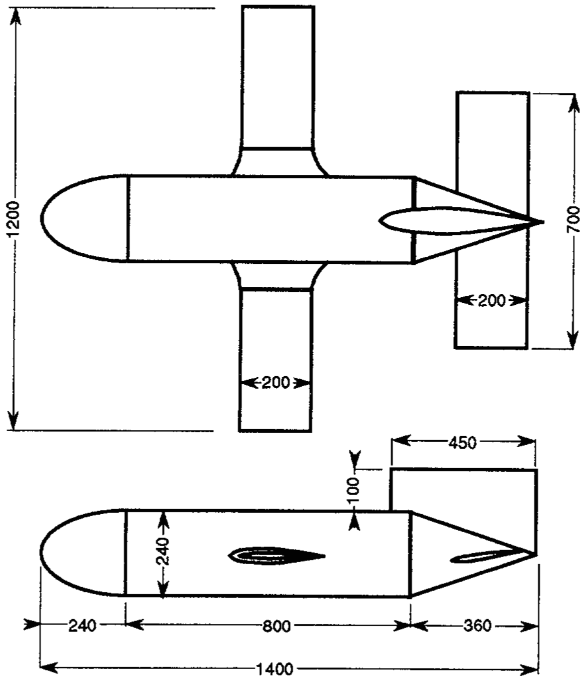


Fig. 1 Dimensions of the ALBAC

Mission Scenario

Deployment of the ALBAC consists of three stages as illustrated in Fig. 2.

1) Decent stage : The ALBAC descends to the destination depth and measures scientific data of water column along a gliding trajectory.

2) Drop of a weight : When the vehicle comes to the destination depth, it drops a decent weight and becomes positive buoyant for ascent. In case of emergency, for instance the vehicle dives over the design depth of 300 meters or the ranging sensor finds an obstacle, the vehicle also drops a weight.

3) Ascent stage : The ALBAC glides upward in the same manner as the decent stage and the oceanographic measurement can be continuously carried out through this stage.

At present the ALBAC is able to carry out the following mission scenarios depending on the software system which controls the gliding angle and the turning radius.

1) Fixed destination : The ALBAC glides to the target point on the bottom and turns back to the other destination on the surface.

2) Constant heading : The ALBAC keeps an azimuth on the way and from the destination depth.

3) Corkscrew dive : Since the gliding angle can be changed from 15 to 30 degrees, the ALBAC glides spirally to descend and ascend vertically. Depth rate can be changed by controlling turning radius.

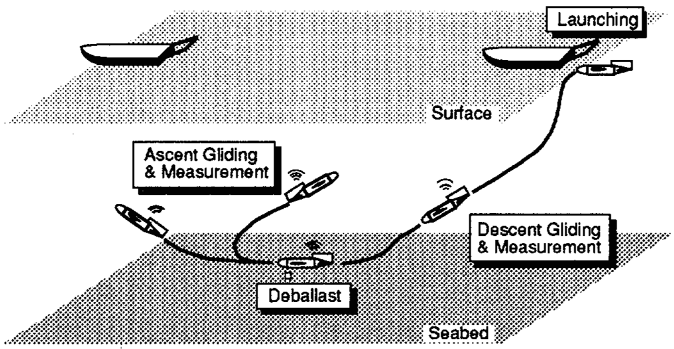


Fig. 2 Mission Scenario of the ALBAC

Estimation of Gliding Performance

The gliding performance of the ALBAC was estimated and evaluated in the first design stage, because it completely depends on the shape of hull. Suppose that the center of gravity of the vehicle O is gliding at speed V. Configuration of the vehicle is illustrated in Fig. 3 where the gliding angle and the angle of attack are denoted by γe and α, respectively. The proportional gliding angle γe and static stability of the system are given by

$$\tan \gamma e = C_D / C_L , \quad (1)$$

$$dC_m / d\alpha < 0. \quad (2)$$

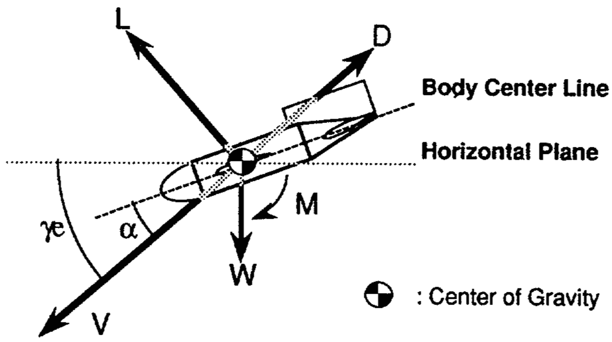


Fig. 3 AUV in Gliding

Here, C_L : lift coefficient, C_D : drag coefficient, C_m : moment coefficient, α : angle of attack. These Coefficients are functions of the shape and the angle of attack, and can be calculated on the basis of USAF DATCOM[3] compiled for estimation of the stability and for improvement of aircraft[4].

Equilibrium equations of forces and moment which determine α, γe and V are given by

$$B - G + (L_W + L_T + L_B) \cos \gamma e + (D_W + D_T + D_B) \sin \gamma e = 0 \quad (3)$$

$$(L_W + L_T + L_B) \sin \gamma e + (D_W + D_T + D_B) \cos \gamma e = 0 \quad (4)$$

$$-[l_G \times G \times \cos(\gamma e - \alpha)] + [l_{buoy} \times B \times \cos(\gamma e - \alpha)] + l_W \times L_W \times \cos\alpha + l_W \times D_W \times \sin\alpha + l_T \times L_T \times \cos\alpha + l_T \times D_T \times \sin\alpha + l_{body} \times L_B \times \cos\alpha + l_{body} \times D_B \times \sin\alpha = 0 \quad (5)$$

Here, B: buoyancy, G : dry weight, L_W : wing lift, D_W : wing drag, L_T : tail lift, D_T : tail drag, L_B : body lift, D_B : body drag, l_G : location of center of gravity from body apex, l_{buoy} : location of center of buoyancy from body apex, l_W : aerodynamic center location of wing from body apex, l_T : aerodynamic center location of tail from body apex, and l_{body} : aerodynamic center location of body from body apex.

At the first stage of development, a 30 cm length model was made and tested to evaluate gliding performance. Results of the test show good agreement with the estimated values as in Fig. 4.

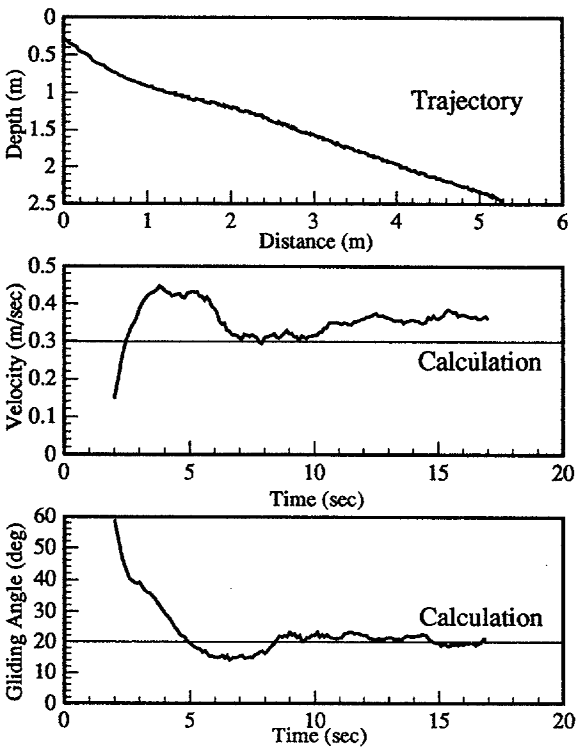


Fig. 4 Results of Gliding Experiment with a Small Model

Construction of the ALBAC

Shape of The ALBAC The body of the ALBAC consists of a 1/2 ellipse shape front cap, a cylindrical pressure hull, a corn shape tail cap with a vertical stabilizing fin, a pair of wings and tail wings, which are made of FRP except the pressure hull.

The dimensions of the vehicle basically depend on that of the cylindrical part of the body which should provide enough space for electric and electronic devices, i.e., a

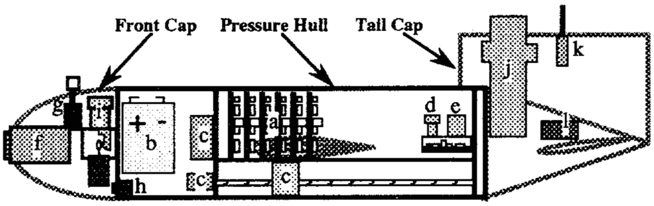


Fig. 5 General Arrangement of the ALBAC

Table 1 Instruments of the ALBAC

a) CPU	NEC V50 x 2
a) Math Processor	INTEL 8087
a) Memory Capacity	128 Kbyte x 2
a) Interface	RS-232C, PIO, Counter, Pulse Generator, AD Converter
b) Power Supply	13.6v, 7Ah (Ni-Zn Battery)
c) Actuators	1 set
d) Gravity Sensor	X, Y, Z Axis Output
e) Magnetic Sensor	X, Y, Z Axis Output
f) Ranging Sensor	500 kHz
g) Velocity Sensor	Propeller Type
h) Depth Sensor	0 to 30 atm.
i) Deballastor	Oil-Immersed Solenoid
j) Transponder	23 kHz
k) Thermistor	-5 to30 ℃ (±10V Output)
l) Tail Angle Trigger	Oil-Immersed Solenoid

depth sensor, a gravity sensor, a magnetic sensor, two CPUs, interface boards and two actuators to trim and roll. A ranging sensor, a velocity sensor, a deballastor, a tail angle trigger and a transponder are fitted in the front and the tail caps (cf. Table 1 and Fig. 5). Consequently, a prototype vehicle of 140 cm in length, 120 cm in span and approximately 45 kg in mass was designed and constructed as shown in Photo 1, Figs. 1, 5 and Tables 1, 2.

Table 2 Specifications of the ALBAC

Diameter of Body	0.236	meter
Volume Overall	55	liters
Mass	45	kg
Pay Load Space	3	liters
Gliding Speed	1～2	knots
Maximum Gliding Angle	20	degrees
Endurant Time of Gliding	30	minutes
Endurant Time of CPU	60	minutes
Maximum Operation Depth	300	meter

<u>Pressure Hull</u> The pressure hull made of aluminum alloy is designed for diving to 300 meter depth with 2.0 safety factor, and provides a space for instruments listed in Table 1 including a 3-liter dry pay load space of 1-atmospheric pressure for scientific measurement devices.

<u>Wings</u> Wings and horizontal tail wings have a NACA 0009 symmetrical foil section considering both upward and downward gliding. The vertical stabilizing fin which prevents side slip has a NACA 0018 foil section[5].

<u>Battery</u> Since the instruments consume 44 watt electric power and time for one mission is estimated about 30 minutes, a nickel-zinc battery cell of 100 watt hour is selected and fitted on the fore bulkhead of the pressure hull.

<u>Ultra Sonic Apparatuses</u> A forward ranging sensor of 500 kHz with 4 degrees in beam width to detect obstacles, and a transponder with which relative position from the mother ship can be detected using a SSBL system, are fitted in the front cap and the tail cap. The transponder is self-contained and has not a link to the CPU of the vehicle.

<u>Attitude Angle Sensing System</u> A compact inertial navigation system which consists of a three-axis gravity sensor and a flux gate magnetic sensor is installed to measure the attitude of the vehicle. From the roll, pitch and yaw angles, their angular velocities are calculated at every 0.1 second.

<u>Sensors</u> A propeller type velocity meter with a electric magnetic encoder to measure the forward velocity and a temperature compensated pressure transducer for the depth are fitted at the top of the front cap and the fore bulkhead, respectively.

<u>Actuators to Displace the Center of Gravity</u> To control the location of the center of gravity, two DC servo motors are driven with PWM by a computer system as illus-

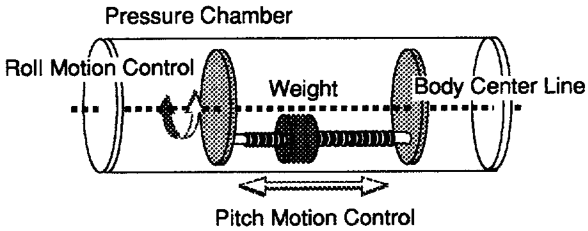


Fig. 6 Mechanism of Actuators

trated in Fig. 6. Capacity of motors are enough to move the weight even if the pitching angle is 90 degrees.

Computer System Design The computer system consists of two NEC V50 CPUs, i.e., one for control of attitude of the vehicle and the other for data logging. The structure of computer system is schematically illustrated in Fig. 7.

Data Transmission Data transmission to load a program and to acquire measured data is utilized RS-232c serial interface between the computer system of the ALBAC and a host computer on deck.

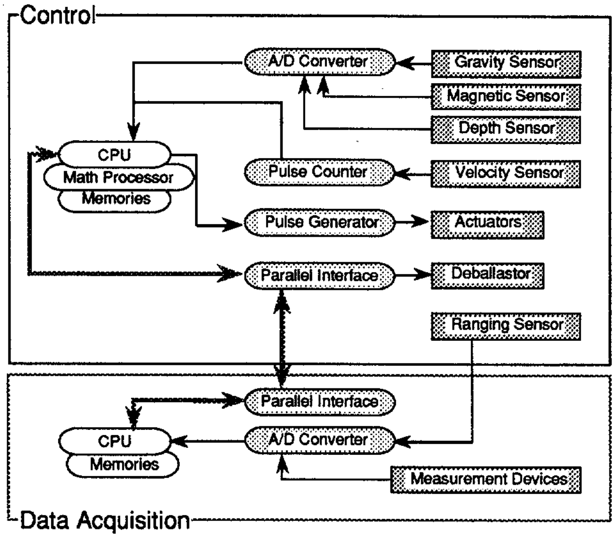


Fig. 7 Schematic Diagram of Computer System

Operation Sequence

A program for one mission is loaded from a host computer to the CPUs of the ALBAC on deck, then the umbilical is disconnected and the vehicle is hung from the deck and released to the sea. When the output of pressure transducer is over a specified level for example 0.6 meters, the control and data acquisition sequence is started. As in the same way of starting, the control and data acquisition sequence is ended when the vehicle ascends to the specific shallow depth. The vehicle on deck is connected to the umbilical and the measurement data are saved. A charged battery is exchanged for the next operation.

Sea Trials

Gliding Performance of the ALBAC To investigate the relation between the location of the center of gravity and the proportional gliding angle, sea trials were conducted at the Ashinoko Lake and the Suruga Bay. The gliding angle of the vehicle is calculated by the next equation based on the forward velocity and the rate of pressure.

$$\gamma e = \sin^{-1}\left(\dot{D}/V\right), \qquad (6)$$

Fig. 8 shows examples of time histories of data of one test. The proportional gliding angle is measured 18.7 degrees which shows good agreement to the estimated value 20 degrees. Fig. 9 shows the correlation between the longitudial location of the center of gravity and the proportional gliding angle in both the descent and ascent stages, where results in the next empirical formulas (in deg).

$$\gamma e = \begin{cases} -1.443\times10^{3}x+7.02\times10^{2} & \text{(Downward)} \\ -1.02\times10^{3}x+4.91\times10^{2} & \text{(Upward)} \end{cases} \qquad (7)$$

Here, x is the ratio of body length and the longitudinal location of the center of gravity measured from the body apex. It is shown in Fig. 9 that the gliding angle in a descent stage can be changed from 15 to 30 degrees.

Turning Performance of the ALBAC When the location of the center of gravity is shifted laterally, the ALBAC rolls and starts to turn in a constant yaw rate as shown in Fig. 10. Because of small misalignment of the tail wings, the vehicle rolls a little even if the weight has not been moved. The relations between the lateral location of the center of gravity and steady state yaw rate are determined as shown in Fig. 11 both in the descent and ascent stages. From these results, the following empirical formulas of yaw rate (in deg/sec) are obtain as,

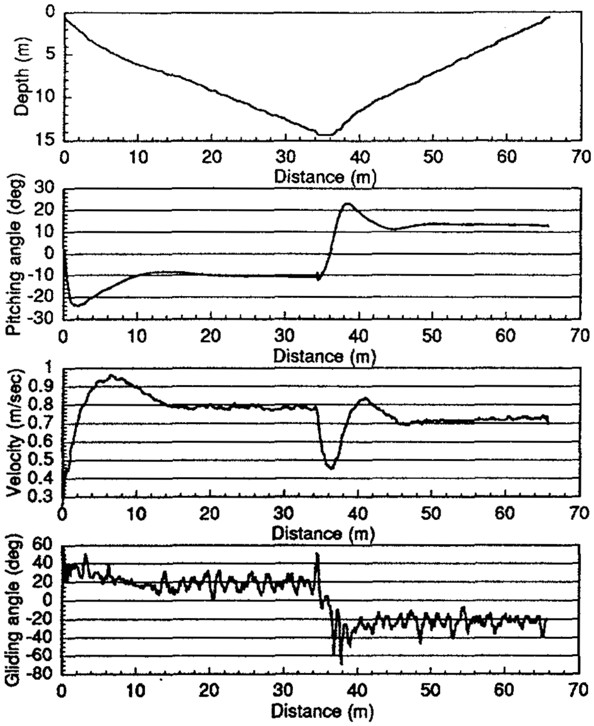


Fig. 8 Results of Gliding Experiment of 0.4788L Longitudinal C.G. Location

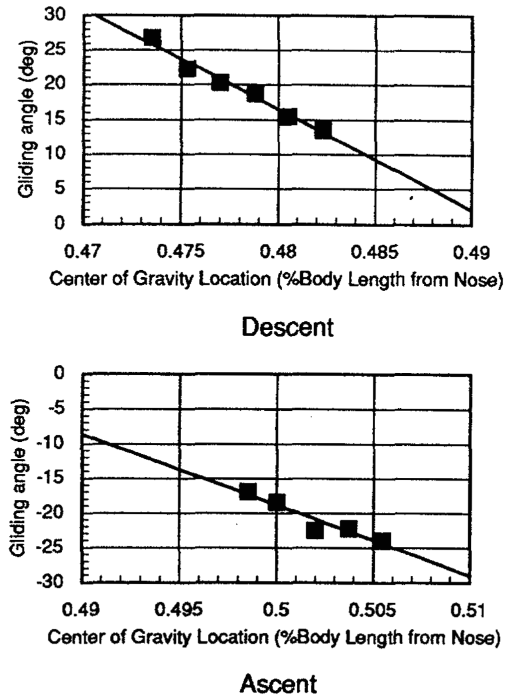


Fig. 9 Correlation between Longitudinal Center of Gravity Location and Gliding Angle

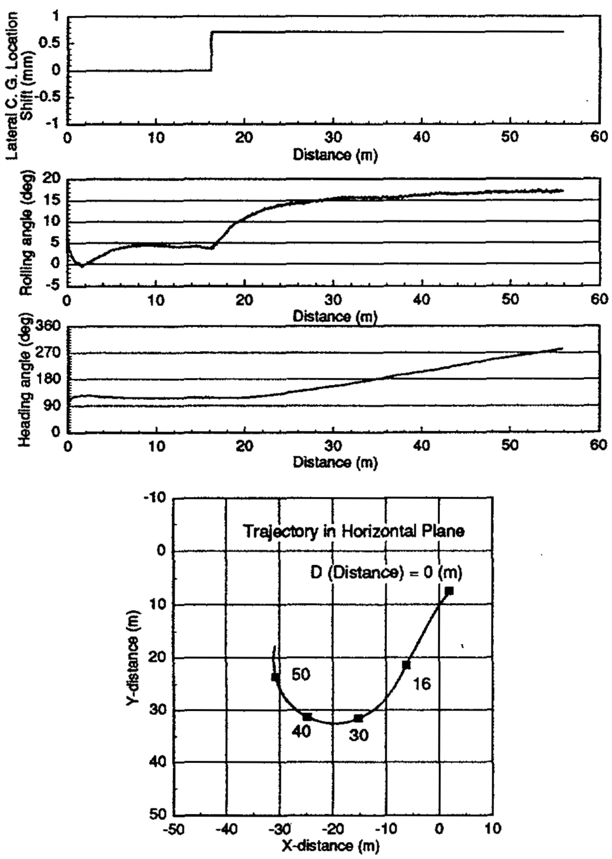


Fig. 10 Results of Step Responce Experiment in Lateral Motion

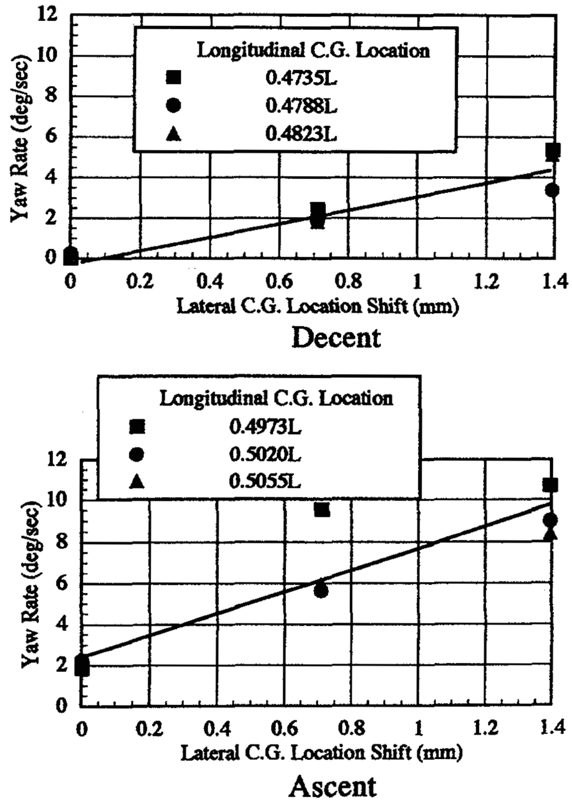


Fig. 11 Correlation between Lateral Center of Gravity Location and Yaw Rate

$$\dot{\Phi} = \begin{cases} 3.26y - 2.64\times10^{-2} & \text{(Downward)} \\ 5.275y + 2.45\times10^{1} & \text{(Upward)} \end{cases} \quad (8)$$

Here, y denotes lateral shift of the location of the center of gravity from the body center line. Exactly speaking, the proportional gliding angle may increase when the vehicle rolls because of decrease of vertical component of lift force. From the results of trials, however, it is concluded that this effect is negligible.

Oceanographic measurement of the ALBAC Fig. 12 shows an example of the distribution of temperature in a shallow water at the Suruga Bay measured by the ALBAC. Resolution and response of the thermistor are 1/100 degree and 1 sec, respectively. From these curves of data, it is expected that shuttle type AUVs can be competitive to the expandable bathythermograph (XBT).

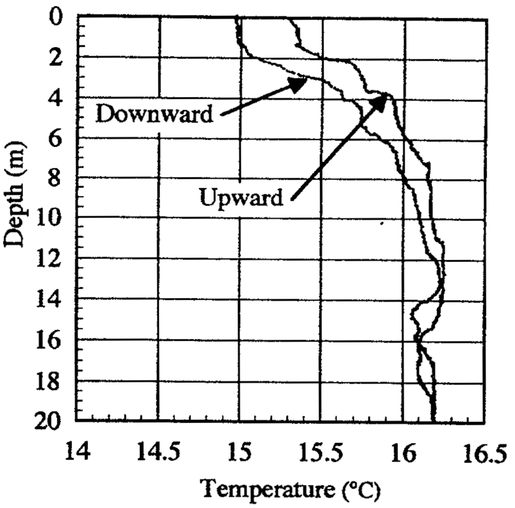


Fig. 12 Distribution of Temperature in Shallow Water, Mito-Hama, Numazu, Shizuoka on January 20th, 1993

Conclusion

The ALBAC was constructed as a practical AUV for oceanographic measurement. This paper introduced the process of design and details of the ALBAC. It is concluded that shuttle type AUVs are practical for oceanographic measurement of water column. The ALBAC is the first vehicle and can be modified for deeper dives by slight change.

Acknowledgment

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