Research on Structural Design and Vision System of Narrow Shallow Water Multipurpose Underwater Robot

Nan Pan
Faculty of Civil Aviation and Aeronautical, Kunming University of Science & Technology, Kunming, P.R. China.

Xiao-Jue Guo
Kunming ZhiYuan Measurement & Control Technology Co., Ltd., Kunming, P.R. China

Jun-Bing Qian
Faculty of Civil Aviation and Aeronautical, Kunming University of Science & Technology, Kunming, P.R. China,
1226160701@qq.com

Yong-You Luo
Fujian Provincial Public Security Department Criminal Technology Corps, Fuzhou, P.R. China.

Yi Liu
Kunming SNLab Tech Co. Ltd., Kunming, P.R. China.

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RESEARCH ON THE STRUCTURAL DESIGN AND VISION SYSTEM OF NARROW SHALLOW WATER MULTI-PURPOSE UNDERWATER VEHICLE

Nan Pan[1], Xiao-Jue Guo[2], Jun-Bing Qian[1], Yong-You Luo[3] and Yi Liu[4]

ABSTRACT

In the narrow shallow water area, the underwater environment is complex and changeable, and the water area is narrow. Because of water body flow, various risks and unpredictable conditions, such as turbulence, vortex, disturbance, and so on exist which could seriously interfere with the motion and control of the underwater vehicle. In this way, the automatic stability and flexibility of multi-dimensional motion under external disturbance becomes the basis and requirement of underwater control and operation. In this paper, the structure design of the main body and power system of the narrow shallow water multi-purpose underwater vehicle was proposed to realize stable and flexible motion, and the driving mode of the coupling degree of freedom was designed and analyzed. The feasibility of the plan was verified via theory and simulation. Its vision system design was also introduced. Simulation and experiment results proved the correctness of the design and analysis.

I. INTRODUCTION

The underwater environment is complex, and most work underwater is currently performed by humans. Due to the quality of the underwater environment, depth of dive, limited dive time, extremely low temperature, and other conditions,

working underwater is difficult, inefficient, and expensive for divers (Kim et al., 2016). Moreover, it is harder to work in narrow water pipes that people cannot enter. The continuous development of navigation and positioning technology in the underwater area, the progress of automatic control technology and computer technology, and the maturing of underwater search and detection technology (Fischer et al., 2014), all allow for underwater vehicles to be used widely in the military and civilian fields. Underwater vehicles increasingly play an important role in deep water, a harsh environment, such as search and rescue, the laying of pipelines, submarine surveys, data collection, drilling support, subsea construction, the maintenance and repair of underwater equipment, aquaculture, rescue, and submarine rescue. When compared with divers, underwater vehicles have absolute advantages (Chen et al., 2019), especially in the narrow shallow water area with a depth of less than 30 m, such as wells and ponds. They will be used broadly in these areas. Underwater vehicles do not need a huge water surface to sustain themselves, rather a small area of the deck is enough, except that, it is quiet, hidden, and cheap (Cao et al., 2019). Underwater vehicles will attract more and more attention, which means that their market expectation would be huge. The dark environment and the interference of many foreign matters cause the effective distance of optical imaging devices to become reduced and the images to become fuzzy in the narrow shallow water area. Currently, just a few small underwater vehicles exist which are not only suited for the shallow water area but also have a low cost. Therefore, it is practical, urgent, and meaningful to start research and develop narrow shallow water multi-purpose underwater vehicles.

II. TOTAL STRUCTURE OF NARROW SHALLOW WATER MULTI-PURPOSE UNDERWATER VEHICLE

According to the application field of narrow shallow water multi-purpose underwater vehicles, they should have the following motion characteristics: (1) The underwater vehicle
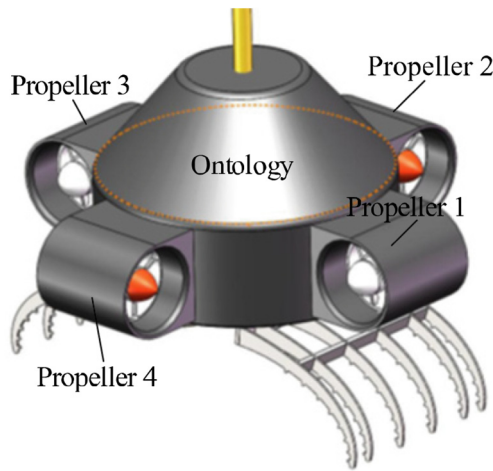
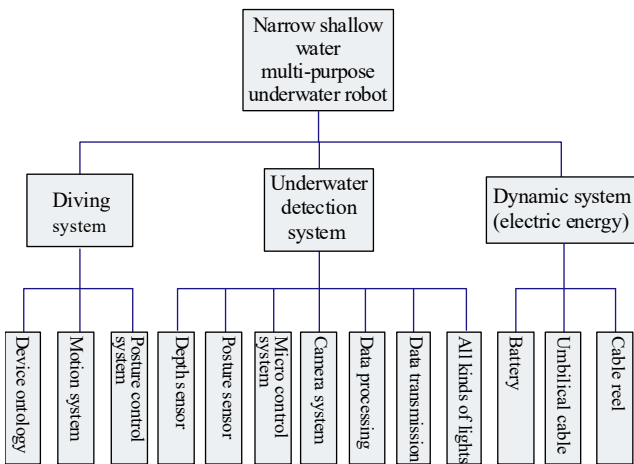Fig. 1. Vehicle prototype and overall structure layout.

Fig. 2. Vehicle function system block diagram.

should move slowly and not violently. (2) Due to the narrow and shallow waters, the propulsion system of the will cause disturbances in the entire water area during the propulsion process. This will affect the underwater propulsion direction of the vehicle; therefore, the vehicle system must have a good propulsion capability. If no efficient and stable power structure and timely adjustment exist in the control system, then it would produce serious dynamic errors, resulting in vehicles that cannot perform normal underwater operations. With this in mind, the design of the underwater vehicle dynamic structure system is shown in Figure 1.

The mechanical structure arrangement has the following advantages of navigation and attitude adjustment: (1) The power propellers were arranged symmetrically. During underwater propulsion navigation, four power propellers can be propelled in the same direction, that is, the same direction of working. In this way, the difficulty and quantity of control can be greatly simplified. (2) When the portable underwater detection equipment is used for an attitude adjustment, since the four power propellers are arranged in two symmetrical arrangements, the
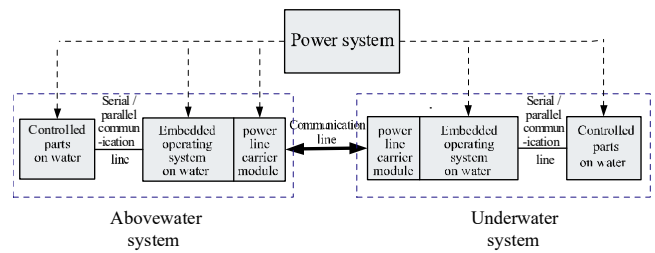

Fig. 3. The block diagram of the structure.

axial symmetry line can be used for an attitude adjustment. Simultaneously, as many as four axisymmetric lines exist for the portable underwater detection equipment, and four attitude adjustment methods can be chosen from, which also provide convenience and choice for subsequent control.

The narrow shallow water multi-purpose underwater vehicles usually work in the field of shallow water. Simultaneously, with the progress of underwater vehicles and the application of underwater vehicles becoming more frequent and extensive, the requirements of people for its functions and tasks are becoming more diversified and utilized. This is the new era of the market and the common needs of technology. The vehicle should have a small size and be light-weight. In this way, an open, modular, and customized multi-purpose underwater search and salvage vehicle will be highlighted (Zhang et al., 2018). The underwater search and salvage vehicle consists of three parts: a diving system, an underwater detection system, and a power system.

The diving system is the foundation and platform of the narrow shallow water multi-purpose underwater vehicle. It includes the equipment body, motion system, and attitude control system. It provides an effective carrier and platform for the implementation and integration of other system functions. The underwater detection system is the detection "organ" of a narrow shallow water multi-purpose underwater vehicle. It completes the perception and detection of the unknown underwater area (Guo et al., 2014). As a data processing and transmission system within the information system, the diving system also contains a variety of sensors, micro-control systems, cameras, and flashlights. The power system (electric energy system) of the portable underwater detection equipment is an auxiliary system. This system includes batteries, transmission cables, and cable reels, which provide power to supply the normal operation of the rest of the equipment (Li et al., 2017).

The design of narrow shallow water multi-purpose underwater vehicles is mainly divided into two relatively independent systems: aquatic systems and underwater systems, with the aquatic system for users and the auxiliary, underwater systems accomplishing detection tasks. Aquatic and underwater systems work together to complete the exploration of the underwater area. The block diagram of this structure is shown in Figure 3.

In the detection work, the power system provides power to the underwater and aquatic systems through cables. The aquatic
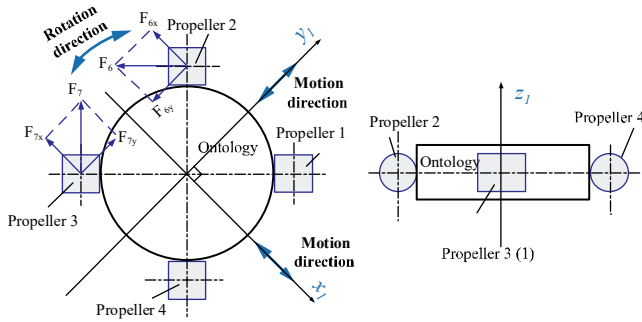
Fig. 4 Vehicle propeller drive diagram.

system interacts with users for tasks and transmits the instruction of the user to the underwater system in the form of power carriers. Simultaneously, it also can upload the underwater system status. The underwater system relies on its various sensors and instruments to complete the detection tasks independently which are issued by the aquatic system.

III. DESIGN AND ANALYSIS OF THE DYNAMIC STRUCTURE OF THE NARROW SHALLOW WATER MULTI-PURPOSE UNDERWATER VEHICLE

The multi-purpose underwater vehicles usually work in turbid shallow waters. The terrain of the water bottom is complicated and changeable and visibility is low. It is often necessary to repeatedly detect and observe certain important areas. Moreover, various undercurrents and surges often appear in the underwater area. All these reasons require the power system of the vehicle to provide a multi-attitude stable structure in the complex shallow water area. According to its dynamic arrangement structure, which symmetrically arranges eight power propellers, the attitude can be adjusted via the axisymmetric line. Figure 4 shows its dynamic analysis.

In the horizontal propeller drive design, as shown in Figure 4, to overcome the counter-torque of a single propeller, a symmetrical co-rotating design was adopted, that is, propeller 1 and propeller 3 are in one group, and propeller 2 and propeller 4 were in a group. The propeller blades in each group rotated in the opposite direction. Similarly, in the design, to ensure the linear drive in x_1 and y_1 directions, propeller 1 and propeller 2, and propeller 3 and propeller 4 were each grouped, as shown in Figure 4.

According to the arrangement of the narrow shallow-water multi-purpose underwater vehicle propeller in the above figure, the horizontal propulsion dynamic equation is as follows:

(1) When the horizontal (x_1 direction) motion is completed, its dynamic analysis is as follows (analysis with x_1 axis direction motion).

Figure 4 shows that in the illustration of a narrow shallow-water multi-purpose underwater vehicle propeller, propeller 2 and propeller 3 were used as a group, propeller 1 and propeller 4 were another group, and the propeller blades of each group

were moving in the same direction of rotation. When it moves in the direction of the x_1 axis, propeller 2 and propeller 3 (propeller 1 and propeller 4) would rotate in reverse to overcome the counter-torque of a single propeller.

$$\begin{cases} M_2 = -M_3 \\ F_2 = F_3 \end{cases} \tag{1}$$

Because both propeller 2 and propeller 3 were at a 45° angle with the x_1 axis and symmetrically arranged, the component forces F_{2y} and F_{3y} in the y_1 direction canceled each other out. The thrust force in the x_1 direction was the sum of the component forces of the two propellers, that is,

$$\begin{cases} F_{2y} + F_{3y} = 0 \\ F_{x1} = F_{2x} + F_{3x} \end{cases} \tag{2}$$

Among these, F_{x1} was the thrust of the narrow shallow water multi-purpose underwater vehicle propeller in the direction of x_1.

(2) When the horizontal movement (y_1 direction) was completed, the dynamic analysis is as follows (analysis with y_1 axis movement).

Similar to the movement in the direction x_1, as shown in Figure 4, a set of propeller 1 and propeller 2 was used, and another set of propeller 3 and propeller 4 was also used; therefore, the propeller blades of each group rotate would be in opposite directions. When it moves in the y_1 axis direction, propeller 1 and propeller 2 (propeller 3 and propeller 4) would rotate in the same direction to generate thrust in the y_1 direction, then, at this time, a counter torque in the same rotation direction was added.

$$\begin{cases} M_1 = M_2 \\ F_1 = F_2 \end{cases} \tag{3}$$

Similar to the motion analysis in the x_1 direction, because the propellers 1 and 2 were 45° from the y_1 axis and were arranged symmetrically, the component force in the x_1 direction could cancel each other out, and the thrust in the y_1 direction was the sum of the component force of the two propellers. Meanwhile, the deflection around the y_1 axis caused by the counter torque would be balanced by the horizontal propeller.

(3) When the rotational movement around the z_1 direction was completed, its dynamic analysis is as follows.

Figure 4 shows that propeller 1 and propeller 3 were used as a group, and propeller 2 and propeller 4 were in another group. The propeller blades of each group rotated in opposite directions. Simultaneously, the installation direction of the two propellers was the opposite. When the propellers were rotated simultaneously, their counter torques canceled each other out, and their thrust forces were opposite.
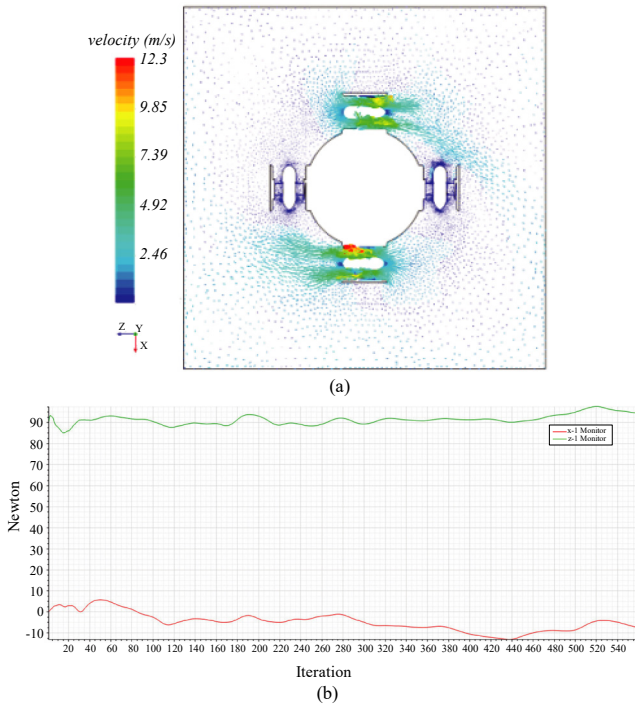
Fig. 5   Simulation results in a rotating state. (a) Velocity field. (b) Thrust curve.

Fig. 6   Simulation results in propulsion state. (a) Velocity field. (b) Thrust curve.

$$\begin{cases} M_1 = -M_3 \\ F_1 = -F_3 \end{cases} \qquad (4)$$

IV. SIMULATION

To verify the design and analysis, the flow field, pressure field, and thrust of the underwater vehicle in the propulsion state were simulated. Figure 5(a) shows that a set of rectangular coordinate system x-y-z was established, and each vector was decomposed into orthogonal components.

Figure 5 (a) shows that the thrust of the propeller formed a pair of couples to complete the rotation movement centered on the vehicle. Figure 5 (b) shows that the component of thrust in the X direction was about zero, and the thrust in the Z direction was approximately constant.

When the vehicle was in the propulsion state, its flow field distribution is that shown in Figure 6 (a). The thrust of propeller I is shown in Figure 6 (b). A thrust of about 100 N in the thrust direction Z of the propeller exists. Due to the mutual interference of the propeller, a component of about 10 N in the vertical direction X of the propeller exists. Since propellers I and II were symmetrically distributed in the propulsion direction, the resistance converted into thrust was overcome to ensure the stability and continuity of the propulsion state.

V. VISION SYSTEM
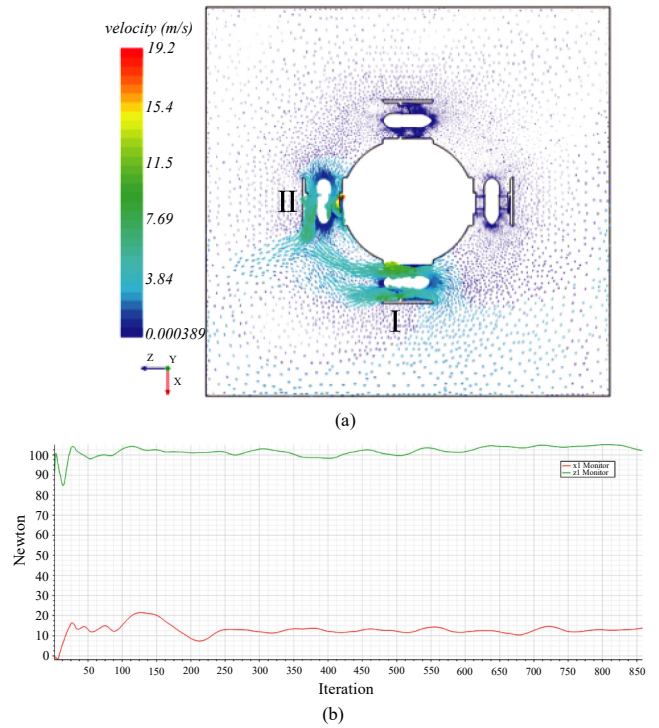
The vision systems of the narrow shallow water multi-

purpose vehicles usually work in the turbid water area, wherein visibility is poor. Even under the condition of an external light source, the image obtained by its vision system has a "fog" effect. This hinders the identification and subsequent salvage of underwater objects. To clear the underwater picture and obtain better visual effects, it is necessary to utilize a "defogging" algorithm to process the visual pictures. As a color theory in the field of image processing, Retinex can balance the three aspects of grayscale dynamic range compression, edge enhancement, and color constancy. Therefore, it can effectively enhance various image types, especially color images. This is a very effective technique and method in image defogging, and its algorithm is as follows:

$$R_i(x,y) = \sum_{n=1}^{N} W_n \left\{ \log\left[I_i(x,y)\right] - \log\left[F_n(x,y) * I_i(x,y)\right] \right\} \qquad (5)$$

In the formula, $R_i(\text{x,y})$ is the output of Retinex, $i \in R,G,B$ represents 3 color bands, $F(x,y)$ is a Gaussian filter function, W_n represents the weighting factor of the scale, N represents the number of scales used, and $N = 3$ represents a color image. $i \in R,G,B$ $N = 1$ means a grayscale image. The formula shows that the characteristic of the MSR algorithm is that it produces an output image that includes two characteristics of tone reproduction and dynamic range compression.

During the enhancement process of the image dehazing algorithm, the increase in noise may cause color distortion in the
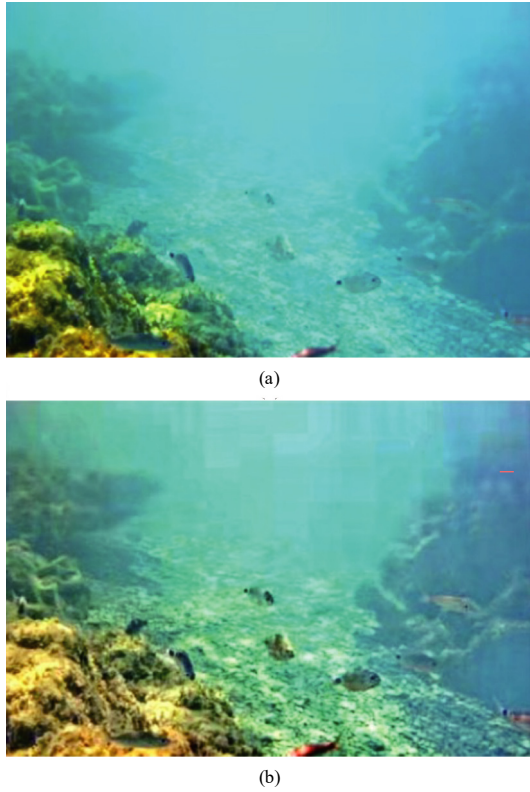
(a)

(b)

Fig. 7 Comparison of underwater image processing. (a) Original underwater image. (b) Processed image

local area of the image, so that the true color effect of the object may not be well displayed. A multi-scale algorithm (MSRCR) with a color recovery factor C is applied to solve the problem, with a color factor C introduced to compensate for the defect of image color distortion caused by the enhancement of the contrast of local regions in the image. The multi-scale algorithm with color restoration factor C (MSRCR) is the result of considering color un-distortion restoration based on multiple fixed scales. In the multi-scale Retinex algorithm, the expression of the color restoration factor C is usually introduced. The formula is

$$R_{MSRCR_i}(x,y) = C_i(x,y)R_{MSR_i}(x,y) \qquad (6)$$

$$C_i(x,y) = f[I_i(x,y)] = f[\frac{I_i(x,y)}{\sum_{j=1}^{N} I_j(x,y)}] \qquad (7)$$

In the formula, C_i represents the color recovery coefficient of the first channel. Its function is to adjust the color ratios of the three channels and $f(\bullet)$ represents the mapping function of the color space. The multi-scale Retinex algorithm (MSRCR) with color recovery adjusts the proportional

relationship between the three color channels in the original image through the coefficient of color recovery factor C, thereby highlighting the information of relatively dark areas to eliminate the image defects in color distortion. After processing, the local contrast of the image was improved, and its brightness was very similar to the real scene, with the image appearing extremely realistic to the visual perception of people. Therefore, the MSR algorithm has better color reproducibility, brightness constancy, and dynamic range compression.

As shown in Figure 7, the visibility of underwater causes the picture in Figure 7 (a) to be blurred, with the environment and outlines of some fishes not easily recognizable. This problem brings out obstacles for underwater detection and salvage. However, object outlines in water can be sharpened while maintaining the original colors as much as possible through multi-scale processing of the image, as shown n in Figure 7(b). It provides better foundations and guarantees for underwater detection.

VI. CONCLUSIONS

Due to the complexity and uncertainty of the working environment, this article designed the driving system of the narrow shallow water multi-purpose vehicle according to its underwater motion characteristics, as well as analyzed its total structure, control system, and visual defogging. Based on the principle prototype and experiments, the reasonable and effective components of the drive system design were verified.

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