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Research of Autonomous Navigation Strategy for an Outdoor Mobile Robot

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Abstract

A kind of autonomous navigation strategy for an outdoor mobile robot is proposed in the real world environment. Encoder disk, electronic compass and GPS are used in the dead reckoning system of outdoor mobile robot. To reduce dead reckoning error, the extend Kalman filter method is adopted to realize data fusion from encoder disk and electronic compass. GPS receiver is used to correct the dead reckoning data to eliminate the accumulation error of the dead reckoning. Laser range finder is used to detect the obstacle and establish the environment map. Filed D algorithm and DWA method are used to realize the obstacle avoidance and path planning. The experimental results show that the outdoor mobile robot can realize the autonomous navigation under the complex road condition.*

Keywords: *mobile robot, autonomous navigation, extend Kalman filter, dead reckoning*

1. Introduction

With the rapid development of robot technology, robots, especially those which can move independently in outdoors environment, have been widely applied in industry, agriculture and military [1-6]. Comparing with traditional robots, outdoor autonomous mobile robots have better abilities on autonomous perception, decision-making and mission execution; they can finish the work independently in an extremely complex outdoor environment. Outdoor autonomous mobile robot must be able to perceive the information of the surrounding environment and its own state when it is moving. Because of the complexity of the surrounding environment and the uncertainty of its own state, it is difficult to obtain completely the external information which is collected by only one sensor. It needs a variety of sensors to collect all kinds of required information which can be used to achieve the robot's autonomy in complex, dynamic and uncertain environments. These sensors mainly include camera, laser range finder, GPS, sonar (ultrasonic), infrared, compass, gyro, odometry (encoder) and so on [7-10].

Recently, there have been many reports about autonomous mobile robots. Some researchers have addressed ways of developing an intelligent system for outdoor autonomous mobile robots. As for wheeled mobile robots, the most direct track method is to design the kinematics model of the system based on the robot's sports mechanism. By measuring angular velocity of the wheel, it can calculate the movement speed and direction of robot and conjecture the navigation track of the robot. The existing dead- reckoning method is mainly used in mobile robot navigation and positioning under 2D environment. It usually uses encoder to acquire the direction and mileage information of robot. However, only relying on encoder, the error of dead-reckoning is very big. Especially, the encoder information is used to calculate mobile robot's course. It is difficult to ensure navigation positioning accuracy of mobile robot. At present, fiber optic gyro and magnetic compass have been widely used in mobile robot navigation control system for measuring the advancing direction of mobile robot.

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A rough-terrain control methodology is proposed that utilizes the actuator redundancy found in multi-wheeled mobile robot systems to improve ground traction. The algorithm is based on rigid-body kinematic equations and utilizes an EKF to fuse noisy sensor signals [11]. Borenstein, *et al.,* presented a kind of method to fuse fiber optic gyro, speedometer and gyrodometry [12]. This method is different from general sensor statistical model fusion method, and is a kind of fusion method based on wheel physical interaction sensor. In the literature [13], by extended Kalman filter, date of the speedometer, ultrasonic sensor and CCD camera were fused to estimate pose position and orientation of mobile robot under the unknown environment. In the literature [14], a light-weight sensor platform that consists of gyro-assisted odometry and a 3D laser scanner was proposed for localization of human-scale robots. The gyro-assisted odometry provides highly accurate positioning only by dead-reckoning. The 3D laser scanner provides a wide field of view and uniforms measuring-point distribution. In the literature [15], two optical encoders were used to perform dead-reckoning for the mobile robot. Meanwhile, an electronic compass and a GPS receiver were used for self-localization of the robot. Position and orientation of the robot can be determined accurately by fusing the sensory data. A PID control law is used to control the right and left angular velocities of the robot.

In this paper, A Pioneer II AT wheeled robot is used as the research platform. Encoder disk, electronic compass, laser range finder and GPS are used in dead reckoning and obstacle avoidance system for outdoor mobile robot. In order to reduce dead reckoning error, the extend Kalman filter method is adopted for data fusion from encoder disk and electronic compass. GPS data is used to correct the dead reckoning system composed of encoder disk and electronic compass to eliminate the accumulation error. Two laser range finders are used to detect the obstacles and establish the local environment map. At the same time, they are working on obstacle avoidance and path planning. Finally the experiment of the autonomous mobile outdoor robot's autonomous moving on the road in real world environment is done.

2. The Composition of the Outdoor Autonomous Mobile Robot System

The appearance and sensor configuration of the outdoor autonomous mobile robot are designed as Figure 1. Robot platform is the Pioneer II-AT robot (American, ActivMedia Company). At the top of the robot, there is an AMS0805WAH electronic compass (South Korean, Amosense Company) which is used to detect the direction of the robot movement. To identify the robot's environment, UTM-X001S and URG04-LX laser range finders (Japan, Hokuyo Company) are adapted, one is mounted on the robot's bottom horizontally, and the other is installed in an angle at the top of robot. The robot has its own encoder disk as one sensor. When the robot is moving, information of the speed and the angular velocity can be read from the function provided by the system. At the same time, there is a CCD camera which is used to record the navigation state of the robot. Laptop computer is used as the robot's control computer. The operating system is Ubuntu/Linux. GPS, laser range finder, electronic compass are connected to control computer through the USB port. The camera connects the computer through 1394 card.

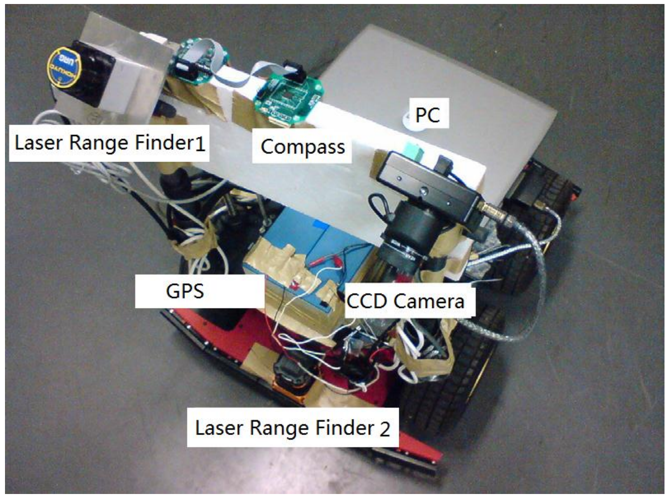

Figure 1. Outdoor Mobile Robot

3. Overall Scheme

The overall scheme of the outdoor mobile is shown in Figure 2. It is composed of dead reckoning, obstacle detection, path planning, obstacle avoidance and other modules.

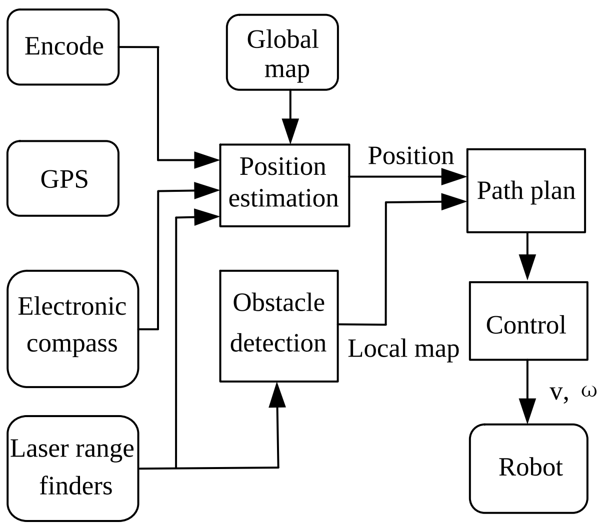

Figure 2. General Scheme of Outdoor Mobile Robot

3.1 Dead Reckoning

3.1.1. Encoder Disk and Electronic Compass Dead Reckoning System: Owing to the wheel slip, road irregularities and other reasons, the position error is large when only encoder disk is applied to the dead reckoning, especially the error of movement direction angle is larger. In this paper, electronic compass is used to detect the direction angle information of the robot's movement. The measurement error is inevitable when the two sensors are working. There will be a larger position error when the robot is doing the dead reckoning based on the two sensors. In the paper, the extend Kalman filter method is used to fuse the data from encoder disk and electronic compass. The moving coordinates of the outdoor mobile robot is shown in Figure 3.

$N(x, y, \theta)$ is the center of the robot; its coordinate represents the position of the robot. Line NN' expresses the robot's movement direction. x is the abscissa of the robot position, y is the ordinate of the robot position, θ is the angle between the robot's movement direction and the x-axis.

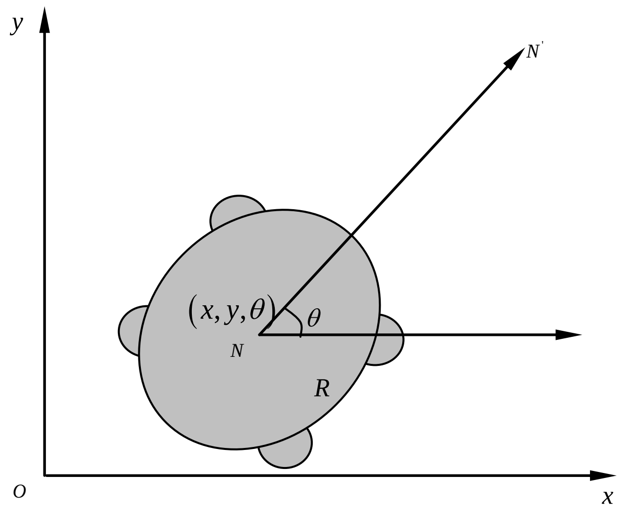

Figure 3. Moving Coordinate of Outdoor Autonomous Mobile Robot

The position and pose of the robot in time $(k\text{-}1)\Delta t$ is $(x_{k-1}, y_{k-1}, \theta_{k-1})$. $(\Delta x_n, \Delta y_n, \Delta\theta_n)$ is the change of the position and pose in time Δt. In time $k\Delta t$, the position and the pose are (x_k, y_k, θ_k), the equations of the robot's movement can be written as

$$\begin{cases} x(k) = x(k-1) + \Delta x(n) \\ y(k) = y(k-1) + \Delta y(n) \\ \theta(k) = \theta(k-1) + \Delta\theta(n) \end{cases} \tag{1}$$

That is

$$\begin{cases} x(k) = x(k-1) + v\Delta T\cos\theta(k-1) \\ y(k) = y(k-1) + v\Delta T\sin\theta(k-1) \\ \theta(k) = \theta(k-1) + \omega\Delta T \end{cases} \tag{2}$$

where ΔT is a sampling time, speed v and angular velocity ω can be obtained from encoder disk. The robot's motion direction can be measured by electronic compass directly.

Extended Kalman filter method is used to integrate the data of encoder disk and electronic compass [16, 17]. According to the robot's kinematic model, the system state equation is:

$$X(k) = \begin{bmatrix} x(k) \\ y(k) \\ \theta(k) \end{bmatrix} = \begin{bmatrix} x(k-1) + v\Delta T\cos\theta(k-1) \\ y(k-1) + v\Delta T\sin\theta(k-1) \\ \theta(k-1) + \omega\Delta T \end{bmatrix} + W(k) \tag{3}$$

System measurement equation is:

$$Z(k) = [\theta(k)] + V(k) \tag{4}$$

where $W(k)$ is the process noise matrix, $\theta(k)$ is the motion direction of the robot. $V(k)$ is the measurement noise matrix.

Time update equation and measurement update equation of the extended Kalman filter are as follows:

Time update equation:

$$\hat{x}(k)^- = f(\hat{x}(k-1), u(k-1), 0) \tag{5}$$

$$P(k)^- = A(k)P(k-1)A^{'}(k) + W(k)Q(k-1)W^{'}(k) \tag{6}$$

where

$$A(k) = \begin{bmatrix} 1 & 0 & -v\Delta t\sin(\theta(k-1)) \\ 0 & 1 & v\Delta t\cos(\theta(k-1)) \\ 0 & 0 & 1 \end{bmatrix},$$

$$W(k) = \begin{bmatrix} -\Delta t\cos(\theta(k-1)) & 0 \\ -\Delta t\sin(\theta(k-1)) & 0 \\ 0 & -\Delta t \end{bmatrix},$$

$$\Delta T = 0.15, P(0) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, Q(k) = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}.$$

Measurement updates equation:

$$K(k) = P(k)^- H^{'}(k)(H(k)P(k)^- H^{'}(k) + V(k)R(k)V^{'}(k))^{-1} \tag{7}$$

$$\hat{x}(k) = \hat{x}(k)^- + K_k(z_k - h(\hat{x}(k)^-, 0)) \tag{8}$$

$$P(k) = (I - K(k)H(k))P(k)^- \tag{9}$$

where $H(k) = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$, $V(k) = \begin{bmatrix} 1 \end{bmatrix}$, $R(k) = \begin{bmatrix} 0.1 \end{bmatrix}$.

The variable's estimated value of the system can be calculated with equations (4)-(9). It substitutes the estimated value into equation (3), the location information from multiple-sensor data fusion can be obtained.

3.1.2 GPS, Encoder Disk and Electronic Compass Dead Reckoning System: Encoder disk, electronic compass and dead reckoning system can provide good location results in short distance. But when the electronic compass is interfered by magnetic field, the direction angle will have a great error, the error of the dead reckoning increases with time and distance. So the dead reckoning system should correct the position every certain time and eliminate the accumulated errors.

Every time GPS determines the absolute position information by satellite data, its value is independent of time and the distance traveled. Therefore, GPS information is easily used to obtain the position of the robot. However, the speed of data collection of GPS is slow (per second sample 1 time), the location of the robot cannot be determined during sampling time. There are disadvantages such as data invalid or data jumping caused by bad weather, occlusions and other reasons.

Thus, encoder disk and electronic compass dead reckoning system can do the robot's dead reckoning in the sampling interval of GPS when the signal of GPS is lost. If GPS is working normally, then it is used to correct the encoder disk and electronic compass dead reckoning system and eliminates the measurement error.

3.2 Path Planning and Obstacle Avoidance

In this paper, two laser range finders are used to detect obstacles and create an environment map, UTM-X001S laser range finder which is set on the bottom of the robot is used to detect obstacles in the front and built the environment map; URG04-LX laser range finder which is installed in 45 degree angle at the top of robot is used to detect the possible pits on the road and low obstacles which cannot be detected by UTM-X001S laser range finder.

Control strategy [18] of outdoor mobile is shown in Figure 4, as follows: (1) When the robot is moving, we sets up a moving sub-goal that locates at 30 meters away in front of the robot's moving direction (2). According to the scanning information of the laser range finder, an environment map is built around the robot's current location, and a local target is set up in the direction of the sub-goal. The robot moves to local target, updates sub-goal local target and environment map in every sampling period (3). When obstacles are detected by laser range finders, the information of the obstacles is represented in 2-D Occupancy grid table, and the path to reach the local target is gotten by Filed D* algorithm [19]. (4) When obstacle avoidance is finished, local target re-tracking is realized with Dynamic Window Approach (DWA) method [20].

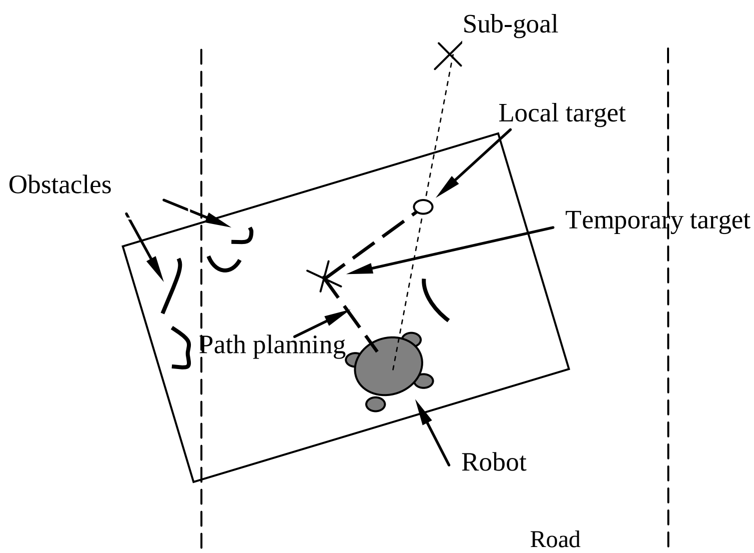

Figure 4. Control Strategy of Outdoor Mobile Robot

4. Experimental Study

To verity the outdoor mobile robot's autonomous moving strategy, the experiments are researched on a road whose length is 1000 meters. The road condition is complex; there exits bridges, cobblestone roads, asphalt roads and narrow avenues (trees, shrubs). Figure 5 is the satellite image of this road. Green line in the figure is the robot's moving route in plan.

Firstly, the encoder disk and electronic compass are used to research the outdoor robot's dead reckoning. Figure 6 is the experimental curve when the robot is under manual wire control operating. The red dotted line is the route that the robot should move, the black solid line is the robot's moving route obtained by dead reckoning system. Figure 6 shows that there are great errors between the actual routes and the plan routes in four locations: 120-170, 200-220, 340-355 and 550-590 meters. This is because there are bridges in these four locations, when the robot is moving there, the metal in the bridges have a great impact on the data of electronic compass. So, the direction angle information is inconsistent with the robot's actual direction, and products a great dead reckoning error. There is a great dead reckoning error between 280 and 310 meters in the Figure. This is because the road is cobblestone road. The strong jolt causes the error of direction angle information. The dead reckoning accumulation error will become greater with the growth of the robot's moving distance. The experiment results show that, the robot is hard to realize independent movement only using the dead reckoning system composed by encoder disk and electronic compass.

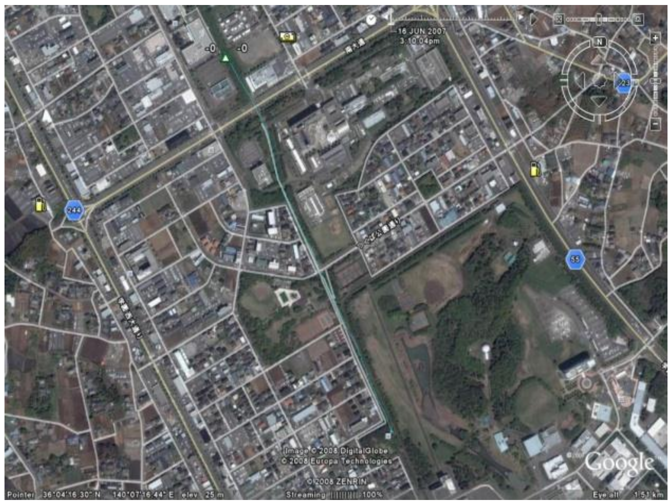

Figure 5. Experimental Curve Surrounding Satellite Map

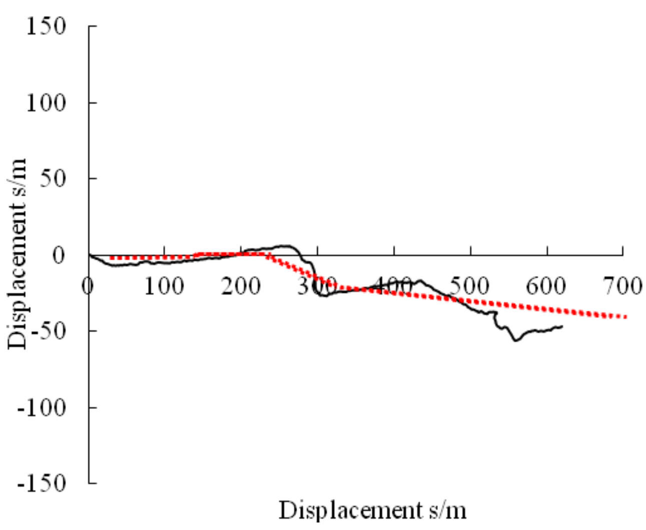

Figure 6. Dead Reckoning Experiment of Encode and Electronic Compass

Figure 7 is the experimental curve of the dead reckoning system composed of GPS, encoder disk and electronic compass. The read dotted line is the route the robot should move; the black solid line is robot's actual moving route when the robot is fully autonomous state. The figure shows the two curves basically coincided. Experimental results show that, after cyclical correction of the robot's location information by GPS, and cooperating with path planning and obstacle avoidance method introduced in this paper, mobile robot can complete the navigation task well.

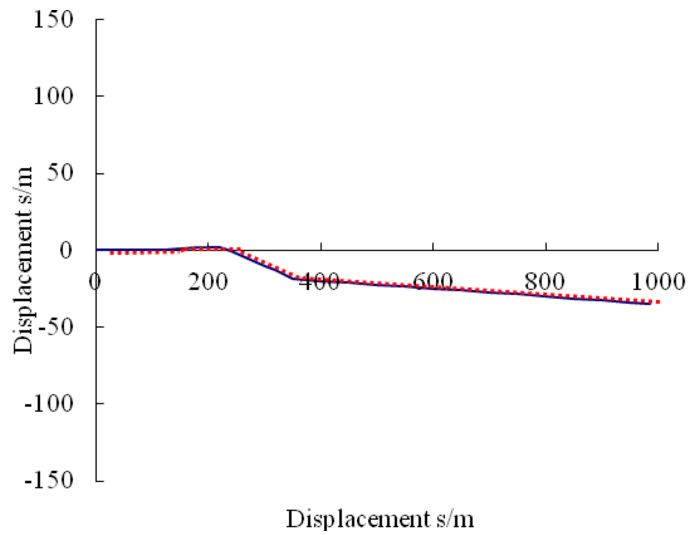

Figure 7. Dead Reckoning Experiment of Encode, Electronic Compass and GPS

5. Conclusions

A kind of autonomous mobile outdoor robot system is designed. GPS, electronic compass and laser range finders are used as the perceptual system which can perceive the external environment. Extended Kalman filter method is used to integrate the data of encoder disk and electronic compass and realize the dead reckoning. GPS is used to correct the encoder disk and electronic compass dead reckoning system to eliminate the measurement error. Filed D* algorithm and DWA method are used to realize the obstacle avoidance and path planning.

To verity the outdoor mobile robot's autonomous moving strategy, the experiments are researched on a road whose length is 1000 meters. The experimental results show that the outdoor autonomous mobile robot proposed in this paper can realize the autonomous navigation task well.

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