Development and Experiments of the Sea-Wing Underwater Glider* 

YU Jian-cheng (俞建成), ZHANG Ai-qun (张艾群), JIN Wen-ming (金文明), CHEN Qi (陈琦), TIAN Yu (田宇) and LIU Chong-jie (刘崇杰) 

State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China 

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ABSTRACT

Underwater gliders, which glide through water columns by use of a pair of wings, are efficient long-distance, long-duration marine environment observatory platforms. The Sea-Wing underwater glider, developed by the Shenyang Institute of Automation, CAS, is designed for the application of deep-sea environment variables observation. The system components, the mechanical design, and the control system design of the Sea-Wing underwater glider are described in this paper. The pitch and roll adjusting models are derived based on the mechanical design, and the adjusting capabilities for the pitch and roll are analyzed according to the models. Field experiments have been carried out for validating the gliding motion and the ability of measuring ocean environment variables. Experimental results of the motion performances of the glider are presented.

Key words: underwater glider; AUV; underwater vehicles; ocean environment observatory

1. Introduction

Underwater gliders adjust buoyancy to generate gliding motion through water columns by a pair of wings. Various types of underwater gliders have been developed and have been tested as efficient long-distance, long-duration ocean sampling platforms. Underwater gliders with the advantages of low cost, long-duration, controllability and reusability are becoming essential ocean environment observatory platforms. Underwater gliders are suitable for the observations of mesoscale and sub-mesoscale ocean dynamic processes, and provide high spatial and temporal resolution observation data for oceanography researches. By taking the advantages of flexibility and controllability, the underwater gliders can be used to explore and track instantaneous marine events. The data collected by underwater gliders can be reported with relatively short delay via satellite communication, and they can operate for several months while covering thousands of kilometers. These advantages make underwater gliders ideal instruments to increase spatial and temporal density of ocean observations and to enlarge the range of scales that can be
resolved (Davis et al., 2002). Therefore, underwater gliders are going to play more important roles for oceanography observatory as versatile, multi-purpose platforms.

Many researches related to underwater gliders have been performed worldwide, after Stommel (1989) proposed the original concept of underwater glider in 1989. ALBAC (Kawaguchi et al., 1993) is an underwater glider prototype, which realizes gliding motion by use of drop weight. The Slocum (Webb et al., 2001), the Seaglider (Eriksen et al., 2001) and the Spray (Sherman et al., 2001), which are small underwater gliders powered by battery, have already been adopted by oceanographic research missions. The thermal SLOCUM is a small gliding AUV of 40000-km operational range, which harvests its propulsive energy from the heat flow between the vehicle engine and the thermal gradient of the temperate and tropical ocean. New designs, such as the Deepglider (Osse and Eriksen, 2007) for 6000 m operating depth, the XRay (ONR, 2006) with heavy load capability, and the BOOMERANG (Nakamura et al., 2008) disk type underwater glider for virtual mooring, are being refined. Wang et al. (2006, 2009) designed a type of underwater glider propelled by thermal energy in ocean. Ni et al. (2008) studied the mechanism for adjusting the performance of a buoyancy regulating system for a thermal underwater glider. Bachmayer et al. (2004) proposed a concept of hybrid underwater glider, and some hybrid underwater gliders are already developed (Caffaz et al., 2010; Wu et al., 2010). A wide range of sensors have already been deployed on gliders, and glider networks appear to be one of the best approaches to achieve subsurface spatial resolution necessary for ocean research (Rudnick et al., 2004; Glenn and Schofield, 2009). Yu et al. (2010) proposed a gliding motion parameter optimization method for maximizing gliding range.

Several fundamental research results about underwater gliders have been reported in the literature. The nonlinear dynamic models presented herein (Leonard and Graver, 2001; Graver, 2005; Bhatta, 2006) provide the basis for motion control. Wang and Wang (2009) derived a dynamic model of an underwater glider, considering both an eccentric rotatable rigid body and a translational rigid body. The pressure hull of underwater glider is optimized for increasing compressibility and reducing weight (Eriksen et al., 2001; Li et al., 2008; Wang et al., 2008a). The optimization design of the shape of underwater gliders has been widely researched based on CFD software or experiments (Gu et al., 2009; Hu et al., 2005; Ma et al., 2006; Ma et al., 2007; Wang et al., 2008b). Zhang et al. (2009) researched the impact of the layout of the buoyancy engine on the performances of underwater glider. Zhao et al. (2009) designed a buoyancy regulating system for an underwater glider and analyzed its dynamic performance. Mahmoudian et al. (2010) developed an approximate analytical expression for steady turning motion, which suggested efficient motion control as well as a planning strategy for energy efficient paths.

The Sea-Wing underwater glider, developed by the Shenyang Institute of Automation, CAS in collaboration with the Institute of Oceanology, CAS, is designed for the application of the observation of deep-sea environment variables. The underwater glider has an individual integrated attitude (pitch and roll) regulating mechanism, which make the attitude regulating unit more compact. The modularized design of the scientific measurement sensor unit allows the glider to be used for multi applications by fitting out corresponding measurement sensors. In this paper, we first describe the system components of the Sea-Wing underwater glider and briefly describe the gliding motion process of the glider. Then the
mechanical design and the control system design of the Sea-Wing are presented, the relationship models of the regulating mechanisms are established, and the performance of the pitch angle regulating device under the impact of other mechanisms is analyzed based on these models. Finally, we present the motion performances of the glider tested during lake experiments, as well as some results of sea trials.

2. Operation Process and System Components

2.1 Operation Process

The operation process of underwater glider contains continuous gliding and sampling along a saw-tooth trajectory. The gliding speed can be controlled through adjusting the driving-buoyancy and the pitch angle of the glider. The heading of the glider is controlled by adjusting the roll angle during gliding motion. High spatial and temporal resolution vertical profiling data are collected by continuously sampling the environment variables during the gliding motion process. Fig. 1 shows the operation process of an underwater glider. The underwater glider ascends to and stays at the surface for fixing its position with GPS module and communicating with a control center with satellite communication, after it completes a full gliding motion sampling cycle. The position and the collected data of the previous sampling cycle are transmitted to the control center by the connected satellite communication channel, and the control center sends new sampling missions to the glider at the same time. When the underwater glider completes the transmission of the collected data, the glider first records its current new position and then begins to execute a new sampling cycle according to the received commands. Once the underwater glider begins to glide downward to execute the gliding sampling cycle, it will lose communication connection with the control center until it completes the sampling cycle and returns to the surface again. During the gliding motion process, the underwater glider autonomously controls its pitch angle, gliding speed and keeps it gliding with an expected heading. The sampling resolutions for the ocean environment variables can be set at a fixed value or be dynamically adjusted based on the distributed feature according to the depth of the measured variables.

![Fig. 1. Operation process of an underwater glider.](image)

2.2 System Components

The Sea-Wing underwater glider (Fig. 2) consists of a pressure hull to which horizontal wings,
vertical fixed rudders and a trailing antenna are attached, and all subsystems of the underwater glider are enclosed in the pressure hull. The glider can be divided into four modules, which are joined to form a complete pressure hull. The subsystems of the glider include a buoyancy-regulating mechanism, a pitch-regulating mechanism, a roll-regulating mechanism, an embedded control system, a communication & navigation system, scientific sensors and an emergency release system.

The buoyancy-regulating mechanism alters the buoyancy of underwater glider by feeding hydraulic oil into or bleeding hydraulic oil out of the external oil bladder to produce the driving buoyancy. The pitch-regulating mechanism controls the pitch angle of underwater glider by moving an internal battery package along the longitudinal axis to change the center of gravity (CG) of the glider, which leads to pitch angle change. The roll-regulating mechanism controls the roll angle of the underwater glider by turning an eccentric module around the longitudinal axis of the underwater glider. The embedded control system, developed based on an ARM low power processor, is responsible for mission management, motion control, data sampling, health states monitoring, and so on. The communication & navigation system consists of Iridium satellite communication, wireless communication, TCM electrical compass, GPS, pressure meter and obstacle avoidance sonar. The scientific sensors refer to all the sensors used for measuring ocean environment variables, such as CTD, oxygen sensor, scattering and backscattering sensor. The current version Sea-Wing underwater glider just installs a CTD sensor for measuring the temperature and salinity of seawater. And the emergency release system with an independent energy package will release a lead-ballast when the glider suffers from emergency conditions. Some specifications of the Sea-Wing underwater glider are summarized in Table 1.

![Fig. 2. Picture of the Sea-Wing underwater glider.](image-url)

| Table 1 | Some specifications of the Sea-Wing underwater glider |
|---------|------------------------------------------------------|
| Size    | Hull diameter 22 cm, vehicle length 2 m, wing span 120 cm |
| Weight  | 65 kg |
| Depth rating | 1200 m |
| Battery | Lithium primary batteries or Lithium secondary batteries |
| Range   | > 500 km |
| Communications | RF modem and Iridium satellite |
| Navigation | GPS, altimeter, TCM |
| Scientific sensor | CTD |
3. Mechanical Design and Analysis

The mechanical design of the underwater glider includes vehicle shape design, pressure hull design, pitch-regulating mechanism design, roll-regulating mechanism design, buoyancy-regulating mechanism design, and other accessories. The vehicle shape design involves the hydrodynamic optimization design of the main body shape, horizontal wings, vertical fixed rudders and the attached positions of the wings and rudders to the main body, for reducing the hydrodynamic drag and improving the hydrodynamic performances of the underwater glider. These works have been studied by using the hydrodynamic calculation software ANSYS CFX, and the results were presented by Hu et al. (2005) and Gu et al. (2009). Besides considering the typical problems of strength and stiffness during the design of the pressure hull, the compressibility of the pressure hull also should be considered. The different compressibility between the pressure hull and seawater will cause additional changes in net buoyancy, which leads to additional energy consumption. Therefore, under the premise of satisfying the design requirement of strength and stiffness for the pressure hull, the additional energy consumption can be reduced by making the compressibility of pressure hull close to that of seawater. The optimization design process for improving the compressibility of the pressure hull is studied by Li et al. (2008).

In the following of this section, we describe the mechanical design of the three internal actuation mechanisms of the Sea-Wing underwater glider. As defining a body-fixed reference coordinate frame $\mathbf{o-xyz}$, where the $\mathbf{o}_x$ axis points to the fore along the longitudinal axis of the glider, the $\mathbf{o}_y$ axis points to the starboard of the glider, and the $\mathbf{o}_z$ axis is determined by the right-hand rule, the origin point of the frame is set to the center of buoyancy (CB) when the glider keeps the neutral buoyancy balance state. When the underwater glider keeps the neutral buoyancy balance state, the gravity is equal to the buoyancy, both pitch angle and roll angle are equal to zero, and the coordinates of CG and CB are defined as $(x^e_G, y^e_G, z^e_G)$ and $(x^e_B, y^e_B, z^e_B)$ respectively. According to the definition of the body-fixed frame, we have $x^e_G = x^e_B = 0$, $y^e_G = y^e_B = 0$, $z^e_B = 0$, and $z^e_G > 0$.

3.1 Pitch-Regulating Mechanism Design

The pitch angle should be adjusted to a desired value for realizing the underwater glider gliding along an expected saw-tooth trajectory. Usually, the pitch angle of underwater glider is adjusted by controlling the relative position between the CG and the CB in $\mathbf{x}$ axis of body-fixed frame. For the Sea-Wing underwater glider, an internal battery package, used as a moving mass module, is driven to move along $\mathbf{x}$-axis direction for changing the coordinate $x^e_g$ of the CG. Fig. 3 shows the schematic of the pitch-regulating mechanism of the Sea-Wing underwater glider. A screw-drive mechanism with self-locking, driven by a motor and planetary gear component, is used to drive the battery package, and the moving distance of the battery package is exactly measured with a line potentiometer.

When the glider keeps neutral buoyancy balance state, we define $(x^p_g, 0, z^p_g)$ as the center of mass (CM) of the battery package. Therefore, the change value of $x$-axis coordinate $x^e_g$ of the CG can be
computed according to $x$-axis coordinate $x_p$ of the CM of the battery package.

$$\Delta x_p = \frac{m_p (x_p - x_p^e)}{m}.$$  (1)

where $m$ is the total mass of the glider and $m_p$ is the mass of the battery package.

### 3.2 Roll-Regulating Mechanism Design

The underwater glider changes its roll angle for adjusting its heading during gliding motion. And the roll angle is adjusted by controlling the $y$-axis coordinate $y_o$ of the CG. For the Sea-Wing underwater glider, the pitch-regulating mechanism is designed as eccentric mass, thus it is acted as an eccentric mass module for the roll-regulating mechanism. So turning the eccentric mass module around $x$-axis of body-fixed frame can control $y$-axis coordinate $y_o$ of the CG. A worm-drive mechanism with self-locking capability is used to turn the eccentric mass module, and the angle of turn is exactly measured with a rotary potentiometer. Fig. 4 shows the schematic of the roll-regulating mechanism.

When the glider keeps the neutral buoyancy balance state, we define the coordinates of the CM of the eccentric mass module as $(x_r^e, 0, z_r^e)$. As the eccentric mass module is the pitch-regulating mechanism, the movement of the battery package during the process of adjusting pitch angle will change $x$-axis coordinate $x_c$ of the CM of eccentric mass module. But the change of $x_c$ will not affect the roll angle of the glider, thus we do not consider the change of the $x_c$ induced by the pitch-regulating mechanism. The $y$-axis coordinate $y_r$ and $z$ axis coordinate $z_r$ of the CM of eccentric mass module can be computed according to the angle of turning $\gamma$ as:

$$y_r = e \sin \gamma;$$  (2)
\[ z_r = e_r \cos \gamma . \]  

Hence, the changes of the \( y \)- and \( z \)-axis coordinates of the CG induced by the roll-regulating mechanism can be computed as:

\[ \Delta y'_G = \frac{m e_r \sin \gamma}{m}; \]  

\[ \Delta z'_G = \frac{m e_r (\cos \gamma - 1)}{m}, \]

where \( m_r \) is the mass of eccentric module; \( e_r \) is the eccentricity of the eccentric module; \( \gamma \) is the angle of turning, and clockwise rotation is defined as negative and counterclockwise rotation is defined as positive.

### 3.3 Buoyancy-Regulating Mechanism Design

The buoyancy-regulating mechanism of the Sea-Wing underwater glider provides the required driving-buoyancy by adjusting the displacement of the vehicle. Fig. 5 shows the principle schematics of the buoyancy-regulating mechanism of the glider. The buoyancy-regulating mechanism changes the buoyancy of the glider by generating the flow of hydraulic oil into or out of an external oil bladder. When the buoyancy is required to increase, a high-pressure hydraulic axial piston pump is used to pump hydraulic oil from an internal oil bladder to the external oil bladder. On the contrary, when the buoyancy is required to reduce, a partial vacuum within the pressure hull enables hydraulic oil to flow out of the external bladder under atmospheric pressure when a solenoid valve is turned on. The quantity of oil change is measured by a linear potentiometer attached to the internal oil bladder.

![Principle schematics of the buoyancy-regulating mechanism.](image)

The coordinates of the CG and the CB will be changed during the process of buoyancy adjusting. Fig. 6 shows the installed positions of the internal oil bladder and the external oil bladder of the buoyancy-regulating mechanism in the Sea-Wing glider. We assume that the \( x \)-axis coordinates of the CM of the internal oil bladder \( x_{ib} \) and the CM of the external oil bladder \( x_{eb} \) would not be changed during the process of buoyancy adjusting. Define the required driving-buoyancy as \( \Delta B = B_{GB} \). When the glider is in neutral buoyancy balanced state, \( \Delta B = 0 \); when the glider glides downward, \( \Delta B > 0 \); and when the glider glides upward, \( \Delta B < 0 \). Then, the changes of the \( x \)-axis coordinates of the CG and the CB induced by driving-buoyancy force \( \Delta B \) can be computed as:
Fig. 6. Installation position of the internal oil bladder and external oil bladder in the glider.

\[
\Delta x^G = \frac{\Delta B \rho_w}{mg \rho_o} (x_b^e - x_{ce}) ;
\]

\[
\Delta x^B = \frac{\Delta B}{mg + \Delta B} (x_{n}^e - x_{nw}) .
\]

Because of \( \Delta B \ll mg \), Eq. (7) can be simplified as:

\[
\Delta x^B = \frac{\Delta B}{mg} (x_{n}^e - x_{nw}) ,
\]

where \( \rho_o \) is the density of hydraulic oil, and \( \rho_w \) is the density of seawater.

3.4 Analysis of Design Results

Based on the above mechanical design results, the coordinates of the CG can be computed as:

\[
\begin{align*}
\left\{ \begin{array}{l}
x_G = x_G^e + \Delta x_G^v + \Delta x_G^y = x_G^e + \frac{m_p (x_p - x_p^e)}{m} + \frac{\Delta B \rho_w}{mg \rho_o} (x_{ns} - x_{ces}) \\
y_G = y_G^e + \Delta y_G^v + \Delta y_G^y = y_G^e + \frac{m_e \sin \gamma}{m} \\
z_G = z_G^e + \Delta z_G^v + \Delta z_G^y = z_G^e + \frac{m_e (\cos \gamma - 1)}{m}
\end{array} \right.
\end{align*}
\]

and the coordinates of the CB can be computed as:

\[
\begin{align*}
\left\{ \begin{array}{l}
x_B = x_B^e + \Delta x_B^v = x_B^e + \frac{\Delta B}{mg} (x_{ns} - x_{nwe}) \\
y_B = y_B^e \\
z_B = z_B^e
\end{array} \right.
\end{align*}
\]

By ignoring the effect of the hydrodynamic torque on the pitch angle during the process of gliding motion, the equilibrium pitch angle \( \theta \) of the glider determined by the three internal mechanisms can be computed as:

\[
\theta = -\arctan \left( \frac{x_G - x_B}{z_G - z_B} \right)
\]

\[
= -\arctan \left[ \frac{m_p \gamma (x_p - x_p^e) + \Delta B \rho_w (x_{ns} - x_{ces}) - \Delta B (x_{n}^e - x_{nw})}{mg (z_G^e - z_B^e) + m_e \gamma (\cos \gamma - 1)} \right]
\]
and the roll angle $\varphi$ of the glider determined by the three internal mechanisms can be computed as:

$$
\varphi = \arctan \left( \frac{y_G - y_a}{z_G - z_a} \right) = \arctan \left[ \frac{m_r e_r \sin \gamma}{m_r e_r \cos \gamma + (m_e e_e - \cos \gamma)} \right].
$$

(12)

It is shown from Eq. (11) that the pitch angle will be impacted by the driving-buoyancy force $\Delta B$ and the angle of turning $\gamma$ of the roll-regulating mechanism, except it can be controlled by the pitch-regulating mechanism.

Table 2 lists the mechanical design parameters of the Sea-Wing underwater glider. Incorporating these parameters into Eq. (11), we can achieve the results shown in Fig. 7 and Fig. 8. Fig. 7 shows the results of the pitch angle controlled by the moving distance $(x_p - x_p')$ of the battery package under different driving-buoyancy without considering the impact of the turning angle of the roll-regulating mechanism. It can be seen from Fig. 7 that the impact of the driving-buoyancy on the pitch angle is significant. On the condition of maintaining the $x$-axis coordinate $x_p$ of the battery package unchanged, the pitch angle will increase with the increase of the driving-buoyancy; on the contrary, the pitch angle will decrease with the decrease of the driving-buoyancy. Fig. 8 shows the results of the pitch angle controlled by the moving distance $(x_p - x_p')$ of the battery package with different angle of turning of the roll-regulating mechanism without considering the effect of the driving-buoyancy. It is shown from Fig. 8 that the angle of turning will enhance the pitch angle adjusting capability of the pitch-regulating mechanism, and the enhancement effect is more significant with the increasing of the turning angle.

| Parameter | Value |
|-----------|-------|
| $m$ (kg)  | 65    |
| $m_r$ (kg) | 10.5  |
| $m_e$ (kg) | 12    |
| $z_G$ - $z_a$ (mm) | 3     |
| $e_r$ (mm)  | 11    |
| $x_p - x_p'$ (mm) | -500  |
| $x_m - x_m'$ (mm) | -287  |
| $\Delta B$ (N) | $-500 \leq \Delta B \leq 5$ |
| $\gamma$ (°) | $-80 \leq \gamma \leq 80$ |

Table 2: Mechanical design parameters of the Sea-Wing underwater glider.
4. Control System Design

4.1 Hardware Design

The control system of the Sea-Wing underwater glider consists of low power embedded controller, power conversion and management, servo control system, data acquisition and storage, communication and navigation system as well as emergency system. The embedded controller, in which low level control software runs, is the core of the control system. The power conversion and management converts the voltage of the battery package to varied desired operation voltages required by the devices and sensors, as well as manages the power supply status for the devices and sensors. The servo control system is in charge of controlling the motors of the three regulating mechanisms. The data acquisition and storage is responsible for collecting the system states and sensors’ data, and making simple process to the collection data before storing these data in an onboard SD card. The communication and navigation system is used to sense the position and attitude of the glider, to transmit the collected data to the control center and to receive new commands. The emergency system is responsible for monitoring the health states of the glider and controlling a ballast-releasing device.

Except for considering the requirement of the control function for the underwater glider, reducing the energy consumption is the most important issue that should be considered during the control system design. In order to reduce the energy consumption of the control system, we have to reduce the energy consumption of the embedded controller and improve the efficiency of the power conversion and management. The power of the embedded controller of the Sea-Wing is significantly reduced by means of adopting low power processor and other chips as well as optimization circuit design. The methods used in the Sea-Wing for improving the efficiency of the power conversion and management include: using switching power converter for power conversion, optimizing the power conversion circuit according to the required operating current of sensors, and adding switches to all the power conversion circuits for completely turning off power supply of the devices and sensors when they are in the idle state.

The ARM processor has been widely used in all kinds of embedded control system for its advantages of low power, high performance, and small size. A NXP LPC series ARM processor chip, which is an ARM7TDMI-S based high-performance 32-bit RISC Microcontroller with Thumb extensions 256kB on-chip Flash ROM with In-System Programming (ISP) and In-Application Programming (IAP) 16KB RAM, is used as the core processor of the controller of the Sea-Wing. To satisfy the requirement of storage space for the low-level control program and memory, the embedded controller additionally extends 8MB low power FLASH and 2MB low power SRAM. Other peripheral circuits for the controller include expanding serial ports, expanding high precision AD converter, expanding DA converter, as well as other states sensing circuit. Using a multi-serial-port chip connected to a SPI serial interface expands eight serial ports. Using an AD converter chip connected to a SPI serial interface expands 4-channel 16-bit AD conversion. A 1GB SD card is connected to a SPI serial interface for storing all the collected data and other states data of the glider. A DA converter chip is connected to an I²C serial interface for expanding 4-channel DA conversion. Fig. 9 shows the basis schematics of the
The low power controller of the Sea-Wing underwater glider. Measurement experiments show that the power of the glider controller is smaller than 1 W when the supply voltage is 24 V.

4.2 Control Software

The low-level control software of the glider is used to manage all the sensors, devices, communication modules, and so on. The control software executes gliding motion control, data acquisition and storage, state sensing, data transformation, as well as other tasks. We divide the control software into three layers, including driver layer, operation system layer and application layer, as shown in Fig. 10. The driver layer is in charge of all operations related to all the hardware, consisting of I2C serial interface driver, SPI serial interface driver, SD card driver, UART driver, and I/O driver. In the operation system layer, an open source code, portable, scalable and multi-task real-time operating system and its file management system are used as the operation system for the control system. The application layer runs the programs related to the path planning, motion control, data acquisition, communication connection, state monitoring.

![Diagram](image-url)
5. Experimental Results

In order to validate the effectiveness of the developed Sea-Wing underwater glider and test its integrated functions in marine environment, we have carried out four field experiments including one time lake experiment and three sea trials. More than 100 gliding motion cycles have been completed during these field experiments.

5.1 Results of Lake Experiments

In 2008, the Sea-Wing underwater glider performed experiments in the Qiandao Lake, Hangzhou. The glider finished 80 times of gliding dive cycles for validating the fundamental gliding function and testing its performances during the lake experiments. The performances of gliding speed and heading control of the glider have been tested during the experiments. Fig. 11 shows experimental results of a gliding motion cycle in the lake experiment. The pitch angle is set to 20°, and the desired heading is set to 180°. It can be seen from Fig. 11 that the glider can successfully complete the gliding motion, and keep its heading around the desired value by adjusting its roll angle during gliding downward and upward.

Two groups of experiments are carried out to test the performance of gliding speed of the glider. One group of experiments test the gliding speed at different pitch angles with a specific driving-buoyancy, and the other group of experiments tests the gliding speed at different driving-buoyancy with a specific pitch angle. Fig. 12 shows the experimental result of the vertical component of gliding speed with different pitch angles for a specific driving-buoyancy. The result shows that the vertical component of gliding speed almost proportionally increases with the increase of the pitch angle for a specific driving-buoyancy. Fig. 13 shows the result of the vertical component of gliding speed with different driving-buoyancies for a specific pitch angle. The pitch angle is set to 20°, and the driving-buoyancies are set to 1.2 N, 2.4 N, 1.5 N and 3 N, respectively. It can be seen from Fig. 13 that the vertical component of gliding speed will increase about 1.5 times when the driving-buoyancy force is doubled.

![Fig. 11. Experimental results of a gliding motion cycle in the lake experiment.](image-url)
The turning direction of heading during gliding motion with different pitch angle and roll angle direction is validated by experiments, and the heading change rate with different roll angles for specific pitch angle and driving-buoyancy is tested. Table 3 shows the experimental results of turning direction of heading during gliding motion with different pitch angle and roll angle direction. Fig. 14 shows the result of the turning rate of heading with different roll angles. The pitch angle is set to 20° and the driving-buoyancy is set to 2.4 N during the experiments. It is shown from Fig. 14 that there exists a proportional relationship between the heading turning rate and roll angle for a specific pitch angle and driving-buoyancy.

### Table 3

| Pitch angle | Roll angle | Heading turning       |
|-------------|------------|-----------------------|
| $\theta < 0^\circ$ | $\varphi < 0^\circ$ | Counter clockwise     |
| $\theta < 0^\circ$ | $\varphi > 0^\circ$ | Clockwise             |
| $\theta > 0^\circ$ | $\varphi < 0^\circ$ | Clockwise             |
| $\theta > 0^\circ$ | $\varphi > 0^\circ$ | Counter clockwise     |

### 5.2 Results of Sea Experiments

The three sea trial experiments for the Sea-Wing underwater glider are carried out in the fields of the South China Sea, the Dalian Bay and the Western Pacific Ocean respectively in 2009. The Sea-Wing underwater glider has finished over 40 times gliding motion cycles during these sea trials, and the basic gliding motion function and the measurement capability for marine environment variables are validated.
under the actual marine environment. Fig. 15 shows the results of a gliding motion cycle in a sea trial. Fig. 16 shows the profile of temperature and conductivity measured by the on-board CTD sensor of the Sea-Wing glider during the sea trial.

![Graphs showing gliding motion cycle and temperature/conductivity profiles](https://via.placeholder.com/150)

**Fig. 15.** Results of a gliding motion cycle in the sea experiment.

**Fig. 16.** Profile of temperature and conductivity measured by the Sea-Wing underwater glider.

### 6. Conclusions

The Sea-Wing underwater glider is developed for the application of deep-sea environment variables observation, and it will become a useful platform for ocean environment observatory. The system components, the mechanical design, and the control system design of the Sea-Wing underwater glider are described in this paper. The effectiveness and reliability of the Sea-Wing underwater glider is validated through several field experiments, and the performances of gliding speed and the turning rate of heading are tested in the experiments. The following conclusions can be drawn.

1) The attitude adjustment models considering the coupled impact between the designed three mechanisms are established based on the design of the three internal actuated mechanisms.

2) A specific low power embedded controller based on the ARM processor is developed for the Sea-Wing underwater glider, and its low power performance and control function are validated by field experiments.
3) The gliding motion function and the measurement capability for marine environment variables are validated during the field experiments.

The Sea-Wing underwater glider has possessed the capability of measuring temperature and conductivity of seawater, and it also can measure other marine environment variables by mounting corresponding scientific sensors to the independent measure-sensor module located in the middle of the main body. The performances of the glider would be continuously improved as applying it in practical ocean environment observatory programs.

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