Kalman Filter-based Navigation System for the Amphibious Spherical Robot

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Abstract - Robust and performing navigation systems for Autonomous Underwater Vehicles (AUVs) play a discriminant role towards the success of complex underwater missions. This paper presents a new design and development of a low-cost INS (Inertial Navigation System) using Miro-Electro-Mechanical-System (MEMS) inertial sensor and the pressure sensor (PS). The intensive pre-processing and modeling MEMES sensor’s primitive, noisy motion data are outline, these techniques transform the erroneous motion data into practical motion indicators illustrated in 3D position, 3D velocity and 3D orientation. INS acts as a dead reckoning device. The pressure sensor is used to detect the depth data of underwater Vehicles. The quality of the filtering algorithm for the estimation of the AUV navigation state strongly affects the performance of the overall system. In this paper, the authors present adapt the Kalman Filter (KF) approach. Experiments were conducted to improve the navigation system performance of the INS and PS installed on the Amphibious Spherical Robot III (ASR III) for motion and attitude estimation. Lastly the experiment results are evaluated and verified using the sensor data from the navigation system.

Index Terms – Amphibious Spherical Robot; Inertial Measurement System; Kalman Filter; Pressure Sensor

I. INTRODUCTION

In recent years, Autonomous Underwater Vehicles (AUVs) were widely used in many fields of application: they are employed for scientific purposes (e.g. sample collection, exploration and surveillance of archaeological sites), to complete industrial tasks at high depths (for instance they are exploited in the Oil & Gas industry) [1],[2], to carry out reconnaissance and patrolling missions in the military field, or even to conduct search and rescue duties.

Regardless of the kind of tasks, the development of accurate and robust navigation system for AUVs [3],[4] is essential to reach the high control performance. In particular, one of the main factors influencing the AUVs navigation accuracy is the algorithm used to estimate the vehicle motion. They are usually based on Kalman Filters (KF), Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF) or Particle Filter (PF) and make use of simplified kinematic or dynamic vehicle models.

Furthermore, different sets of sensors are employed during the underwater robot navigation. They may include, for instance, Inertial Measurement Units (IMU), or Fiber Optic Gyros (FOG) to measure underwater robot orientation, Pressure Sensors (PS) for depth measurements, Doppler Velocity Logs (DVL) [5],[6] to measure the vehicle translational velocity, acoustic localization systems [7] based on range measurements or on Ultra-Short BaseLine (USBL) [8]. Those sensors are mainly applied to the large AUV, and can assist the AUVs to have a robust and performing navigation systems. However, for some small underwater robots [9]-[11] including amphibious spherical robot, sensors, such as FOG, DVL, and USBL are too larger, heavier, and more difficult to be fixed on the robots. Therefore, we proposed a new Kalman filter-based navigation system employing IMU and the PS for the ASR-III.

The rest of paper is organized as follows. In section II, the novel amphibious spherical robot, also with its control method and some sensors mounted on it are introduced. In section III, the outline of the Kalman filter-based navigation system is presented. The navigation experiment with IMU and the pressure sensor is described in Section IV. And the conclusion and future work are presented in Section V.

II. AMPHIBIOUS SPHERICAL UNDERWATER ROBOT

A. The Design of Robot

Fig.1 The overview structure of the ASR-III
The ASR-III (Amphibious Spherical Robot III) mainly consists of a sealed upper hemisphere hull, a plastic circular plate, four actuating units, a main thruster and sensors, such as the pressure sensor, IMU, cameras. The overview structure diagram of the robot is shown as Fig. 1. Four actuating units are symmetrical installed on the plastic circular plate. The control circuits, sensors and batteries are installed inside the sealed upper hemisphere hull in order to achieve the waterproof effect. As shown in Fig. 2 (a), each actuating unit includes two servo motors, a water-jet thruster. Fig. 2 (b) shows the mechanical structure of main thruster and Fig.2 (c) is the prototype of main thruster.

Fig.2 The actuating system (a. one actuating unit of mechanical leg, b. the mechanical structure of main thruster, c. the prototype of main thruster)

B. The Propulsion System

In the past of the research on the amphibious spherical robot [13]-[17], the on-land and underwater locomotion mainly rely on the four water-jet thrusters [12], but the velocity of the robot is very small and it need a more power thruster. In my research, I added a propeller thruster under the middle bottom board and it can implement exploration in wide-area environment. The main propeller thruster is shown as Fig.3. It can rotate in the horizontal plane, and the propeller thruster can realize the high-velocity motion after adjusting the orientation.

The four water-jet thrusters help the ASR-III realize the rotation movement with zero radius, sinking and floating movement as shown in Fig. 3. Fig.3 (a) shows the distribution of four water-jet thrusters to realize the rotation movement with zero radius. Fig.3 (b) and Fig.3 (c) indicate the vertical movement, sinking and floating respectively.

C. The Sensors

The ASR-III carries multiple sensors for the navigation system. Fig.4 shows IMU (ADSI16365), and PS.

Hereafter, the measurement equations modelling the sensor behavior will derived by taking into account the main features of the employed sensors and the main noise sources affecting the measurements:

1. Robot depth $\eta_{1z}$ measured by the depth sensor:
   \[ \eta_{1z}^w = \eta_{1z} + \delta_{1z} \]  
   where $\eta_{1z}^w$ and $\eta_{1z}$ are the measured and the true depths and $\delta_{1z}$ are the measurement noises.

2. Robot orientations $\eta_2$ provided by IMU ADSI16365 (including 3D gyroscope, 3D accelerometer) through the attitude estimation filter starting from the following measures:
   - Robot angular velocity $\nu_2$ measured by the 3D gyroscope:
     \[ \nu_2^w = \nu_2 + \delta_{2\nu} \]  
     where $\nu_2^w$ and $\nu_2$ denote the measured and the true angular velocities and $\delta_{2\nu}$ is the measurement noise;
   - Robot linear acceleration measured by the 3D accelerometer:
     \[ a_2^w = a_2 + \delta_a \]  
     where $a_2^w$ and $a_2$ denote the measured and true linear accelerations and $\delta_a$ is the measurement noise;

By suitably processing the above measurements, the attitude estimation filter is able to estimate the robot orientation $\eta_2$ that will be used in the subsequent developments of this paper as a visual measurement $\eta_2^w$ modelled as:
   \[ \eta_2^w = \eta_2 + \delta_{2\eta} \]  
   where $\delta_{2\eta}$ is a further measurement noises.

Introducing the measurement vector $z = (((\eta_{1z}^w)^T, (\eta_2^w)^T)^T$, the measurement equations can be summarized as follows:
   \[ z = f(x) + v \]  
   \[ f(x) = \begin{pmatrix} O_{w3} & O_{w3} & I_{w3} & O_{w3} & I_{w3} \\ O_{w3} & O_{w3} & I_{w3} & O_{w3} & I_{w3} \end{pmatrix} x \]  

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\[ \delta_{\eta} = (\delta_{\eta_1}, \delta_{\eta_2}, \delta_{\eta_3})^T \]  
\[ v = (\delta_{\eta_1}^T, \delta_{\eta_2}^T, \delta_{\eta_3}^T)^T = (\delta_{\eta_1}, \delta_{\eta_2}, \delta_{\eta_3})^T \]  

\[ D. \ The \ Control \ System \ of \ the \ ASR-III \]

The robot control system of Amphibious Spherical Robot in Underwater is based on a traditional PID approach which is working on all the controlled DOFs of the robot (longitudinal, lateral and vertical translations and yaw rotations)

\[ u(t) = K_p e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \]  
\[ e(t) = x(t) - y(t) \]

where \( K_p, K_i, K_d \) are suitable (proportional, integral, derivative) gain matrices to be properly tuned so as to achieve the required control performance, \( e(t) \) is the control error on all the robot DOFs (i.e. the difference between the desired value and the actual value) at time \( t \), \( T_i \) and \( T_d \) are the time constant matrix of integration and derivative, \( u(t) \) are the desired control force working on the robot (to be achieved through suitable control signals \( x(t) \) of the robot motors, that is the motor rotation speed).

\[ \hat{x}_k = A \hat{x}_{k-1} + B u_k \]  
\[ P_k = A P_{k-1} A^T + Q \]

In the system equation (1) (2), \( \hat{x}_k \) is the state variable that want to optimize as the Kalman filter, \( A \) is the transform coefficients that connected between the previous step and the next step, \( B \) and \( u_k \) are the additional input value regardless of the system. \( P \) is the error covariance value, so it can be obtained by the system error \( Q \) and covariance value in the previous step. In the Kalman filter, \( Q \) is the most important element with the \( R \) of the observation equation.

\[ K_k = P_k H^T (H P_k H^T + R)^{-1} \]  
\[ \hat{x}_k = \hat{x}_{k-1} + K_k (z_k - H \hat{x}_{k-1}) \]  
\[ P_k = P_{k-1} - K_k H P_k \]

In the observation equation (3) (4) (5), Kalman gain \( K_k \) is obtained by the error covariance \( P \) and the observation error \( R \). Through the obtained Kalman gain previously, state variable values can be determined by predicted state variable values. This process not end instead of a single calculation and \( P \) values of the current state are readjusted by the Kalman gain, affect to the next step.

As Section I mentioned, the ASR-III allows to easily and effectively test the performance of different navigation algorithms. The typical test architecture is schematized in Fig. 6.

A. Kalman Filter

Many researchers study to solve estimation problem of states variables about the dynamic system. The method based on theory of probability is configured probability space consisting of state variables. It is based on the estimate about state variable using system's dynamic characteristics and the measurement value. Typically based on Bayesian estimation technique, Kalman filter (KF), a particle filter and so forth have been actively studied in the field of localization.

\[ v_{pd}(t_0) \]
\[ r_{pd}(t_0) \]

\[ v_{pd}(t) = v_{pd}(t_0) + \int_{t_0}^t a_{pd}(\tau)d\tau' \]  

Similarly, Given the position at the initial time \( t_0 \) as \( r_{pd}(t_0) \), then the position at time \( t \) can be get via the integration of the velocity.
\[ r_{\psi}(t) = r_{\psi}(t_0) + \int_{t_0}^{t} v_{\psi}(t')dt' \]
\[ = r_{\psi}(t_0) + (t - t_0) v_{\psi}(t_0) + \int_{t_0}^{t} a_{\psi}(t')dt' \]

Given the heading at the initial time \( t_0 \) as \( \psi_{\psi}(t_0) \), then the heading at time \( t \) can be get via the integration of the angular rate \( \dot{\psi}_{\psi,z} \).

\[ \psi_{\psi}(t) = \psi_{\psi}(t_0) + \int_{t_0}^{t} \dot{\psi}_{\psi}(t')dt' \]

IV. EXPERIMENTAL RESULTS

This section outlines the experimental results generated from the navigation system of the ASR-III with the IMU and the pressure sensor installed. In order to realize the navigation system, firstly, we evaluate our actuating system of the ASR-III and then take the heading control. Those experiments were conducted in an indoor pool of our laboratory, the size of which is 3m*2m*1m (height*width*depth), and the water is static without disturbances.

A. Thruster Force Testing and Evaluation

In our propulsion system, we have two types of thrusters. The type in Fig.2 (a) has low horsepower, and can not be used in wider area exploration. However, the resistance of rotation motion with zero radius is pretty slight because of the special spherical structure. Therefore, we use it to realize rotation control. And its force testing has been researched. There is no need to research on it. The other type showed in Fig.2 (c) has strong horsepower, and can move with large velocity. Here we test the characteristics of the main thruster by the simple device showed in Fig.8. After force analysis of the main thruster, we get the relationship between PWM signals and the thrust force by the equation (21).

\[ F = mg \sin \theta \] (21)

Fig. 9 shows that the force changes with the PWM signals (9%~13%), which is approximately linear. Therefore, the performance of the thruster is verified.

B. Navigation System Experiment

To evaluate the navigation system for the ASR-III, we carried out the experiment which the robot moves on a rectangle about 1.5m*2m. Fig.11 shows a video sequence of the horizontal underwater motion without disturbances and the depth value is about 15cm. In the experiment, we changed the heading angle, 0°, 90°, 180°, 270° at each turning point.
the curve after Kalman filter is smoother and Kalman filter
can reduce measurement error, especially in Fig. 12 (the
acceleration data).

Fig. 10 Depth data experiment (the green curve is measured with the pressure
sensor; the red curve is predicted by Kalman filter)

Fig. 13 is the snapshots of our video about our navigation
system experiment. We set the trajectory as a rectangle. And
Our robot will last about 10s once on the rectangle (1.5m*2m).
Fig. 14 and Fig. 15 show the attitude and trajectory obtained by
the ASR-III on the rectangle in the lab pool, so the ASR-III
will turn three times, and the angle is 0°, 90°, 180°, 270°
in Fig. 14. The length of the rectangle trajectory is about 7m
totally. As we can see, in Fig. 15, the accumulation error
become larger over time.

Fig. 12 Acceleration of IMU (the green line is the measured data, and the red
line is predicted by Kalman filter)

Fig. 11 Angle rate of IMU (The green line is the measured data, and the red
line is predicted by Kalman filter)

V. CONCLUSION AND FUTURE WORK

This paper presents a new low cost integrated navigation
system using MEMS, inertial sensor and the pressure sensor
for the ASR-III. Firstly, we designed the ASR-III including a
waterproof hull, an electrical system and a navigation system.
And then we proposed a Kalman filter-based navigation
system for the ASR-III. Finally, we conducted the
experiments in a pool of our laboratory, and the results
verified the accuracy of the navigation system. In the future,
we will focus on the accuracy of the navigation system of the
ASR-III via advanced methods based on Bayesian estimation
technique, such as UKF, EKF and a particle filter. And for
outdoor experiment, we will extend the navigation system by
GPS (during periodic resurfacing), which will help the ASR-
III realize the wider area navigation system.

Fig. 13 Screenshots of our navigation experiment

Fig. 14 Attitude of ASR-III
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