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# Vision-based Waypoints Tracking Control for an Amphibious Spherical Robot

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***Abstract* – The localization plays an important role in the motion control and trajectory tracking of amphibious spherical robot. However, due to the complex environment in the water, some methods localization on land such as GPS cannot be applied to amphibious spherical robot. Therefore, a new method is needed to locate the amphibious spherical robot. This paper proposes an image recognition method using a global camera to locate the robot. In this method, the global camera is mounted on a platform with a known position, and the computer vision algorithm is used to identify the position of the amphibious spherical robot in the image, then calculate the coordinates and moving speed of the amphibious spherical robot. We applied this method to an amphibious spherical robot and verified it experimentally. In the experiment, the amphibious spherical robot can swim along the set rectangular trajectory by using this localization method, indicating that this localization method is effective.**

***Index Terms* – *Amphibious Spherical Robot; waypoint tracking; Computer Vision;***

## I. INTRODUCTION

In the research of robots, robot localization has always been a very important research direction. The trajectory of the robot can only be controlled by first localization the robot. For terrestrial and aerial robots, localization is relatively easy. In the field of industrial robots, there are many ways to position using optical sensors[1][2][3][4]. C. Liu proposed an indoor light wave localization system with correlation operations[5]. B. Cui proposed a method for localization using fixed landmarks[6]. There are many other localization methods for robots that move on land, such as laser localization[7], using visual localization[8]-[12], using particle filter algorithm to locate[13]. For underwater robots, especially amphibious spherical robots, due to the complicated environment in the water, GPS cannot be used. Or some optical method of localization, which makes it difficult to position the robot in the water[14][15][16][17]. Therefore, many researchers have conducted research on the localization and motion control of amphibious spherical robots. Y. He studied underwater motion characteristics evaluation of multi amphibious spherical robots[18][19]. X. Hou designed a NewWater-Jet Thruster for an amphibious spherical robot[20]. L. Zheng studied the communication and stability evaluation of amphibious spherical robots[21]. S. Pan designed a kinds of kinect-based real-time compressive tracking prototype system for amphibious Spherical robots[22][23].

In this paper, we propose a method for locating amphibious spherical robots using computer vision. Above the robot, a fixed camera is installed. The program on the external server recognizes the position and speed of the robot through the image captured by the camera, and then sends the measurement result to the robot's processor through underwater acoustic communication. In this way, the robot can obtain its own position and speed information. During the movement of the robot, the heading, depth and speed of the Confucius itself will be based on the target point and the current coordinates, so that the movement according to the set route can be realized. The robot selects different movement modes according to the relative position of the target point and the current coordinates, such as back and forth movement or left and right movement, so as to ensure that the movement direction is changed as little as possible during the movement of the robot, thereby improving the stability of the movement. Using the localization method of this paper, the robot can accurately position, depth, and move along a rectangular trajectory in the pool.

The reminder of this paper is organized as follow: Section 2 introduces the amphibious spherical robot. Section 3 propose a localization method based on computer vision algorithms. Section 4 conducted the experiment. Section 5 is a conclusion of this paper.

## II. AMPHIBIOUS SPHERICAL ROBOT

The traditional underwater autonomous submersible is not suitable for use in a narrow space or in a tidal environment because of its large size and amphibious function[24][25]. Therefore, in order to solve this problem, our team designed an amphibious spherical robot (ASR-IV), which is smaller in size, lower in power consumption and amphibious than the traditional

AUV, capable of coping with complex environments such as river bottoms and shoals[26]. The basic shape of ASR-IV is spherical. This symmetrical structure makes its control model simpler and has good motion flexibility.

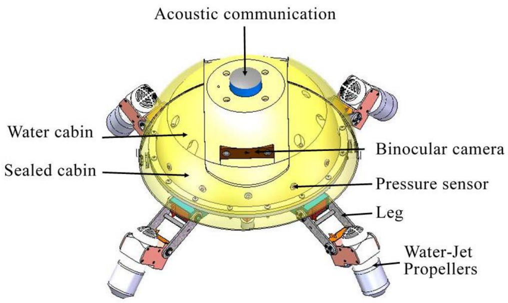


Fig. 1. The mechanical structure of ASR-IV.

The mechanical structure of ASR-IV is shown in Fig 1. Its basic shape is a sphere divided into upper and lower hemispheres. The upper hemisphere is divided into two bins - a water cabin and a sealed cabin. An underwater acoustic communication module (Acoustic communication) is installed above the water inlet to transmit information to the outside world. A binocular camera (Stereo camera) is also placed in front of the water inlet to identify the target in the water. The capsule is equipped with a robotic electronic control system that includes a Jetson TK1 processor and a control board. There are 12 pressure sensors around the sealed chamber to detect the depth of the robot in the water. The lower hemisphere shell consists of two quarter-ball shells that can be opened and closed, with a battery compartment and four legs of the robot. The ability of each leg of the robot to specifically travel on land and in the water is shown in Fig 2. Each leg is driven by three servo motors and several water jet propellers. When the machine is walking on land, the water jet propeller is closed and only provides support to the robot. When the robot swims in the water, the water jet thruster provides thrust to the robot and controls the direction of the thrust by changing the direction of the servo motor.

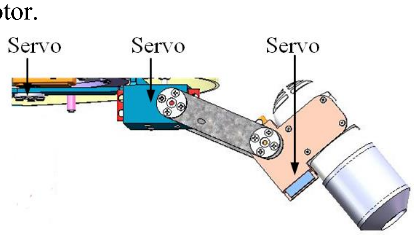


Fig. 2. Leg structure of ASR-IV.

## III. Localization Method

### A. Control Model

ASR-IV relies on a water jet propeller in the water to support the thrust, and can control the direction of the thrust by changing the direction of the servo motor. ASR-IV has four motion modes in the water, front-back motion, left-right motion, rotary motion, and up-down motion. Each sport mode is shown in Fig 3. Among them, Fig 3. (a) is the front- back motion mode. At this time, the front-back motion is realized by controlling the difference between the forward and backward thrust of the water jet propeller. Fig 3. (b) is the left-right motion mode. The difference between the left and right thrusts of the water jet propeller is to achieve the left and right motion. Fig 3. (c) is the rotary motion mode. At this time, the rotational motion is realized by controlling the difference between the thrusts of the adjacent waterjet propellers. Fig 3. (d) indicates the up and down motion mode. At this time, the direction of the water jet propeller is changed by controlling the angle of the end servo motor to achieve up and down motion. In robot motion control, we use the PID controller to calculate the difference of thrust in each direction. Through these four motion modes, we can flexibly control the heading, speed and position of the robot in the water. When the robot moves in the water, the four motion modes are not performed separately, but can occur simultaneously in a combined manner. For example, when controlling the difference between the forward and backward thrusts of the waterjet, it is possible to simultaneously control the thrust difference of the adjacent waterjets, so that a combination of forward and backward motion and rotational motion can be achieved, that is, at the control speed. At the same time control the heading. Similarly, when controlling the speed and heading, the up and down motion can be achieved by changing the angle of the end servo motor, that is, controlling the speed, heading, and depth at the same time.

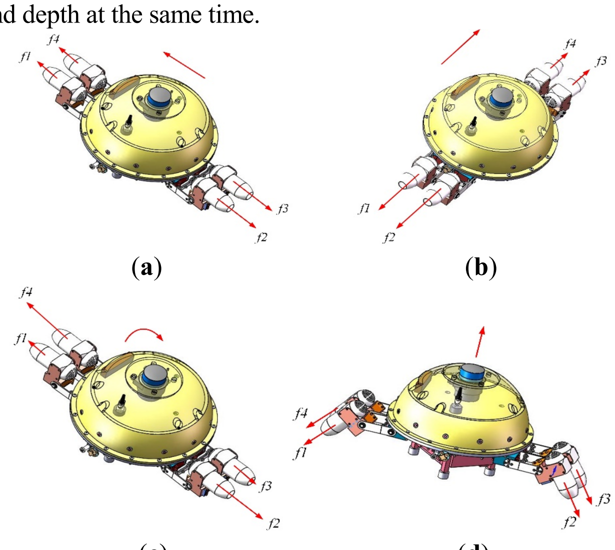


Fig. 3. Four motion modes in the water of ASR-IV. (a) front-back motion. (b) left-right motion. (c) rotary motion. (d) up-down motion.

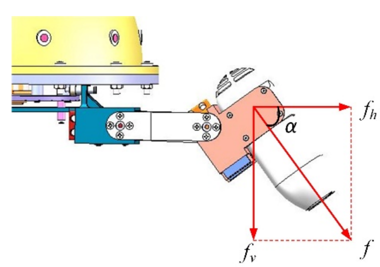


Fig. 4. Thrust decomposition of Water-Jet Propellers.

Therefore, by calculating the thrust of each waterjet and the angle of the end servo motor, the three-dimensional motion control of the robot in the water can be realized. We analyze the process by establishing a mechanical model. First, the force of each waterjet is decomposed into $f_h$ and $f_v$, as shown in Fig. 4, where $f_h$ represents the component of the waterjet in the horizontal direction, and $f_v$ represents the component of the water jet propeller in the vertical direction. Since $f_h$ and $f_v$ are orthogonal, for each waterjet, we can calculate $f_h$ and $f_v$ separately by the PID controller, and finally calculate each waterjet. The angle of the thrust and the end servo motor.

### *B. Robot Localization Model*

In order to control the movement of the amphibious spherical robot, it is necessary to measure the position. The traditional method to measure the position is use GPS[27], due to the shielding effect of water on the electromagnetic waves, the robot in the water cannot receive the GPS signal, so GPS cannot be used. Other methods for underwater robot localization include using fixed landmarks[28] or using the robot's own camera for visual relative localization[29][30], but this methods cannot be used in amphibious area. In order to measure the robot position in amphibious area, a vision-based localization system through a fixed global camera is designed, see in Fig. 5. This system can achieve higher localization accuracy and can locate multiple targets at the same time, so it can be applied to multi-robot collaborative control. In this system, a fixed camera is installed 3m above the center of the pool. The video captured by the camera calculates the position of the robot in the water in real time. The depth of the robot is obtained by the depth sensor installed on the robot. In this way, we can get the three-dimensional coordinates of the robot in the water. By differentiating the three-dimensional coordinates of the robot against time, the three-dimensional velocity of the robot can be calculated.

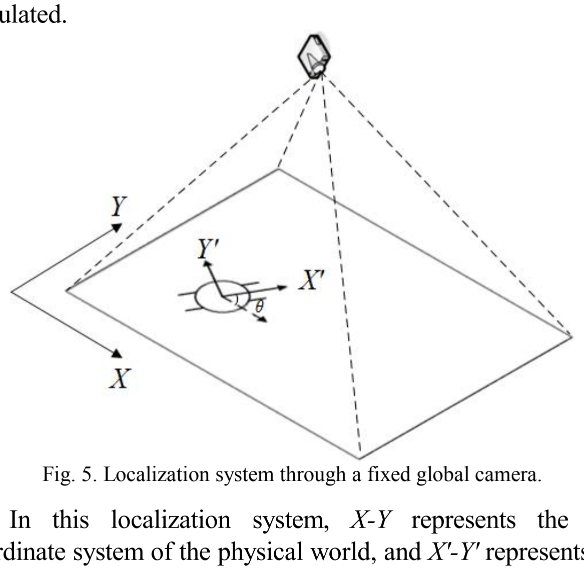


Fig. 5. Localization system through a fixed global camera.

In this localization system, *X*-*Y* represents the real coordinate system of the physical world, and *X'*-*Y'* represents the coordinate system with reference to the robot center. The fixed global camera calculates the pixel coordinates of the robot in the image through computer vision algorithm, then calculates the coordinates of the robot in the physical space through a coordinate transformation, Equation (1) obtained, where matrix **A** is obtained by image Calibration. After calculating the position of the robot, the speed of the robot can be calculated by deriving the position of the robot, Equation (2) obtained.

$$\begin{pmatrix} x \\ y \end{pmatrix} = \mathbf{A} \begin{pmatrix} p_x \\ p_y \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} V_x \\ V_y \end{pmatrix} = \mathrm{d}\left( \mathbf{A} \begin{pmatrix} p_x \\ p_y \end{pmatrix} \right) \Big/ \mathrm{dt} \tag{2}$$

Because the robot coordinates recognized by the image have noise, the speed fluctuation is very severe, so it is necessary to calculate the speed through a low-pass filter, that the accurate speed can be calculated.

In order to control the speed and yaw angle of the robot, it is necessary to calculate the speed of each direction in the coordinate system of the robot. Therefore, it is necessary to map the speed of the robot in the water environment coordinate system to the speed in the robot coordinate system. The IMU module is installed on the robot, which can measure the yaw angle of the robot while it is moving. The velocity in the robot coordinate system is obtained by Equation (2), which is a coordinate rotation transformation. In this equation, $\theta$ is the yaw angle of robot.

$$\begin{pmatrix} V_x' \\ V_y' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} V_x \\ V_y \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \left[ \mathrm{d}\left( \mathbf{A} \begin{pmatrix} p_x \\ p_y \end{pmatrix} \right) \Big/ \mathrm{dt} \right] \tag{3}$$

When we calculate the speed in the x, y direction of the robot coordinate system, we can use the PID controller to accurately control the speed and position of the robot.

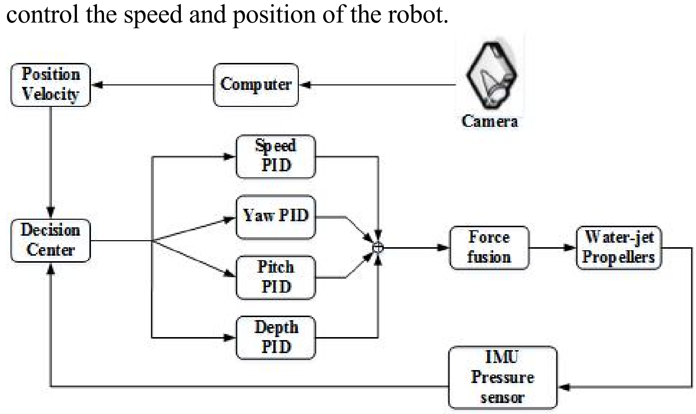


Fig. 6. Diagram of waypoints tracking control algorithm.

### *C. Waypoints Tracking Control*

The control algorithm framework used in this paper is shown in Fig 6, which is a closed-loop control system. First, the global camera captures the video image of the robot in the pool. The video image is processed by an external PC to identify the position and speed of the robot, and the recognition result is sent to the robot-mounted processor through underwater acoustic communication. Subsequently, the decision center on the robot processor plans a motion path based on the current position and the desired position, and calculates the speed and posture of the motion, and transmits the data to the PID controller. The PID controller on the robot is logically composed of four independent, parallel PID controllers, which control the speed, heading angle, pitch angle, and depth of the robot. The output of the PID controller will be transmitted to a force synthesizer, which maps the results of the four PID controllers to the thrust of each waterjet and the angle of the end servo motor. The water jet propeller and the end servo motor are then driven by a motor drive. Finally, the inertial measurement unit mounted on the robot detects the current attitude of the robot and returns the result to the decision center for closed-loop control.

## IV. EXPERIMENT

The experiment was carried out in a pool of 3.5 m x 2.5 m and a water depth of 1m, as shown in Fig. 7. In the experiment, we planned a rectangular path for the robot to let the robot move periodically along this rectangular path, as shown in Fig 8. In the image, we have planned four target points A, B, C, D for the robot.  These four points form a rectangle. The length of the rectangle is 1.8m and the width is 1.5m. Let the robot follow these four points. Go out of a rectangular track.

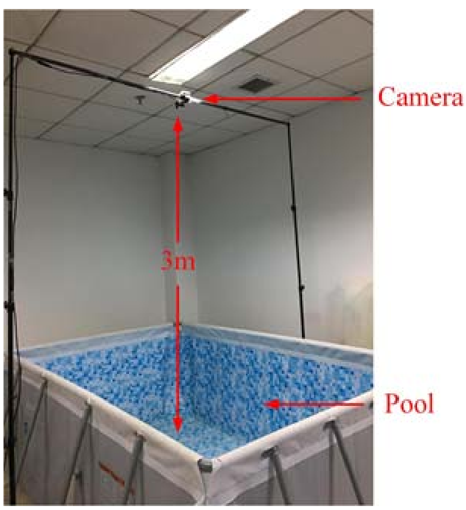


Fig. 7. Experiment environment.

In the figure, the blue box indicates the robot identified by the video image, and the coordinates of the center point of the box represent the coordinates of the robot. The green line indicates the trajectory of the robot during the movement. The motion process of the robot is shown in Fig 9. As can be seen from the results, the robot has entered four points A, B, C, and D, and the motion trajectory constitutes a rectangle.

By analyzing the trajectory of the robot motion, we found that the robot can accurately move to the set target point, the trajectory tracking error is shown in Fig 10. The result shows that the trajectory tracking error does not exceed 0.2m, which that the robot has higher motion control accuracy. And the robot can maintain linear motion between two adjacent target points.

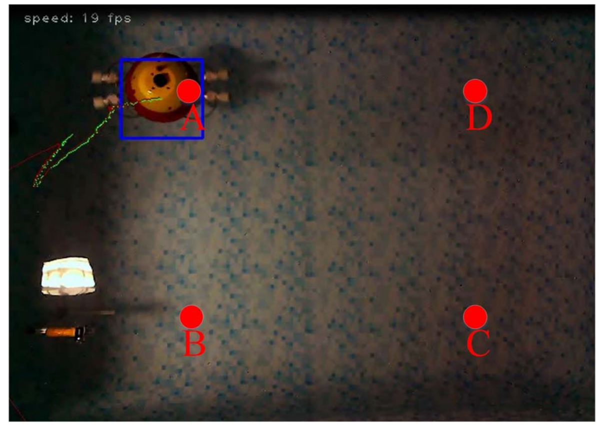


Fig. 8. Motion target points for robot.

When the robot is about to move to the next target point, the position of the robot will drift due to the need to rotate the direction greatly, which makes the robot's trajectory near the target point unstable. In general, the actual control effect proves that the control method proposed in this paper is effective. This control method can be improved in the future. For example, the camera can be mounted on a drone, and the drone can use the camera to position the multiple robots on the water surface in the air, so that the multi-robot and the drone can work together.

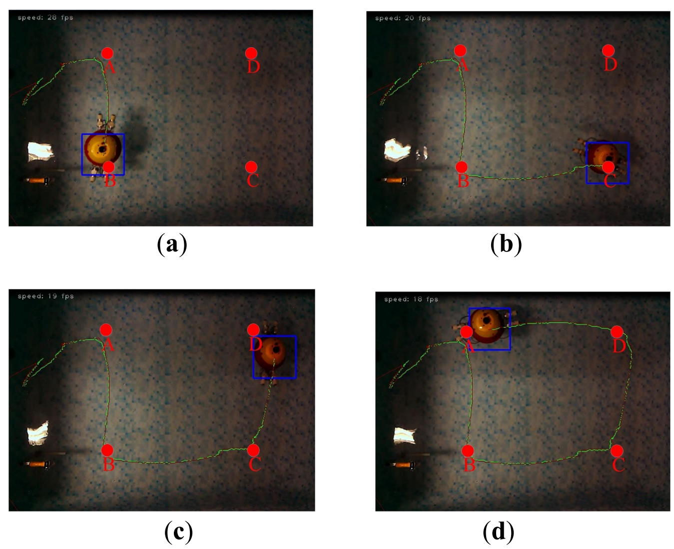


Fig. 9. Waypoints tracking results . (a) Go past B point. (b) Go past C point. (c) Go past D point. (d) Go past A point.

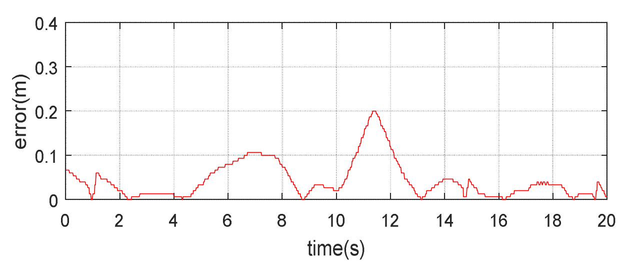


Fig. 10. Trajectory tracking error

## V. Conclusion

This paper designs a system for localization and motion control of amphibious spherical robots. This robot is a four-legged and water jet propeller composite robot. We propose four motion modes for amphibious spherical robots. Under the combination of these four motion modes, the robot can realize three-dimensional motion in water. Subsequently, we designed an amphibious spherical robot localization system with a global camera and a target recognition tracking algorithm that identifies the position and velocity of the robot. Secondly, we implement a robot motion control algorithm based on the PID controller, which can control the speed, yaw angle and motion trajectory of the robot in real time. Finally, we verified the localization and control methods in the pool through experiments. The experimental results show that this control method can effectively locate and control the amphibious spherical robot.

## Acknowledgment

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