Research on dead-reckoning based localization for cleaning robot

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Abstract. The cleaning robot can perform cleaning tasks autonomously and intelligently, thus saving people from boring and heavy physical labour. Autonomous positioning is one of the indicators for intelligent level of cleaning robots. In this paper, dead-reckoning method based on encoder is adopted. The kinematics model of the robot is established to optimize the existing cleaning robot positioning method by using arc model. The positioning effect of the cleaning robot is tested by experiment. Through experiments, it is found that there are two main problems in the estimation of the track. One is that during the turning process, the calculation of the angle is affected by the slip, which causes a large deviation. Another is that the displacement deviation of linear motion gradually increases with the increase of the driving distance due to system error. Based on the above analysis, a positioning scheme is proposed. Gyro sensor and RFID tag are introduced to correct the angular deviation and assist positioning and improve the positioning accuracy of the cleaning robot.

1. Introduction

The changes of people' lifestyle have generated a large demand for service robots as service industries develop. A service robot is a fully autonomous or semi-autonomous robot that can perform service activities that are beneficial to humans, but not engaged in production[1]. Among them, cleaning robot is one of the most widely used service robot product.

For cleaning robots, positioning and path planning techniques are the most critical factors in determining their level of intelligence. Positioning is the basis for navigation and serves for path planning[2]. Positioning technology can be generally divided into indoor positioning and outdoor positioning. In terms of outdoor positioning, satellite positioning is mainly used[3]. Indoor positioning is more complicated because the environment is complex and variable, and there are various sources of interference such as temperature, light, sound, etc. Indoor positioning methods are complicated and numerous, but each technology has its own limitations. Commonly used indoor positioning methods, in principle, are mainly divided into multilateral measurement method, fingerprint matching method and track estimation method. Multilateral measurement methods include positioning based on TOA(time of arrival)[4], TDOA(time difference of arrival)[5] and RSSI(received signal strength indicator)[6]. Multilateral measurement technology relies on a series of beacons of known features in the environment, and it is necessary to install a sensor on the mobile robot to observe the beacon and determine the position coordinates of the robot based on the distance between the measured robot and the beacon. The fingerprint matching method requires a database to correlate the signal strength with the location in the environment[7]. It is mainly used in a positioning system based on a WLAN. Dead reckoning is a widely used positioning method in mobile robot positioning[8]. This method uses the known initial position to estimate the position and direction of the robot in real time according to the change of the heading angle and the displacement information during the walking process. This method has the characteristics of high autonomy and being less influenced by external factors. Generally, stable and high-precision positioning coordinates can be obtained in a short distance, but as time and distance increase, the cumulative error will become larger and larger. Methods such as Kalman filtering, complementary filtering are usually used to minimize noise in acceleration and angular velocity.

Considering factors including cost, stability, algorithm complexity and feasibility, this paper adopts the dead reckoning as the main positioning scheme of cleaning robot. A more accurate dead reckoning model based on photoelectric encoder is analyzed and the dead reckoning experiment is carried out. The deficiencies in this positioning scheme are pointed out through experiments. Aiming at the problems, a positioning scheme combining dead reckoning and RFID positioning is proposed.

2. Encoder-based track estimation

In this paper, the cleaning robot determines positioning mainly by the encoder-based dead reckoning. The encoder is sampled once every fixed sampling period. By recording the number of pulses output by the encoder in each sampling period, the displacement of the left and right wheels in each sampling period can be obtained. By integrating each displacement, the pose of the robot can be obtained.

2.1. Establishment of the coordinate system

Considering that the ground in the actual working environment is relatively flat, the robot can be seen as moving in two dimensions. The coordinate system includes a global coordinate system and a local coordinate system. The global coordinate system is used to mark the absolute coordinates and position of the robot. The robot coordinate model is shown in Figure 1, where XOY represents the global coordinate system and $X_R O_R Y_R$ represents the local coordinate system. In the global coordinate system, the pose of the robot at any time can be represented by the state vector $\left[x, y, \theta\right]^T$, where x and y respectively represent the coordinates of the robot in the global coordinate system, and θ represents the angle between the forward direction of the robot and the X-axis. The angle is positive in the counter-clockwise direction and ranges from 0 to 360 degrees.

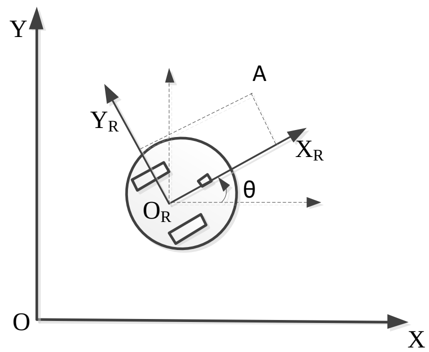

Figure 1. Robot coordinate model

If the coordinates of a point A in the local coordinate system are $\left[x_r, y_r\right]$, the coordinates $\left[x_g, y_g\right]$ of the point in the world coordinate system can be obtained by Equation (1).

$$\begin{cases} x_g = x + x_r \cos\theta - y_r \sin\theta \\ y_g = y + x_r \sin\theta - y_r \cos\theta \end{cases} \tag{1}$$

2.2. Kinematics model based on dead reckoning

The cleaning robot can be regarded as a rigid body when it moves in a plane. This paper uses the motion of the centre point of the two drive wheel connections to replace the motion of the robot. The initial position is known. The real-time pose of the robot can be estimated based on changes in displacement and heading angle. The displacement and speed of the wheels can be obtained by the incremental photoelectric encoder mounted on the drive wheel.

Let the diameter of the drive wheel be D, the width between the two wheels be W, and the number of pulses per revolution of the encoder be P. If the number of encoder pulses captured in Δt time is N, and the distance the wheel moves is Δd, then:

$$\Delta d = \pi DN / P \tag{2}$$

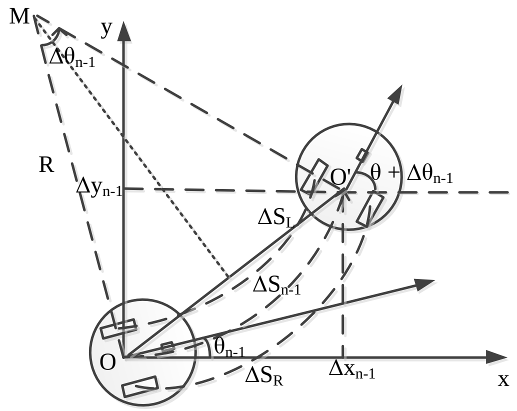

Figure 2. Dead reckoning model

The commonly used dead reckoning model assumes that the trajectory of the robot is approximately straight in a short sampling time[9]. This motion estimation model is inaccurate, and a more accurate arc model is used here. As shown in Figure 2, the pose of the robot at t_{n-1} is $\left[x_{n-1}, y_{n-1}, \theta_{n-1}\right]^T$, the pose at t_n is $\left[x_n, y_n, \theta_n\right]^T$, the pose increment is $\left[\Delta x_{n-1}, \Delta y_{n-1}, \Delta\theta_{n-1}\right]^T$. The distances the left and right wheels move are ΔS_L and ΔS_R, respectively. Assuming that the ground is flat during the movement and there is no slippage, the distance the robot moves in Δt can be represented by the dotted li

$$\Delta S_{n-1} = (\Delta S_L + \Delta S_R) / 2 \tag{3}$$

where

$$\Delta S_{n-1} = (R - W/2) \cdot \Delta\theta_{n-1} \tag{4}$$

$$\Delta S_R = (R + W/2) \cdot \Delta\theta_{n-1} \tag{5}$$

So, the angle that the robot turns is

$$\Delta\theta_{n-1} = (\Delta S_R - \Delta S_L) / W \tag{6}$$

The radius of rotation is

$$R = \Delta S_{n-1} / \Delta\theta_{n-1} \tag{7}$$

According to geometric relationship,

$$\Delta x_{n-1} = 2R \cdot \sin(\Delta\theta_{n-1}/2) \cdot \cos(\theta_{n-1} + \Delta\theta_{n-1}/2) = \frac{\Delta S_{n-1}}{\Delta\theta_{n-1}}\left[\sin(\theta_{n-1} + \Delta\theta_{n-1}) - \sin\theta_{n-1}\right] \tag{8}$$

$$\Delta y_{n-1} = 2R \cdot \sin(\Delta\theta_{n-1}/2) \cdot \sin(\theta_{n-1} + \Delta\theta_{n-1}/2) = \frac{\Delta S_{n-1}}{\Delta\theta_{n-1}}\left[\cos\theta_{n-1} - \cos(\theta_{n-1} + \Delta\theta_{n-1})\right] \tag{9}$$

When the sampling time is short enough or the robot moves in a straight line, $\Delta\theta_{n-1} \to 0$. Therefore, the pose of the robot at t_n is

$$\begin{cases} x_n = x_{n-1} + \Delta x_{n-1} = x_{n-1} + \dfrac{\Delta S_{n-1}}{\Delta\theta_{n-1}}\left[\sin(\theta_{n-1} + \Delta\theta_{n-1}) - \sin\theta_{n-1}\right] \\ y_n = y_{n-1} + \Delta y_{n-1} = y_{n-1} + \dfrac{\Delta S_{n-1}}{\Delta\theta_{n-1}}\left[\cos\theta_{n-1} - \cos(\theta_{n-1} + \Delta\theta_{n-1})\right] \\ \theta_n = \theta_{n-1} + \Delta\theta_{n-1} \end{cases} \tag{10}$$

The robot measures the distance of the left and right wheels and the angle of the offset in each sampling interval by the encoder. The pose change of the next moment relative to the previous moment can be derived by formula (10). Assuming that the robot position at the initial moment is determined, the robot coordinates at any time can be obtained in theory.

3. Positioning experiment

In the previous section, the kinematics model of the cleaning robot based on dead reckoning is theoretically deduced, but the positioning effect could not be obtained intuitively. Therefore, it is necessary to further discover the problems through experiments.

In this section, the positioning experiments of the linear motion and the 90 degree turn of the cleaning robot are carried out. The encoder is sampled every 250ms, and mean filtering integration over collected motor speed information is done to obtain the displacement within the sampling time. Based on the formula derived in the previous section, the coordinates of each sampling moment can be obtained.

The reckoning trajectory of linear motion is shown in Figure 3. It can be found that when the robot makes a linear motion, the positioning error is not very large, but there is a certain cumulative error which increases with the increase of the moving distance. This is mainly caused by the asymmetry of the two drive wheels on the mechanical structure.

Figure 4 shows the dead reckoning trajectory of the robot for a 90 degree turn. In order to ensure that the robot performs a standard 90 degree turn, when it turns, set one of the wheels output speed to 0 and the other to rotate at a fixed speed until the robot's orientation is exactly 90 degrees. It can be found that the robot has a significant deviation in its direction of motion after the turn.

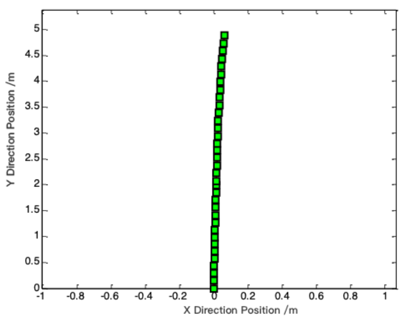

Figure 3. Linear motion track.

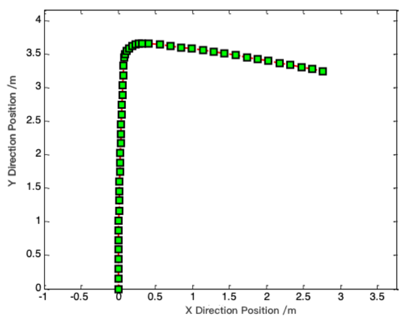

Figure 4. 90 degree turn track.

4. Discussion

The derivation of the trajectory estimation formula is based on the ideal environment. That means it assumes that the angle at which the drive wheel rotates is linear with the distance that the robot actually moves. However, in actual situations, this linear relationship cannot be established due to the interference factors such as wheel idling and uneven ground. In addition, there are a number of factors that can cause errors in positioning. In general, the sources of error can be divided into two categories: systematic errors and non-systematic errors[10].

Under normal circumstances, the system error has been accumulated in the robot positioning process. It has nothing to do with the external environment and does not change for a long time, so it has a great influence on the positioning accuracy of the robot. But when the robot is running on uneven ground, or when it has to go through more turns, non-systematic errors dominate. Non-systematic errors are mainly caused by the interaction between robots and environmental factors[11]. One non-systematic error is that the ground is uneven, or there are small obstacles on the ground that prevent the robot from walking normally. When the robot is operating in this environment, the theoretically calculated displacement increment is either smaller or larger than the actual walking distance. Another non-systematic error can be drive wheel slips. Water or oil on the local surface, sudden acceleration or deceleration of the robot, and obstacles can all cause the wheels to slip.

In the positioning experiment in the previous section, since the cleaning robot needs to undergo the process of decelerating and then accelerating when turning, this will cause the wheel to slip to some extent. The calculation of the angle is affected by the slip and the error is large, which causes a large deviation in the direction of motion. In order to improve the positioning accuracy, a positioning scheme is proposed. RFID tag can be used to estimate the absolute coordinates of the cleaning robot with known location information of the work area to correct the cumulative error. And gyroscopes can be introduced. It is a sensor for measuring the angular velocity of a moving object and can be added to correct the angular deviation of the cleaning robot.

5. Conclusions

This paper explores dead reckoning method by establishing kinematics model of the robot and a more accurate arc model is used here. Experiments for dead reckoning based on encoder are carried out to find how to optimize the positioning method. Based on the above analysis, a combined positioning scheme is proposed. Gyroscope and FRID tag can be applied to reduce error and correct deviation.

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