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To cite this article: Zhang Yi et al 2005 J. Phys.: Conf. Ser. 13 127

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A Novel Method of Range Measuring for a Mobile Robot Based on Multi-sensor Information Fusion

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Abstract: The traditional measuring range for a mobile robot is based on a sonar sensor. Because of different working environments, it is very difficult to obtain high precision by using just one single method of range measurement. So, a hybrid sonar sensor and laser scanner method is put forward to overcome these shortcomings. A novel fusion model is proposed based on basic theory and a method of information fusion. An optimal measurement result has been obtained with information fusion from different sensors. After large numbers of experiments and performance analysis, a conclusion can be drawn that the laser scanner and sonar sensor method with multi-sensor information fusion have a higher precision than the single method of sonar. It can also be the same with different environments.

Keywords: range measuring, extended Kalman filter (EKF), Multi-sensor information fusion

1. Introduction

A mobile robot is a robot which is self-planning, self-organizing and has adaptive ability in a complicated environment. Navigation technique is the key in relative technical study of a mobile robot. There are many navigation methods, including inertial navigation, vision navigation, data navigation based sensors and satellite navigation, etc. These navigation methods can be the same in all kinds of environments, including indoor and outdoor environments, structured environment and non-structured environment. Each method has a different navigation performance, so a data fusion method often used to combine the information from multi-sensors. In order to detect the relationship between the robot and the environment, the robot has a tactile sensor, vision sensor, inner force sensor, approach sensor, ultrasonic sensor and sound sensor, these sensors greatly improve the working condition of the robot so that robot can adequately finish complicated work.

The distance sensor can be used to navigate and avoid any obstructions, and can be used to locate the robot, there are some odometry by now, such as ultrasonic odometry and laser odometry. The Methods for mobile robot positioning can roughly be categorized into two groups, i.e. relative and absolute position measurements. Relative position measurements include use of encoders, gyroscopes and accelerometer. Absolute position measurement uses active beacons, artificial landmark recognition and natural landmark recognition[1-3].

The navigation method is multi-sensor based and is a developmental direction for mobile robot navigation. The resource of multi-sensors can be utilized with multi-sensor information fusion, the complementary information from multi-sensors is fused according to some criterion, then consistency
explanation or the description of the measurand can be found. The navigation accuracy and robustness of the system have been improved. In the navigation research of a mobile robot, the positioning technique is very important, and the positioning method is based on parameter measurement of the surrounding environment. In this paper, data fusion based EKF is raised to fuse the information from a sonar sensor and a laser scanner.

2. State equation of positioning system[4-5].

The state of the robot at the \((k+1)\)th sampling time is expressed as follows:

\[
X(k+1) = \begin{bmatrix} x(k+1), y(k+1), \theta(k+1) \end{bmatrix}^T
\]

(1)

Where \(x(k+1), y(k+1)\) and \(\theta(k+1)\) is the position and orientation of the robot at the \(k\)th sampling time, respectively. In the same way, the position and orientation of the robot at the \(k\)th sampling time is

\[
X(k) = \begin{bmatrix} x(k), y(k), \theta(k) \end{bmatrix}^T
\]

We can get the following state equation of the robot

\[
X(k+1) = \begin{bmatrix} x(k+1) \\ y(k+1) \\ \theta(k+1) \\ r_r(k+1) \\ r_l(k+1) \\ B(k+1) \end{bmatrix} = \begin{bmatrix} x(k) + \Delta x(k+1) \cos[\theta(k)+\Delta\theta(k+1)/2] \\ y(k) + \Delta y(k+1) \sin[\theta(k)+\Delta\theta(k+1)/2] \\ \theta(k) + \Delta\theta(k+1) \\ r_r(k) + v_r(k) \\ r_l(k) + v_l(k) \\ B(k) + v_b(k) \end{bmatrix} + V(k)
\]

(2)

Where \(\Delta x(k+1)\) and \(\Delta\theta(k+1)\) is the increments of distance and orientation, \(r_r(k+1), r_l(k+1)\) and \(B(k+1)\) is radius of right wheel, radius of left wheel and distance between wheels.

3. Measurement equation of positioning system[6-7].

3.1 Sonar measurement equation

The Pioneer 2 with eight transducers provides object detection and range information for feature recognition, as well as navigation around obstacles. The sonar positions are fixed in an array: one on each side and six facing outward at 20-degree intervals, together providing 160 degrees of nearly seamless sensing. The sonar firing rate is 25Hz(40 milliseconds per sonar per array) and sensitivity ranges from ten cm(six inches) to more than five meters.

Assuming the vector \(X_s(k) = (x_s(k), y_s(k), \alpha_s(k))^T\) and the vector \(L_s = (x'_s, y'_s, \alpha'_s)^T\) to express the sonar’s global and local position and orientation, respectively, then we can derive the relationship among the vectors \(X(k), X_s(k)\) and \(L_s\) as follows:

\[
\begin{align*}
    x_s(k) &= x(k) + x'_s \cos(\theta(k)) - y'_s \sin(\theta(k)) \\
    y_s(k) &= y(k) + x'_s \cos(\theta(k)) + y'_s \sin(\theta(k)) \\
    \alpha_s(k) &= \theta(k) + \alpha'_s
\end{align*}
\]

(3)

A mobile robot mainly meets four kinds of objects, i.e. smooth planes, vertical concave corners, vertical convex edges and cylinders in a indoor environment, in a two-dimension environment, we can consider these as line segments, points and circles, respectively.

Suppose that \(\theta_{pi}\) is the \(i\)th line segment and the positive direction of the \(x\)-axis of the global coordinate system, we have:
\[ \tan(\theta_{oi}) = -\cotg(\theta_{pi}) \] (4)

We can get the distance between the \( j \)-th (\( j = 1, 2, ..., 8 \)) sonar and the \( i \)-th line segment, i.e. the measurement equation of line segments

\[ h_{s-p} = d_{pi} - x_{s-j}(k) \cos(\theta_{oi}) - y_{s-j}(k) \sin(\theta_{oi}) \] (5)

Where \( (x_{s-j}, y_{s-j}) \) is the global coordinate of the \( j \)-th (\( j = 1, 2, ..., 8 \)) sonar.

3.2 Measurement equation of the laser scanner with artificial beacons

The method is an absolute positioning technique, which measures their bearing relative to each other by scanning the artificial beacons. The measurement model expresses a beacon’s bearing in terms of the pose of the robot and the coordinate value of the observed beacons, then we can get

\[ Z(k) = h[k, X(k)] + W(k) \]

\[ h[k, X(k)] = a \tan \left( \frac{y_i - y(k)}{x_i - x(k)} \right) - \theta(k) \] (6)

Where \((x_i, y_i)\) is position of \( i \)-th beacon.

4. Position based Extended Kalman Filter Algorithm\(^{[5-8]}\).

Discrete kinematic equation of nonlinear system can be expressed as

\[ X(k+1) = f[k, X(k)] + G(k)V(k) \] (7)

To be convenient for mathematical processing, assume that there isn’t control input, and process noise is Gaussian noise with zero mean, and noise distribution matrix \( G(k) \) is known, i.e.

\[ E[V(k)] = 0, E[V(k)V'(j)] = Q(k) \delta_{ij} \] (8)

The observation equation can be expressed as

\[ Z(k) = h[k, X(k)] + W(k) \] (9)

Where the observation equation is Gaussian noise with zero mean, i.e.

\[ E[W(k)] = 0, E[W(k)W'(j)] = R(k) \delta_{ij} \] (10)

From analysis, we can get following operation flow chart of EKF, which is showed as figure 1.

![Figure 1. Operation flow chart of extended Kalman filter algorithm](image)
The state equation based fusion is the same as equation (2). From equation (2), we can get the associated variance of the prediction can be calculated, where jacobian matrix $f_X(k)$ can be calculated by following equation

$$f_X(k+1)=
\begin{bmatrix}
1 & 0 & -\Delta s(k+1)\sin(\hat{\theta}(k)) & 0 & 0 & 0 \\
0 & 1 & \Delta s(k+1)\cos(\hat{\theta}(k)) & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
$$

(11)

From equation (5), we have the measurement Jacobian matrix corresponding to planes

$$h_X(k+1)=
\begin{bmatrix}
-x_i \sin(\hat{\theta}(k+1)-\theta_m)
-f_i \sin(\hat{\theta}(k+1)-\theta_m)
\end{bmatrix}
$$

(12)

From equation (6), the measurement Jacobian matrix of laser scanner is

$$h^T_{X}(k+1)=
\begin{bmatrix}
\frac{\partial h}{\partial x} & \frac{\partial h}{\partial y} & \frac{\partial h}{\partial \theta}
\end{bmatrix}
$$

(13)

where

$$\frac{\partial h}{\partial x} = \frac{-\left(y_i - y(k)\right)}{(x_i - x(k))^2 + (y_i - y(k))^2}, \quad \frac{\partial h}{\partial y} = \frac{-\left(x_i - x(k)\right)}{(x_i - x(k))^2 + (y_i - y(k))^2}, \quad \frac{\partial h}{\partial \theta} = -1
$$

The measurement Jacobian matrix of data fusion based sonar and laser scanner is

$$h^T_{X}(k+1)=
\begin{bmatrix}
-x_i \sin(\hat{\theta}(k+1)-\theta_m)
-f_i \sin(\hat{\theta}(k+1)-\theta_m)
\end{bmatrix}
$$

(14)

5. Simulation

In order to analyze the performance of the proposed mobile robot positioning based on sonar measurements and the laser scanner, suppose that the mobile robot starts at $X_0=(1.18, -0.2, 2.62)$, which is set to be the initial position and orientation.

$$P(0) = \text{diag}(2 \times 10^{-3}, 2 \times 10^{-3}, 2 \times 10^{-3}, 2 \times 10^{-4}, 2 \times 10^{-4}, 2 \times 10^{-4}),$$

$$Q(0) = \text{diag}(1 / 10^3, 1 / 10^3), \quad R(0) = \text{diag}(1 \times 10^{-6}, 1 \times 10^{-6}, 1 \times 10^{-7})$$

We used the data fusion method as shown in Fig.2 to estimate the coordinates of the feature points in 2D.

The estimated right and left wheel radius and wheel distance of mobile based data fusion is showed as figure 3. Figure 4 shows the mean-squared position error curves of sonar, laser scanner, and multi-sensor fusion based EKF. From these figures we can see that estimation results of multi-sensor based EKF approach the actual value as time increases more than inertial sensors, single camera. The Mean-squared uncertainty decreases to approach a constant with time. The method of multi-sensor fusion based EKF has the best estimation precision at all the methods of sonar, laser scanner, multi-sensor fusion based EKF, followed by laser scanner and sonar method.
6. Conclusion
This paper proposes a multi-sensor based positioning system for a mobile robot. The system is based on sonar sensor, laser scanner and data fusion algorithms. Extended Kalman filter based data fusion algorithms are proposed to estimate the position of the mobile robot. Simulation results show that the multi-sensor fusion method based on EKF can minimise the MSE using the estimated covariance obtained from all the sensors, and has a reasonably good performance.

Acknowledgment
The paper was sponsored by the project of ‘ChunHui plan’ of Ministry of Education of the People’s Republic of China and item of backbone teacher of middle age and youth of Chongqing, item of science and research foundation of Chongqing University of Posts and Telecommunications.

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