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Multi-Sensor Fusion Based Localization System for an Amphibious Spherical Robot

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***Abstract* –Many techniques for robot localization rely on inertial navigation system which suffers from drift and huge computational cost. So, this paper presents a localization method which has a good real-time performance, high-precision and low-cost assumption for a compact amphibious spherical robot. Specifically, this system can navigate the robot along a predefined path without the need for any additional external sensors. Meanwhile, the proposed approach combines various information using extend Kalman filter (EKF), include depth data from a pressure sensor, pose from an Inertial Measurement Unit (IMU), velocity from optical flow and pose estimation from multiple planar markers. A monocular downward facing camera is used to track feature about optical flow and detect artificial landmarks. Moreover, to validate our approach, we conducted experiment in an indoor pool with varying lighting and visibility conditions, and we demonstrate the online localization method is highly accurate, robust and successful application with limited computational capacities and low-cost sensing devices on our compact robot.**

Index Terms - Localization. Amphibious Spherical Robot (ASR). Sensor Fusion.

I. INTRODUCTION

Autonomous amphibious robot can perform flexible operations in complex amphibious environments where humans cannot reach due to their autonomy. So many research efforts are devoted to autonomous amphibious robot [1]. In the deep-sea environment, the development of various types of underwater robots has been relatively mature. They can perform complicated work by remote human operation and have been used for underwater construction and rescue purposes [2]. On land, the development of robots is more intelligent [3], some service robots, medical robots and so on, are emerging in an endless stream. However, there are few compact robots that can be used in the amphibious environment and the coastal and shoal environment [4]. Therefore, in this paper, the proposed method and experiments are both based on our compact amphibious spherical robot platform applied in shallow water environment.

Whatever the circumstances, localization with a good performance is a vital components of autonomous tasks. In addition, the realization of online self-localization significantly improves the autonomy and intelligence of underwater robots when performing tasks in complex or unknown environment [5]. The previous research in the field of localization can be divided into several different approaches, including inertial navigation system [6]-[8], acoustic-based system [9]–[11] and vision-based localization system [12]-[14]. Inertial navigation system usually consists of inertial measurement unit (IMU) and Doppler velocity log (DVL) which have been equipped with large-size sensors and high-performance processors. Besides, errors will accumulate over time due to the drift of these inertial sensors. Acoustic-based localization system which have been widely used in some deep-sea navigation, is suitable for large-range localization, but there are many sources of disturbance that can affect its accuracy. Therefore, these deficiencies make the two approaches can not be applied to the close-range localization system for compact robots with high requirements for security, accuracy, real-time performance and low computational cost.

On the contrary, vision-based localization system has become a hot topic in recent years, not only due to the wide used of low price of sensors, but more importantly because of its technical advances such as high flexibility, high operating precision [15]. The robot can position itself through a series of image analysis features provided by the optical camera under appropriate visibility conditions [16], like small shallow water environment. And localization using visual information usually relies on some markers whose geometry is known. Although, vision-marker based localization has high-precision, it is limited by the distribution of the markers. Aiming at these shortcomings, multi-sensor fusion provides a better solution.

Motivated by the aforementioned discussion, a multi-sensor fusion based localization system for an amphibious spherical robot is proposed for our amphibious spherical robot platform in this paper. Information from a down-looking camera, a high-precision IMU and multiple planar markers are processed on an ARM processor for real-time localization system without the need for any additional external sensors. The extend Kalman Filter (EKF) is used to fuse the multi-source information, including heading angle from IMU, velocity from optical flow and depth from pressure sensor. Thus, the localization method can effectively reduce the position drift caused by the absence of markers in the field of vision for a long time. When the marker appears in the field of

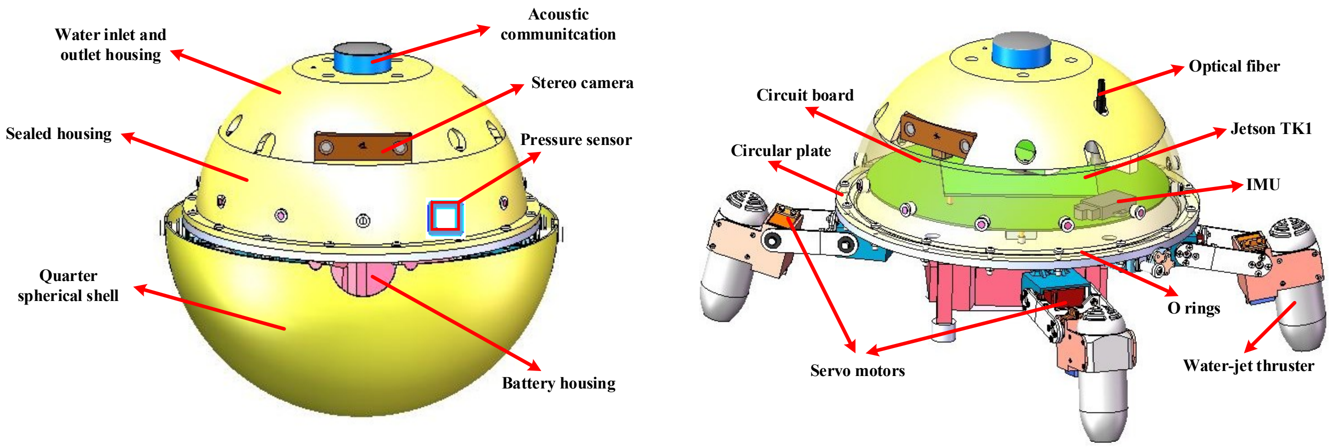

Fig. 1. Structure of proposed spherical robot

vision, this more accuracy position data is used to correct the error accumulated over time due to the drift. And the main contents of our study are as follows:

1) A brief introduction of our robot platform and date acquisition from different sensors;

2) The procedure of data fusion using extend Kalman Filter (EKF) is described in detail;

3) To evaluate the proposed method, systematical experiments are carried out.

The rest of this paper is organized as follows. Section II presents the related works that include a brief introduction about our new generation spherical robot and the data acquisition from different sensors mounted on the robot. Section III reviews the multi-sensor fusion based localization system, that is to say the detailed description of data fusion. Experiments and results are provide in Section IV in order to assess the performance of the proposed approach. Section V provides a conclusion of the whole paper.

II. Related Works

In this section, we present the related works, composed of two parts. First, the structure of amphibious spherical robot is introduced. Then, the multi-data acquisition from different sensors is elaborated, including the velocity from optical flow, position from Aruco markers, heading angle from IMU and depth from pressure sensor.

A. *The Amphibious Spherical Robot*

On the basis of the robot mentioned in the references [17]-[19], we developed a new generation of amphibious spherical robot with more perfect performance, whose structure is shown in Fig.1. The shape of the whole robot is a sphere with the diameter of 300mm, which is separated into the upper and lower hemispheres by an aluminum alloy circular plate. The upper hemisphere is divided into two parts, the inlet and outlet housing and the seal housing. The seal housing contains the main control board Jetson TK1, the circuit board, IMU and pressure sensors. The acoustic communication module and stereo camera are carried in upper part. The lower part of the sphere is symmetrically mounted with four mechanical legs and a waterproof battery housing. Three waterproof servo motors and a water jet thruster constitute a driving device. Each leg has two degrees of freedom that can move horizontally and vertically [20]-[22].

B. *Data Acquisition from Sensors*

A localization method based on multi-sensor fusion is proposed in this paper, which can build and correct the localization information online and avoids the distortion caused by lack of correction. It can be easily implemented on a hardware platform with poor performance and low power consumption such as a Jetson TK1 and a STM32 micro controllers.

In particular, a high-precision IMU and a low-cost tiny down-looking camera are mounted on the robot, which are utilize to get position by fusion the heading angle and velocity. The IMU is mounted in parallel with the robot principal axes to monitor the yaw, pitch, roll angle. Meanwhile, it can provide the more accurate attitude information and it is necessary to transfer the quaternion to euler angle by equation (1)-(3).

$$pitch = \frac{180}{\pi}\arcsin(-2q_1q_3 + 2q_0q_2) \tag{1}$$

$$roll = \frac{180}{\pi}\arctan(\frac{2q_2q_3 + 2q_0q_1}{-2q_1q_2 - 2q_2q_2 + 1}) \tag{2}$$

$$yaw = \frac{180}{\pi}\arctan(\frac{2q_1q_2 + 2q_0q_3}{q_0q_0 + q_1q_1 - q_2q_2 - q_3q_3}) \tag{3}$$

The down-looking camera is used to capture the images of water surface. The size of the image taken by it is 640×480 pixels. However, in order to meet the real-time requirements with the low-performance processor, the size of 320×240 pixels is adopted in the system, so that can be employed to capture the optical flow by which can calculate the velocity, and the schematic diagram is shown in Fig.2. The point O is the optic center of the camera, A is a feature point in the image and B is the same feature point in the next frame. A' and B' are the point of the feature point relative to the camera at different moments. So, the velocity of this feature point, that is to say that the velocity of the camera can be calculated by equations (4)-(6).

$$\frac{AB_x}{A'B'_x} = \frac{f}{h} = \frac{AB_y}{A'B'_y} \tag{4}$$

$$v_x = \frac{|u_B - u_A| \cdot h}{f \cdot \Delta t} \tag{5}$$

$$v_y = \frac{|v_B - v_A| \cdot h}{f \cdot \Delta t} \tag{6}$$

Where h is the distance between the down-looking camera and the feature point, which can be obtained by pressure sensor. The focal length of the camera is f and Δt is the interval time.

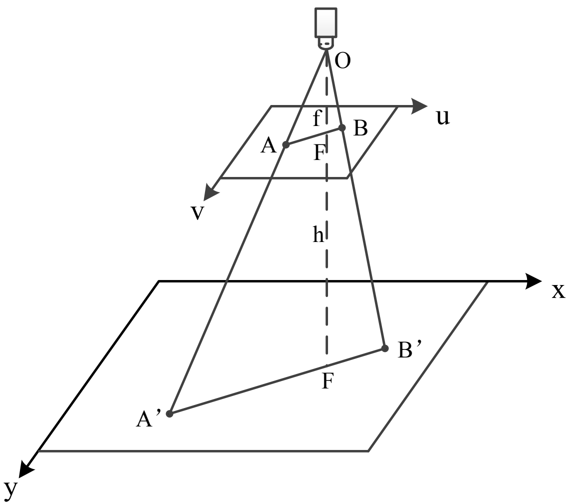

Fig.2. Schematic diagram of optical flow

Considering that the localization drift due to the long-term localization that only rely on IMU and optical flow, it is necessary to utilize some artificial landmarks to correct the drift. Planar markers assisted localization technology is widely used in robots that use low-cost visual navigation systems. It can provide accurate position information of the camera. At the same time, the marker can be easily and accurately identified from a wider range of viewpoints. Therefore, the marker array is widely employed in featureless indoor environments such as a shallow test tank [23]. The Aruco marker [24] as shown in Fig.3，can provide precise position information with less computation consumption. The accurate six-degrees-of-freedom information of camera can be obtained when the markers are detected by camera, as shown in Fig.4.

The proposed localization system, the array of planar markers is arranged neatly so as to describe the geometric relationship among the markers. When a marker first appears in the field of vision, the center is considered as the origin of coordinates. Thereafter, as long as more than two markers are seen in the same frame, the relative relationship between them can be known. Thus, a precise map containing the poses of markers is obtained. For localization, the locate information will be calibrated when any marker is identified using camera to avoid error accumulation.

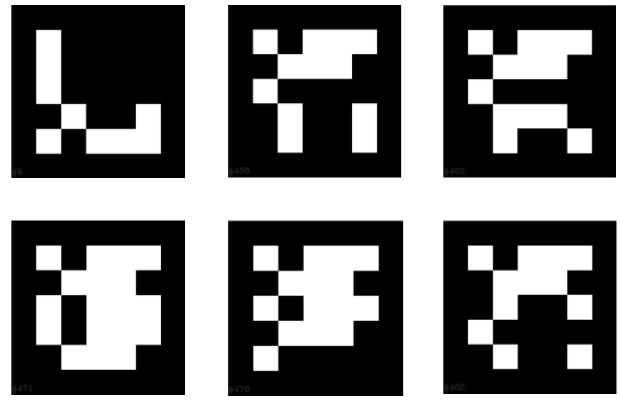
Fig.3. Samples of Aruco markers

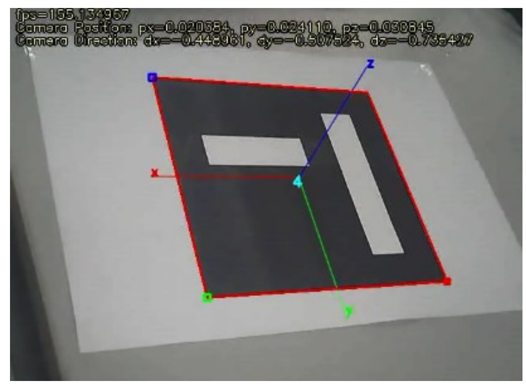
Fig.4. Detection of the Aruco markers

III. Multi-Sensor Fusion based Localization System

This section introduce that the EKF is used to fuse the multi-source information from IMU, pressure sensor, optical flow and markers. The process of data fusion is described in detail, including the state model, measurement model and the data fusion.

A. State Model and Measurement Model

IMU and optical flow are utilized in position estimation. The state vector $X(k) = [x(k), y(k), z(k), \theta(k), v(k)]^T$, the model diagram is shown in Fig.6. And the system function is given below:

$$X(k+1) = f(X(k),k) = \begin{bmatrix} x(k) + v(k)\cdot\Delta t\cdot\cos\theta \\ y(k) + v(k)\cdot\Delta t\cdot\sin\theta \\ z(k) \\ \theta(k) \\ v(k) \end{bmatrix} + \sigma(k) \tag{7}$$

Where Δt is the interval time, and $\sigma(k)$ is Gaussian white noise of system and $E[\sigma(k)\sigma(k)^T] = Q(k)$.

The measurement $Z(k) = [z(k), \theta(k), v(k)]^T$ includes the depth from pressure sensor, yaw angle from IMU and velocity from optical flow. Therefore, the measurement function is given below:

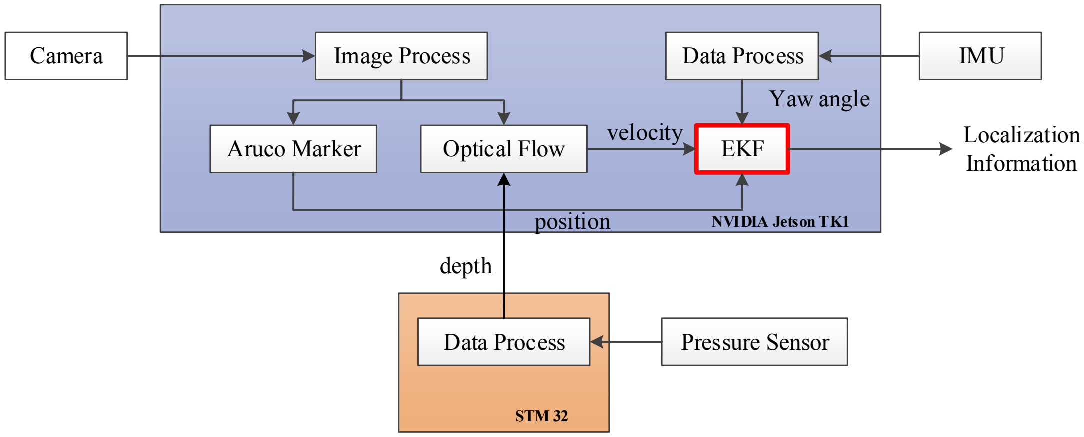

Fig.5. Multi-sensor fusion based localization system

$$Z(k) = h(X(k), k) + v(k) \tag{8}$$

Where $v(k)$ is the measurement noise and $E[v(k)v(k)^T] = R(k)$.

B. Data Fusion using EKF

EKF equations of data fusion module are given below.

$$\hat{x}(k,k-1) = f(\hat{x}(k-1), k-1) \tag{9}$$

$$P(k,k-1) = F(k-1)P(k-1)F(k-1)^T + Q(k) \tag{10}$$

$$K(k) = P(k,k-1)H(k)^T(H(k)P(k,k-1)H(k)^T + R(k))^{-1} \tag{11}$$

$$\hat{x}(k) = \hat{x}(k,k-1) + K(k)[z(k) - h(\hat{x}(k,k-1), k)] \tag{12}$$

$$P(k) = (I - K(k)H(k))P(k,k-1) \tag{13}$$

Where $P(k)$ and $K(k)$ are the covariance matrix and Kalman gain matrices, respectively. $Q(k)$ is the system covariance matrix and $R(k)$ is the measurement covariance matrix, they cannot be determined by theories, so they are usually tuned experimentally by a trial-and-error method. $F(k)$ and $H(k)$ are Jacobi matrices of the nonlinear system function $f(x(k))$ and measurement function $h(x(k))$ respectively. They are given below.

$$F(k) = \begin{bmatrix} 1 & 0 & 0 & v\cdot\Delta t\cdot\cos\theta & \Delta t\cdot\sin\theta \\ 0 & 1 & 0 & -v\cdot\Delta t\cdot\sin\theta & \Delta t\cdot\cos\theta \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

$$H(k) = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

Generally, localization system based on multi-information fusion for an amphibious spherical robot consists of three steps, as shown in Fig.5. In addition, other sensors can be easily extended to this system to further improve localization accuracy and redundancy.

1) When there is no marker in the field of vision, only the heading angle information provided by IMU and the speed information provided by optical flow are combined to perform simple position estimation.

2) Depth value measured by the pressure sensor are available at the same sampling frequency as the velocity from optical flow. Because the calculation of the velocity need the depth information.

3) If the Aruco marker is present in the current image, the 3D position can be easily calculated to correct the entire state vector, especially the integration drift due to the position estimation.

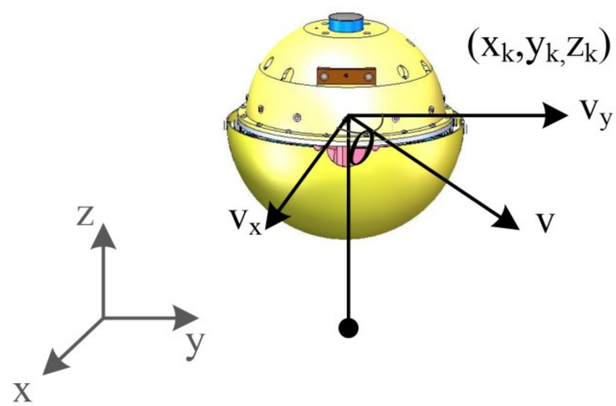

Fig.6. Diagram of state model

IV. Experiments and Results

This section demonstrates the real-time performance, robustness and effectiveness of proposed localization system using a series of experiments employing a compact amphibious spherical robot. In particular, Section IV-A introduces the experimental setup, and Section IV-B presents the experimental results with our proposed localization method.

A. Experimental Setup

The experiments were carried out in our laboratory tank, with dimensions 3m×2m×1m as shown in Fig.7. The bottom of the tank is covered by many markers whose array and geometry relationship are known. A downward-looking camera with 640×480 pixels and 30 frames per second

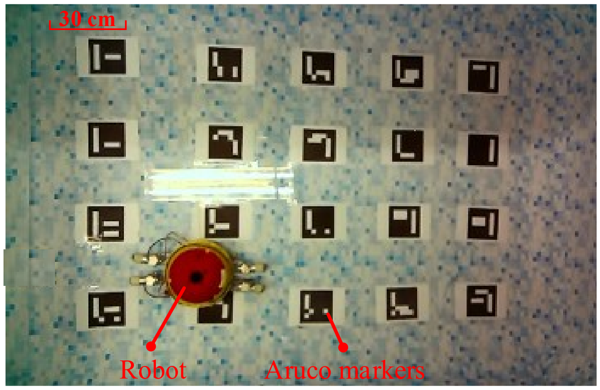

Fig.7. Experimental setup

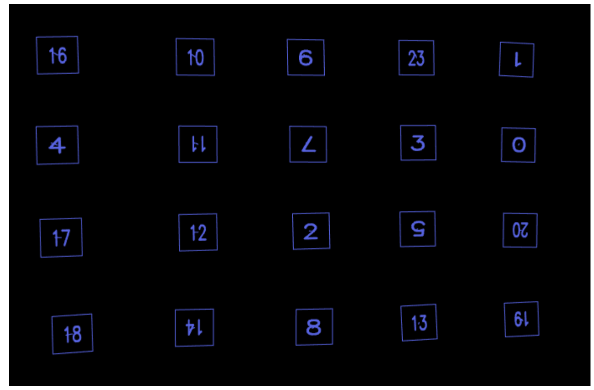

Fig.9. Map of Aruco markers

enclosed in a waterproof case, is mounted on our robot. And it is employed to detect the markers and capture the optical flow. A high-precision IMU is also equipped in the sealed housing to measure the yaw, pitch and roll angle of the robot. A pressure sensor, mounted on the top of the robot's waterproof housing, has centimeter level errors. Specially, a global camera is mounted directly above the tank to assess positioning accuracy. Finally, the proposed multi-sensor fusion based localization system is implemented with C++ under the robot operating system (ROS) [25]. The subscription and publish relationships for messages between nodes is shown in the Fig.8.

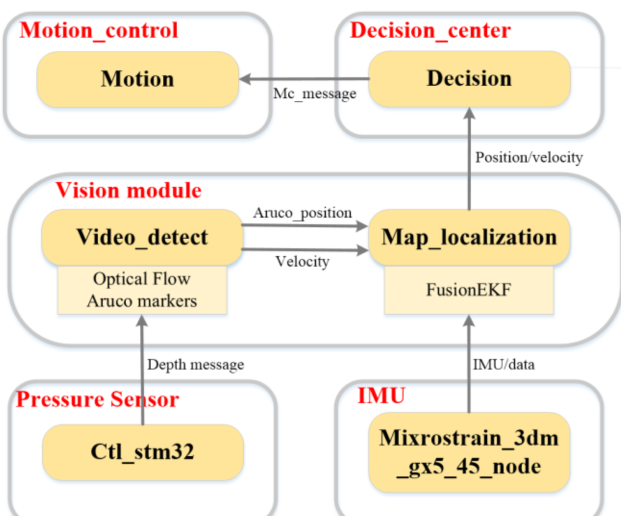

Fig.8. Relationship between nodes

B. Experimental Results

The performance of the proposed method is tested using designed experiments in this part. The robot was driven manually and its trajectory is a rectangle. Using aforementioned method, the marker number and layout which can be regarded as known map, as shown in Fig.9. And the estimated horizontal position of the robot using EKF is depicted in Fig.10, with the marker localization correction (red line), and the reference position by global camera is the black line. The depth data of the robot from pressure sensor is

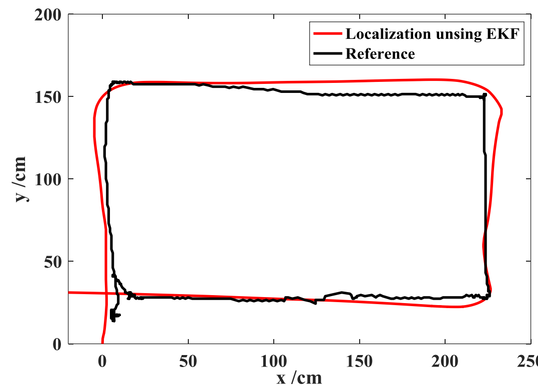

Fig.10. Localization results of proposed method

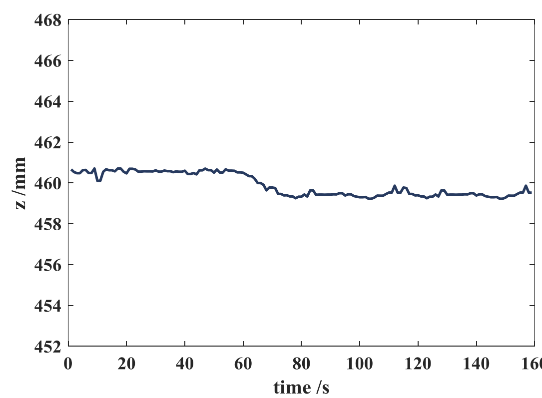

Fig.11. Depth (expressed by z) of robot in this experiment

illustrated in Fig.11. The curves show that the depth of the robot in the tank remains basically unchanged. It is worth noting that due to the limited markers in the test tank, the markers are not always exist in the field of view during the movement of the robot, so the drift may happen without any marker correction, and proposed approach can estimate the position information more accurately without obvious drift. As a result, the value of localization may produce jumps between marker data and the IMU-optical flow data.

In conclusion, the aforementioned experiment have proved that the proposed localization system has high accuracy and robustness for our miniature amphibious robot with low computational capacities and low-cost sensors. Moreover, the proposed localization system is not suitable for open-sea application due to the poor visual system performance that caused by low-light conditions, lack of features and unenforceability of marker layout. However, this localization method can meet the needs of small robots for high-accuracy navigation in shallow underwater environment.

V. Conclusion and Future Work

Aiming at the problem that many techniques for robot localization rely on inertial navigation system which suffers from drift and huge computational cost. This paper presents a multi-sensor fusion based localization system which has a good real-time performance, high-precision and low-cost assumption for a compact amphibious spherical robot. Meanwhile, the proposed approach combines various information using extend EKF, include depth information from a pressure sensor, pose from IMU, velocity from optical flow and pose estimation from multiple planar markers. Moreover, the experiments have validated that the proposed localization system is highly accurate, robust and successful application with limited computational capacities and low-cost sensing devices on our compact robot.

Future research efforts will be devoted toward solving the limitation of unknown map. The proposed method in this paper needs to know the layout of markers in advance, so, it is not suitable for localization in complex and unknown environment. This limitation brings the requirement of finding a better localization algorithm, which is the subject to be researched in the future work.

Acknowledgment

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