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Quadrotor Vision-based Localization for Amphibious Robots in Amphibious Area

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***Abstract* – Considering imaging qualities and air-water medium changes, the localization of multiple amphibious robots in GPS-denied outdoors is a great challenge. This paper presents a vision-based localization approach for multiple amphibious robots in amphibious environment using a quadrotor hovering over the head of robots. In terms of the circular shape observed by the quadrotor on land, a shape and color-based detection method is designed to identify robots. An improved Hough transform was used to speed up the shape detection of our robot. Then we use the color information to identify different robots. In water, ASRobot is able to realize multiple motion with different configurations of legs. Therefore, in view of different shapes generated by different configurations, a multiple size-varying template matching method is utilized to recognize different robots in water. On account of the refraction of rays, the vision-based localization model was built in amphibious environment. Finally, experiments of localization were conducted, and the results verified the feasibility of the proposed vision-based localization approach for ASRobots.**

Index Terms* – *Amphibious Spherical Robots; vision-based localization; quadrotor-based localization

I. INTRODUCTION

In recent years, with the increasing demand of coastal and amphibious environments, exploration and research of this area are becoming crucial activities. Due to the limitations of a single robot, many researchers focus on the cooperation of multiple amphibious robots. In order to realize the cooperation of robots, challenges are present for obtaining location information. the localization of amphibious robots on land and in water needs to be settled firstly.

The widely known method is Global Navigation Satellite System [1], which contains the commercially used Global Positioning System (GPS). However, as like wireless-based localization [xx], the signals from GNSS is easily disturbed, such as severe weather. Any robot that is submerged merely 20cm underneath surface will lost signal. Besides, the low accuracy is not suitable for the close-range localization of robots. Nevertheless, various approaches for underwater localization do exist and are widely proposed, such as Acoustic localization method [2], inertial navigation method [3]. Because higher frequency signals attenuate rapidly in water. In order to send signals to remote place, these devices, such as acoustic device, DVL, INS and sonar, are produced with large size. However, these methods are not suitable for small-scale robots.

Besides these mainstream methods of underwater localization, cameras are the very useful for localization in performing short-range tasks. Using the forward-looking camera, Kim *et al.* proposed a novel vision-based localization method [4] with artificial landmarks using the forward-looking camera in structured underwater environments. Unlike the forward-looking camera, Carreras *et al.* proposed a down-looking camera-based localization approach [5,6] to estimate the position and orientation of an underwater robot using a coded pattern placed on the bottom of a water tank. In order to realize automated self-assembly of large Maritime structures, four overhead cameras were used to detect and position the structures marked with APRIL Tags [7,8] via the cv2cg package. The elaborate arrangement of the structured 3D environment or the robots limits the application of the marker-based localization.

Unlike the marker-based method, Josep and Nuno *et al.* proposed a new close-range tracking system [9,10] for autonomous underwater vehicles (AUVs) navigating in a close formation, using active light beacons and computer vision. This proposed system allows the estimation of the pose and location of a target vehicle at short ranges with an omnidirectional camera in an extended field of view. Faessler *et al*. proposed a new pose estimation system [11] that includes multiple infrared LEDs and cameras with an infrared-pass filter. The quadrotor with LEDs was positioning by an observing ground robot equipped with a camera. The infrared LEDs can be detected by vision system, thus their position on the target object can be precisely determined. However, if the infrared LEDs and active light beacons are sheltered by the body of the robot or others, the location and pose of the robot will not be estimated. These maker-based methods also are limited. Get rid of the markers, active LEDs or lights, Shao *et al*. proposed a double-template matching-based algorithm [12] to track the robotic fish using an overhead camera. Using pinhole camera model. The position of the fish on a water surface is calculated.

All these methods cannot deal with the localization of amphibious robot in complex amphibious environment. Therefore, based on the developed amphibious robot [13-19], this paper proposed a novel vision-based localization approach for amphibious robots in amphibious environment. As shown in Fig. 1, an onboard camera amounted on a quadrotor is used to recognize and position the robots on land and in water.

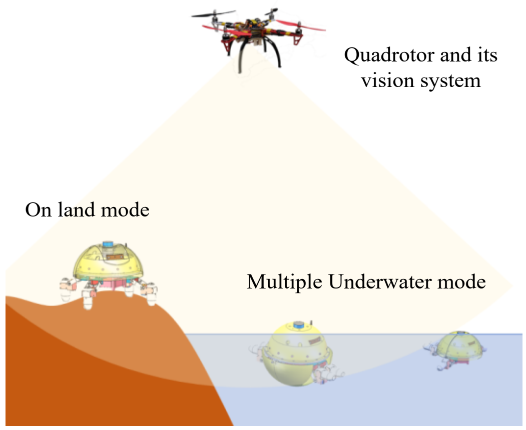


Fig. 1. The schematic diagram of our vision-based localization approach for amphibious robots on land and in aquatic environment.

The reminder of this paper is organized as follows: Section 2 introduces system overview, i.e., an amphibious robot and a quadrotor. In Section 3, we present the recognition method for amphibious robots in amphibious environment. Section 4 gives the proposed localization approach using quadrotor vision. Experiments of vision-based localization approach with amphibious robots are conducted in Section 5. Finally, Section 6 conclude this paper.

II. SYSTEM OVERVIEW

In order to position multiple amphibious robots in outdoors, a quadrotor equipped with a camera is utilized. Hovering above the robots, the quadrotor is able to detect the robots and provide the positions on land and in water.

A. *The Amphibious Robot*

In consideration of the benefits of spherical robots, such as the stability of mechanical structure, the anti-disturbance performance, the sample kinematics model with three-plane symmetry, and the strong loading capacity, a small-scale amphibious spherical robot was designed to monitor the littoral environment. As shown in Fig. 2, the robot mainly consists of a sealed cabin, a top shell that keep stereo camera and communication module, a middle aluminum alloy plate, two quarter-spherical hulls, four legs and a detachable battery cabin with three batteries containing 13200mAh. Both the sealed cabin and the shell can keep a hemisphere shape. And with two quarter-spherical hulls, the robot has a spherical shape. On the sealed cabin is a waterproof plug which can make the robot communicate with the remote computer via an optical fiber cable smoothly and steady. An O-ring is placed between the seal cabin and middle plant to ensure waterproofing, which makes the robot dive to a maximum of 10m. In water, the two quarter-spherical hulls close up like a ball and the robot moves using four vectored water-jet propellers. On land, two hulls open and the robot can walk using the legged driving mechanism.

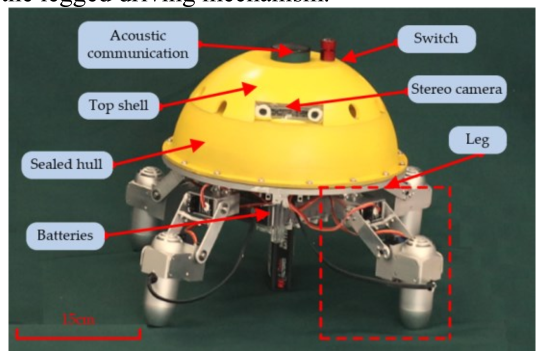


Fig. 2. The overview structure of the developed amphibious robot

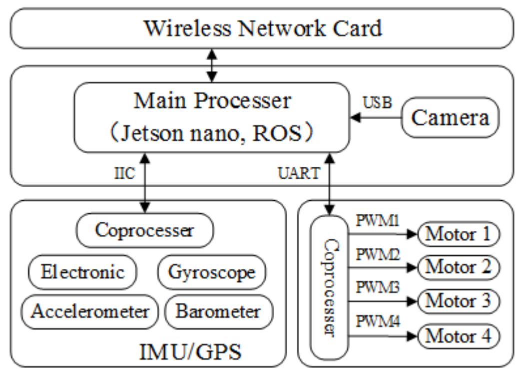


Fig. 3. The control system of the quadrotor.

TABLE I
TECHNICAL SPECIFICATION OF THE ROBOT

Items	Parameters
Dimension (L×W×H)	30cm×30cm×30cm
Total mass in air	6.5 Kg
Hover precision	V: ±0.05m
Processors	Jetson TK1 (12V), STM32F407 (3.3 V)
Max. Speed (cm/s)	5cm/s (on land), 40cm/s (underwater)
Communication mode	Wireless mode (2.4GHz, 5GHz)
Power supply	7.4 V rechargeable Ni-MH batteries (13200mAh)
Operation Time	~ 100 min

B. *Quadrotor*

In our research, a quadrotor with a vision-based object tracking and localization system has been built. This control system is illustrated in Fig. 3. In order to realize real-time object tracking, Jetson nano, a tiny credit card size computer with 64-bit quad-core processor, is adopted to be main processor, and its compatible operating system is Ubuntu 18.04. This processor is applied for executing all image processing, motion prediction and object tracking with a USB camera. This camera facing downward is mounted under the bottom of the quadrotor platform and connect to main processor. The resolution is 640×480 and the frame rate is 60

Frame Per Second (FPS). Besides, two coprocessors are integrated into our quadrotor. One is used to obtain the attitude information with accelerometer, gyroscope, magnetometer and barometer, the position information with Global Position System (GPS); another is to yield PWM signals. Main processer acquires the attitude and position information via IIC bus, and sends control signals to another processor via UART. Moreover, main processor transmits the position information of objects to the ground station by wireless network card. Table II lists the specifications.

TABLE II
TECHNICAL SPECIFICATION OF THE QUADROTOR

Items	Parameters
Dimension (L×W×H)	50cm×50cm×19cm
Total mass in air	1.28Kg
Hover precision	H: ±0.2m, V: ±0.1m
Processors	Raspherry Pi 3 (5V), STM32F407 (3.3 V)
Max. Speed (cm/s)	200 cm/s
Communication mode	Wireless mode (2.4GHz, 5GHz)
Power supply	7.4 V rechargeable Ni-MH batteries (6000mAh)
Operation Time	~ 40 min

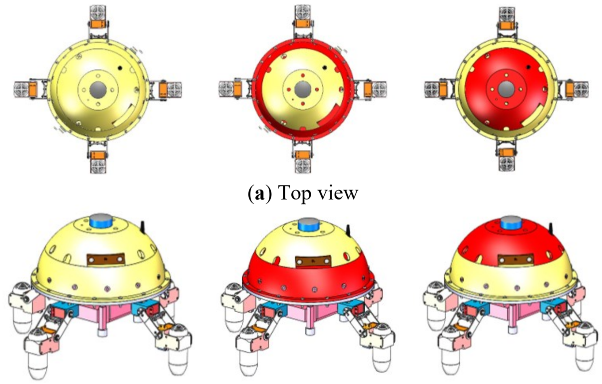
III. ASROBOT RECOGNITION

For real-time object detecting and tracking system or surveillance system, background subtraction algorithm and frame difference algorithm are the two algorithms widely applied with low complexity. The background subtraction algorithm requires the camera to be fixed. Then the background will be stable. The difference in gray scale between current frame and the background is caused by the object moving, i.e., the foreground is detected. The whole part of the target is obtained in background subtraction algorithm, while only the differential part is obtained by frame difference algorithm. In this section, in terms of the spherical shape of ASRobot, a novel vision-based detection approach for ASRobot in outdoors using a quadrotor over the head of ASRobots was proposed. Firstly, on land, a shape and color-based method is designed to identify ASRobots. In water, a multiple size-varying template matching method is utilized to recognize different robots.

A. *ASRobot Recognition on Land*

On land, our amphibious robot moves with four legs. In crawling, turning, rotation at original spot, the robot can keep the body horizontal. Thus, observed from the top, the shape of the sealed cabin is approximately circular. Therefore, in order to realize real-time ASRobot detection, a shape and color-based vision recognition method is proposed.

For the circular shape from the top, an improved Hough transform method for circle detection is designed. Only the circular area of our robot is detected successfully, After the circle area of our robot is obtained, we have not accomplished the identification of the robot. Therefore, using these robots marked by a variety of color combinations, the robot is able to be identified. As shown in Fig. 4, amphibious robots are marked with different color combinations, such as yellow, red. Fig. 4 (a) can be regard as the robot in the perspective of the quadrotor.



(**a**) Top view

(**b**) Front view

Fig. 4. ASRobot with color combinations.

B. *ASRobot Recognition in Aquatic Environment*

In aquatic environment, the color information will be changed by water. Therefore, the color information is unsuitable for the recognition of our robot. In water, our robot can realize multiple locomotion mode with different configuration of legs. Therefore, the shape character will benefit the recognition of our robots, and in fact the final experiment verified this point. As shown in Fig. 5, the six typical templates of ASRobot is generated using different configurations of legs.

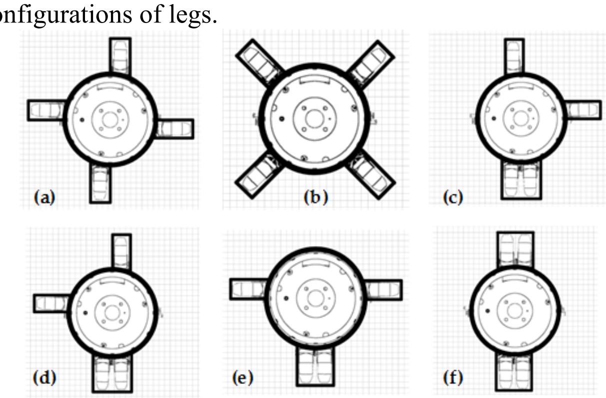


Fig. 5. Templates of ASRobot with different configuration of legs.

Using the shape-based recognition method, the most important step is the image preprocessing. Only after the high quality of image preprocessing, the contour of our robot will be obtained, and the robot is identified. However, when capturing an image via digital cameras, an inappropriate light source often leads to the uneven illumination of the frame. After graying and binarization of image, huge amounts of irregular outline occur, which leads to recognition failure. Due to the effect of the illumination, the pixels of the image have a slow changing trend. This paper proposes a correction rectify method the detected tendency of image. The flow of the method is as follows:

1) Compute the average grayscale v of the source image I;
2) According to a certain size, divide the image into $n \times m$ blocks. By computing the average value of each block, a luma matrix D is obtained;

3) Calculate the luma difference matrix E using the difference of each element of Matrix D and the value v.
4) Utilizing the bicubic interpolation algorithm, the matrix E is interpolated into a luma distribution matrix R, the size of which is the same as the source image.
5) The corrected image is obtained by the difference of the source image I and Matrix R.

With the specific size of our robot, the contour area of our robot can almost be determined at a given altitude of the quadrotor. The approximately linear relationship between the contour area of our robot and the altitude of the quadrotor can be used to filter out some noisy contours.

After this pre-processing, a high-quality contour is obtained. These different templates can be identified by Hu moments. Hu derived a set of seven moments which are translation, orientation and scale invariant. Maitra extended Hu invariants to be invariant under image contrast. Equations of Hu-Moments are given. These seven moments are calculated by second and third order moments.

IV. Quadrotor Vision -Based Localization Approach

A. Quadrotor Vision-based Localization Approach

In Xie's researches, the position of robotic fish swimming on the water surface can be obtained by a fixed global camera indoors. However, it cannot position the robotic fish out of doors. In order to realize the localization for amphibious multiple robots in amphibious area, a vision-based localization system mounted on the quadrotor is designed. The performance of the hovering motion directly influences the precision of the positioning of ASRobot.

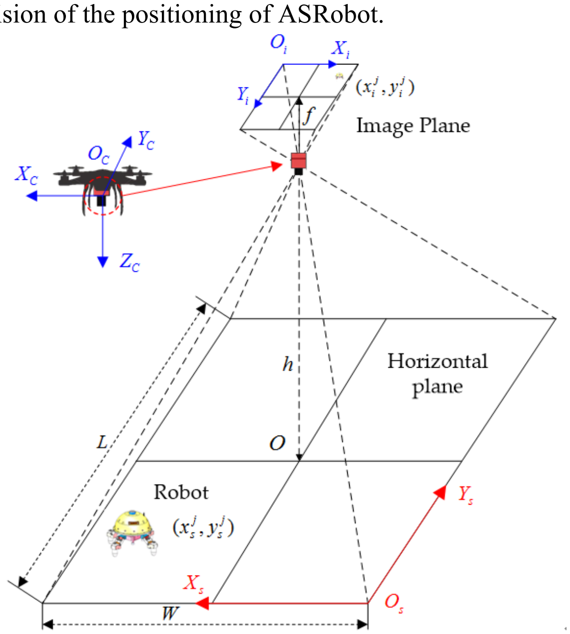


Fig. 6. Localization schematic using a quadrotor with the camera.

Assumption 1: In the hovering motion, the quadrotor has high stability and keep going horizontally, i.e., the image plane is parallel to the horizon plane and the water surface plane.

To describe the localization simply, three coordinate systems were defined, i.e., a pixel frame $\{o-uv\}$, an image frame $\{o_i - x_i y_i\}$, water surface frame $\{o_s - x_s y_s\}$, a camera frame $\{O_C - X_C Y_C Z_C\}$, a body frame $\{O_B - X_B Y_B Z_B\}$ and an earth-fixed frame $\{O_E - X_E Y_E Z_E\}$. To optimize performance, the optical center axis of the camera lay perpendicular to the water surface plane. As shown in Fig. 6, the robot j positions detected by the camera running the Kalman Consensus Filter (KCF) algorithm in the pixel frame and water surface planes are (u^j, v^j) and (x_s^j, y_s^j) respectively. Using the principle of pinhole imaging, Equation (1) was obtained.

$$\begin{cases} x_s^j = h(u^j - u_0)/f_x \\ y_s^j = h(v^j - v_0)/f_y \end{cases} \tag{1}$$

where (u_0, v_0) are the principal point coordinates relative to the image plane, f_x and f_y are the focal lengths of the camera in the x and y axis, respectively. h is the height of the quadrotor from the water surface, and it can be calculated by Equation (2) at time t.

$$h_t = k(p_t^q - p_0) \tag{2}$$

where, p_0 is the barometric pressure on the water surface, p_t is the barometric pressure at time t, k is a coefficient from the barometric pressure to the height.

For ASRobots on land, h is the distance from the quadrotor to the ASRobot in vertical direction.

$$h_t = k(p_t^q - p_t^a) \tag{3}$$

where, p_t^q is the barometric pressure of the quadrotor on land, and p_t^a is the barometric pressure of the ASRobot at time t.

Therefore, the robot position on land was obtained using Equation (4).

$$p_C^i = \begin{bmatrix} x_C^j \\ y_C^j \\ z_C^j \end{bmatrix} = \begin{bmatrix} k(p_t^q - p_t^a)(u^j - u_0)/f_x \\ k(p_t^q - p_t^a)(v^j - v_0)/f_y \\ k(p_t^q - p_t^a) \end{bmatrix} \tag{4}$$

The robot in water also can be obtained by Equation (4), and h is the distance from the quadrotor to the water surface.

B. Localization Procedure

In this section, ASRobots on land and on the surface of water is positioned by a camera amount on an overhead quadrotor. The procedure of the vision-based 3-D localization approach is depicted in Fig. 7. It is composed of three main steps. The first step is to capture image and read barometric pressures of the quadrotor and ASRobots. These barometric pressures are used to calculate the vertical distance between the quadrotor and ASRobots using Equation xx. Then, in order to detect the robots, image preprocessing is essential. And it contains rectifying the image with calibration results and image enhance that compensates the uneven illumination. The next step is to locate the ASRobot on land. Owing to the shape of our robot, the circle detection with Hough transform is used. But before circle detection, the edge of the image needs to be detected with Canny algorithm. In order to identify the robot, color combinations of our robots are recognized. If robots are detected, the coordinate (u^j, v^j) of the robot j is the center of the circle. The position p_C^i in the world coordinate frame is estimated with Kalman filter using Equation xx. If no robots on land are recognized, positioning the ASRobot in water will be carried out. Because of the different shapes with different configuration of legs, multi-contour matching method is used to detect the robot. First convert the frame to binarization image. Morphological algorithm is used to remove the noises of small contours. Then Hu moment is computed to match the Hu moment of different contours. If the smallest value is bigger than the threshold, there are no robots. Otherwise, the smallest value corresponds to the robot with this configuration of legs. The coordinate (u^j, v^j) of the contour is the position of the robot in pixel coordinate frame. Using Equation xx, the position p_C^i of the robot in the world coordinate frame is estimated with Kalman filter. Here is one circle, and the circles of localization will continue until the task finished.

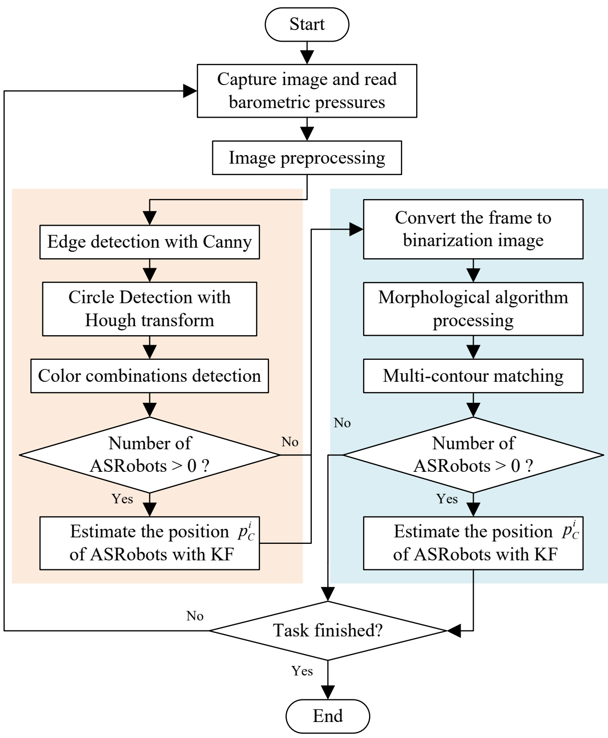


Fig. 7. Flow diagram of the proposed localization approach.

V. Localization Experiment

In this section, to widen the range of detection area, a wide-angled camera with distortion is mounted on the quadrotor. Thus, camera calibration was conducted to obtain the accurate positioning. The intrinsic parameters and distortion parameters are list in Table III and Table IV, respectively. Then, the recognition experiment was conducted on land and in water. finally, the localization experiment was carried out.

Table III
The intrinsic parameters table of camera

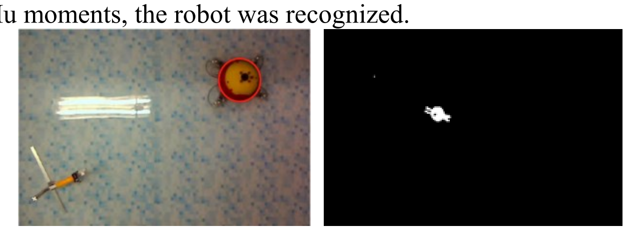
Camera	Distortion parameters			
	f_x	f_y	u_0	v_0
	550.462	552.321	322.891	241.175

Table IV
Distortion parameters table of camera

Camera	Distortion parameters				
	k_1	k_2	k_3	p_1	p_2
	0.09891	0.04458	-0.44803	-0.00065	0.00217

A. *Recognition Experiment*

In order to realize real-time object tracking, Jetson nano, a low-cost tiny credit card size AI computer with quad-core ARM A57 64-bit CPU and an integrated 128-core Maxwell GPU, is adopted to be main processor, and its compatible operating system is Ubuntu 18.04. And it is mounted under the quadrotor with a downward looking camera. the recognition program is developed with OpenCV library. As shown in Fig. 8 (a), the robot walks with climbing gait. With images captured by the camera of the Quadrotor, the circle shape is clear. And we used the proposed method to detect the circle. As shown in Fig. 8 (a), the red circle indicates the recognized robot. As shown in Fig. 8 (b), the contour area of the robot was obtained after preprocessing. By computing the Hu moments, the robot was recognized.



(**a**) On land locomotion (**b**) underwater locomotion

Fig. 8. Recognition Results of robots on land and in water.

B. *Localization Experiment in Aquatic Environment*

The localization on land and in water exists the similarity. Therefore, only quadrotor vision-based underwater localization experiment in water was carried out. As shown in Fig. 9, one quadrotor with a down-looking camera was hovering about three meters above the water. In this experiment, four points were set in the frame of the quadrotor vision, and that are (130cm, 50cm), (350cm, 50cm), (350cm, 230cm) and (130, 230). The robot starts from (130cm, 50cm). As shown in Fig. 10, the red curve is the position detected by the quadrotor. In order to improve the localization precision, Kalman Filter was used to estimate the robot position and the KF estimated trajectory was shown by the blue curve. KF estimated trajectory is much smoother than the actual robot trajectory. The maximum error is about 25cm. This proposed method can guide the robot track the desired point and this experiment verified this effectiveness of this approach.

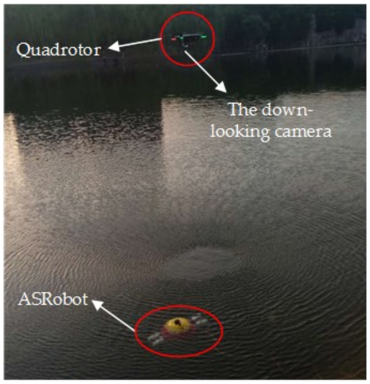


Fig. 9. Quadrotor vision-based localization experiment setup in water.

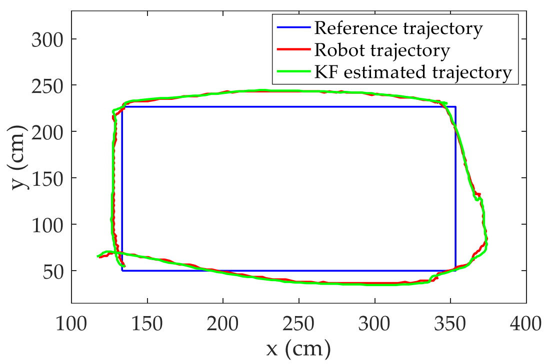


Fig. 10. Tracking trajectory with the proposed method in water.

V. Conclusion and Future Work

Considering imaging qualities and air-water medium changes, the localization of multiple amphibious robots in GPS-denied outdoors is a great challenge. This paper presents a vision-based localization approach for multiple amphibious robots in amphibious environment using a quadrotor hovering over the head of robots. In terms of the circular shape observed by the quadrotor on land, a shape and color-based detection method is designed to identify ASRobots. An improved Hough transform was used to speed up the shape detection of our robot. Then we use the color information to identify different robots. In water, ASRobot is able to realize multiple motion with different configurations of legs. Therefore, in view of different shapes generated by different configurations, a multiple size-varying template matching method is utilized to recognize different robots in water. On account of the refraction of rays, the vision-based localization model was built in amphibious environment. Finally, experiments of localization were conducted, and the results verified the feasibility of the proposed vision-based localization approach for ASRobots.

Acknowledgment

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