Design and Control of Two Degree of Freedom Powered Caster Wheels Based Omni-Directional Robot

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Abstract. Omni-directional robot has the ability of 0–360° motions are received much attention in recent years. They have locomotive advantages and are widely deployed in larger range of application fields especially in constrained narrow space. This paper introduce a novel omni-directional robot with four powered caster wheels, each caster wheel has two degree of freedom (DOF) and made by two outer rotor motors connected mechanically. The kinematics of the system are analyzed, the prototype has been developed. The developed omni-directional robot is able to realize the moving motions along x and y axis and rotate about z-axis. All of the software are implemented on Robot Operation Systems (ROS) and the velocity trajectory planner is employed and embedded in the software. The squared position curve is given and tested by using lase tracker, the result is analyzed, and it shown that the following error of the system is about 2.5 cm while the width of the square is 70 cm.

Keywords: Omni-directional robot · Powered caster wheels
Direct motor · Kinematics · Control

1 Introduction

The intelligent manufacturing and E-commerce logistics producing a huge demands on the Automated Guided Vehicle (AGV) which motivated the development of mobile robot technology [1]. The mobile robot have to fulfill various movement and tasks, especially, they should have a strong pass through ability to fit for narrow and crowd environment. Also they need to adaptive, safe, and flexible for intelligent factory applications [2]. These properties are hard to achieve by traditional differential mobile robot due to they need a big turning radius while moving.

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There are many omni-directional mobile has been developed, the platforms are employed ball wheels [3], Mecanum wheels [4] and Caster wheels [5, 6] in normally. But the ball wheel is usually have the problems that it is hard to control, moreover, it is easy to get dirty that slow down their motion accuracy. They are seldom been built for industrial applications but only in laboratory. The mecanum wheels has been already used for some omni-directional roots [7, 8], but the problem is that the sliding friction exists between the wheels and the ground while the robot moving, this will restrict their application area. The robot with powered caster wheels is designed by Holmberg and Slater in 2002, their caster wheels has one problem that the steering motion of the caster wheels will generate a parasite rolling motion inevitably which make it hard to design the system controller [9]. Wada et al. developed the powered active caster wheel by using dual-ball transmission, but they are taking two balls as the transmission mechanisms [10]. Professor Yang [11] et al. have been developed the decoupled active caster wheels are applied in their mobile robot system, which showing a high performance on the robot behaving. But the designed robot need the gear system to decouple the roll motion and steer motion where the gear system will slow down the system positioning accuracy due to the backlash.

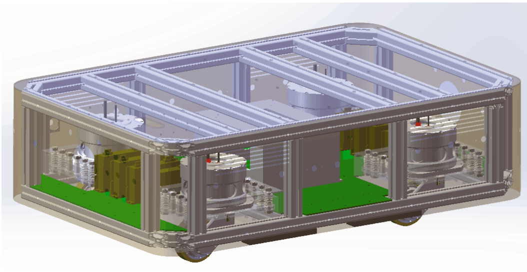
To avoid the above problems, this paper developed a novel decoupled caster wheels which is able to do the rolling motion and steering motion independently and simultaneously. The steering motion and rolling motion are decoupled. The caster is made of two outer rotor motors, the rolling motor is hang under the steering motor, these motors are designed as direct drive motor which doesn't have the reduction box and don't need the decouple mechanisms so that the motions of the caster wheels can be accurately.

In this paper we developed a two DOF wheeled power casters and built the entire omni-directional robot prototype based on it. The following Sects. 2 and 3 will introducing the mechanical design of the robot, the kinematics, and the control system will introduced at Sect. 4, final section is the experiment results and discuss about this omni-directional robot system.

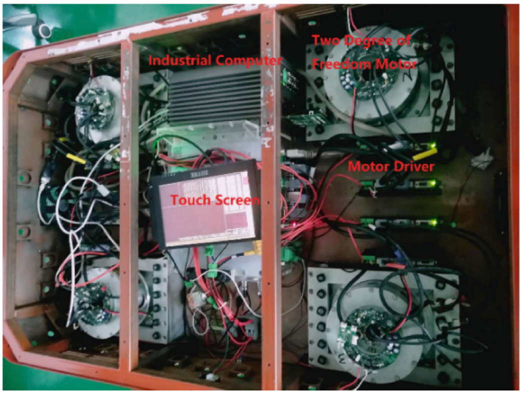
2 Robot Mechanical Design

2.1 The Mobile Prototype Design

The intelligent manufacturing have the strong demands that the factory should have the flexible ability, where mobile robot will be an important execution unit of the system. The developed omni-direction mobile robot is aim to serve the major link of the intelligent manufacturing and act as a transport tool for the factory such as the cargo transfer and storage. The application environments are commonly favorable indoor sites crowded with equipment and materials, the omni-direction mobile robot is required to move flexibly and have the ability of moving towards to any direction or it can be say that have 3 DOF, that is moving along x and y axis and rotate about z axis. Our mobile robot prototype is shown in Fig. 1. Which are included four developed powered caster wheels. Figure 1(a) is the 3D model and Fig. 1(b) is the prototype.



(a) 3D model



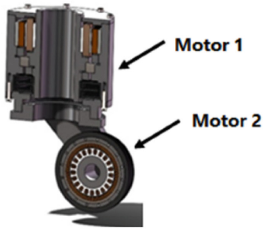
(b) Prototype

Fig. 1. Omni-directional mobile robot 3D model and the prototype machine (a) 3D model (b) prototype

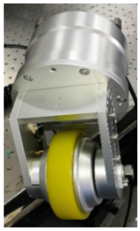
2.2 The Two Degree of Freedom Caster Design

As mentioned before, our two DOF caster wheel is made of two outer rotor motor, as shown in Fig. 2(a) and (b). In Fig. 2(a) motor 1 is used to produce the steering motion and motor 2 is used to produce rolling motion. Motor 1 has been designed as center hollow structure so that the drive cable and encode cable of the motor 2 can be pass through of it. The motor 2 is hang under the motor 1 which is actually been designed as a hub motor. A modular structure with spring buffer connector mechanism has been considered in the wheel system as shown in Fig. 2(c). The spring buffer connector has been arranged in two rows (six of each) and mounted in parallel at both sides of the wheels which can absorb the shock energy and some damping energy. The stiffness of the spring was calculated according to the typical loads of the design requirements. Normally the roll motor is contact to the ground directly, it may producing the vibrations in the platform. To solve this problem we use polyurethane adhesive process to deal with the out layer of the motor.

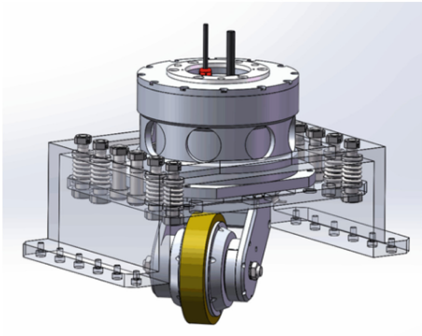
The parameters of the omni-directional mobile system are shown in Table 1, this prototype is designed for the application of car engine transportation workshop.



(a) The 3D model of the two DOF caster



(b) the prototype of the two DOF caster



(c) The modular of the wheels with suspension system

Fig. 2. The active two DOF caster wheel and its suspension system.

Table 1. Parameters of the omni-directional mobile robot platform

Description	Quantity
Body length	1.2 m
Body width	0.8 m
High from the ground	0.38 m
Wheel diameter	0.128 m
Wheel bias	0.05 m
Mass of the body	150 kg
Maximum Load	200 kg
Max velocity of the body	1 m/s^2
Max rotational velocity of the body	2.5 rad/s

The weight of the car engine is 180 kg which is offered by the car producer company. So the typical load for the mobile robot is designed as 200 kg. Here the steering motor and the rolling motor should have a bias which will allowing the robot produce pure rolling motion without slip [12].

3 Kinematics

The developed omni-directional robot prototype employed four powered active caster wheel. The wheels mounted in symmetrically at the four corner of the robot. The simplified schematic of the robot is shown in Fig. 3.

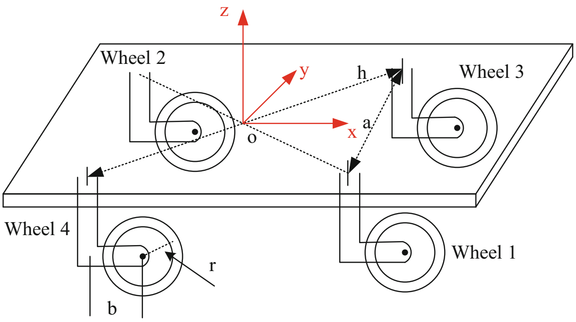


Fig. 3. The simplified robot schematic

In Fig. 3 the coordinates system has been attached on the robot, where h is the length of the diagonal line, a is the length between wheel 1 and wheel 2, b is the bias of the steering motor and rolling motor, r is the radius of the rolling wheel. Since the four wheels are arranged symmetrically, one of the two DOF caster wheels can be treated as a modular, then the kinematics of the system can be calculated first by only take one modular. Figure 4 shown the kinematics geometric relationship for one modular in 2D plane.

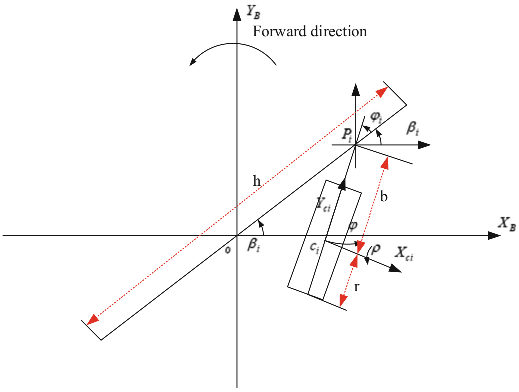


Fig. 4. Kinematics geometric relationship for one modular in 2D plane

In Fig. 4, the x-axis and y-axis of the coordinate system XYZ in Fig. 3 has been renamed as X_B and Y_B. Here we attached a new coordinate system on the rolling motor and X_{ci}, Y_{ci} is the name of x-axis and y-axis. φ_i is the angle between the rolling motor y-axis and the prototype body diagonal line. β_i is the angle between the prototype body x-axis and the body diagonal line. Then the velocity of the wheel center shown in frame $X_B o Y_B$ is given by:

$$^{B}v_{ci} = {^{B}v} + {^{B}\omega} \times {^{B}P_{ci}} \tag{1}$$

The velocity of $^{B}v_{Ci}$ can be also expressed as alongside the wheels and perpendicular to the wheels due to the no slip condition:

$$^{B}v_{ci} = {^{B}v_{cix}} + {^{B}v_{ciy}} \tag{2}$$

Combine Eqs. (1) and (2) gives:

$$^{B}v + {^{B}\omega} \times {^{B}P_{ci}} = b\dot{\phi}_i {^{B}x_{ci}} + r\dot{\rho}_i {^{B}y_{ci}} \tag{3}$$

where

$$^{B}x_{ci} = \begin{bmatrix} \sin(\beta_i + \varphi_i) \\ -\cos(\beta_i + \varphi_i) \end{bmatrix} {^{B}Y_{ci}} = \begin{bmatrix} -\cos(\beta_i + \varphi_i) \\ -\sin(\beta_i + \varphi_i) \end{bmatrix} \tag{4}$$

Equation (1) can be also written as:

$$^{B}\omega \times {^{B}P_{ci}} = \omega e_z \times {^{B}P_{ci}} = \omega {^{B}t_{ci}} \tag{5}$$

Notice that ω is a scalar, then the Eq. (3) is given by:

$$\begin{bmatrix} I_{2\times 2} & {^{B}t_{ci}} \end{bmatrix} \begin{bmatrix} {^{B}v} \\ \omega \end{bmatrix} = \begin{bmatrix} b{^{B}X_{ci}} & r{^{B}Y_{ci}} \end{bmatrix} \begin{bmatrix} \dot{\phi}_i \\ \dot{\rho}_i \end{bmatrix} \tag{6}$$

where

$$^{B}t_{ci} = e_z \times {^{B}P_{ci}},\ e_z = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T,$$

$$^{B}P_{ci} = \overrightarrow{BP}_i + \overrightarrow{P_i}\ C_i = \overrightarrow{BP}_i + \left(b{^{B}Y_{Ci}}\right)$$

Then the inverse kinematics can be rewritten as matrix style:

$$\mathbf{AX} = \mathbf{B\dot{q}} \Rightarrow \mathbf{\dot{q}} = B^{-1}A\dot{\mathbf{X}} \tag{7}$$

where

$$\dot{\mathbf{q}} = [b\dot{\varphi}_i \quad r\dot{\rho}_i]^T,\ \mathbf{A} = \begin{bmatrix} 1 & 0 & -h\,\sin\beta_i + b\,\sin(\beta_i + \varphi_i) \\ 0 & 1 & h\,\cos\beta_i - b\,\cos(\beta_i + \varphi_i) \end{bmatrix},$$
$$\mathbf{B} = \begin{bmatrix} \sin(\beta_i + \varphi_i) & -\cos(\beta_i + \varphi_i) \\ -\cos(\beta_i + \varphi_i) & -sin(\beta_i + \varphi_i) \end{bmatrix}$$

Then, the inverse kinematics of four wheels is given by:

$$\dot{\mathbf{q}} = \begin{bmatrix} \sin(\beta_1 + \varphi_1) & -\cos(\beta_1 + \varphi_1) & -h\,\cos(\varphi_1) + b \\ -\cos(\beta_1 + \varphi_1) & -sin(\beta_1 + \varphi_1) & -h\,\sin(\varphi_1) \\ \sin(\beta_2 + \varphi_2) & -\cos(\beta_2 + \varphi_2) & -h\,\cos(\varphi_2) + b \\ -\cos(\beta_2 + \varphi_2) & -sin(\beta_2 + \varphi_2) & -h\,\sin(\varphi_2) \\ \sin(\beta_3 + \varphi_3) & -\cos(\beta_3 + \varphi_4) & -h\,\cos(\varphi_3) + b \\ -\cos(\beta_3 + \varphi_3) & -sin(\beta_3 + \varphi_4) & -h\,\cos(\varphi_3) + b \\ \sin(\beta_4 + \varphi_4) & -\cos(\beta_3 + \varphi_4) & -h\,\cos(\varphi_4) + b \\ -\cos(\beta_4 + \varphi_4) & -sin(\beta_3 + \varphi_4) & -h\,\cos(\varphi_4) + b \end{bmatrix} \dot{\mathbf{X}}$$

where $\beta_2 = \pi + \beta_1$ $\beta_4 = \pi + \beta_3$ and $\beta_1 = a\,\cos(a/h)$.

The forward kinematics can be written as: $\dot{\mathbf{X}}=\mathbf{A}^{-1}\mathbf{B}\dot{\mathbf{q}}$ or by solving the equation $\mathbf{A}\dot{\mathbf{X}} = \mathbf{B}\dot{\mathbf{q}}$

4 Robot Control System and Software System

4.1 The Robot Control System

The robot chassis layer have the mechanical body and powered caster wheels modular mounted on it, also with the motor driver and battery. The parameters of our motors are shown in Table 2, and the incremental magnetic grating encoder has embedded into the

Table 2. The parameters of the motors

Steering motor	Power	48 V, 200 W
	Diameter	0.145 m
	Continuous current	6.8A
	Maximum current	12A
	Continuous torque	6 N
	Maximum toque	15 N
Rolling motor	Power	48 V, 100 W
	Diameter	0.128 m
	Continuous current	3.5A
	Maximum current	8.3A
	Continuous torque	3 N.m
	Maximum toque	9 N

motors with 2048 pulse/circle, the capacity of the battery is 48 V 40 Ah. The motor driver is Copley and the maximum continuous current of the driver is 20 A.

The control layer is equipped with an industrial computer and a motion control card form Galil which is mounted into the PCI slot of Industrial PC. The motor encoder message has already separate into two copy's, one is send to the motor driver for local velocity and current control and the other copy is send to motion control card used for the velocity close-loop control. The motion control card send the analog signal to the driver according to the calculated kinematic results. Different with the traditional mobile platform, the caster wheel based mobile robot need to know the precision position of each steering wheel so that we need to initialize each steering wheel at the initial start time. To help the steering motor find the initial position, some infrared switches are mounted at the mechanical initial position of the body. The bumpers and ultrasonic sensors also mounted and used for obstacle avoidance. The Bluetooth joystick from Sony are used for the wireless velocity control of the robot, Wi-Fi module allowing for robot remote control via socket protocol, a touch screen is used for robot local operation. The block diagram of the omni-directional robot hardware is shown in Fig. 5.

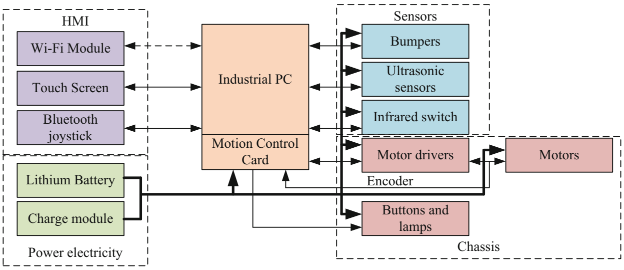


Fig. 5. The block diagram of the omni-directional robot

4.2 The Robot Software System

The software is based on the ROS system, ROS is the robot operational system which are widely used for robot program, it available for c++ code and python code, by using this software platform, the code for each function can be built as an node, you don't need care about how the software deal with the data and exchanged between different node by using ROS operation system.

The omni-directional robot software has been designed as three mainly part, part I is the chassi controller for solving the kinematics and inverse kinematics, part II is the lowlevel controller used for accedence avoidance and joystick control, part III is the trajectory planner and highlevel control. The chassi movement node accept the external velocity information from the robot operational space and deal with the kinematics module and inverse kinematic node, the S-curve producer is used to generate the continuous taskspace velocity for the robot. The inverse kinematic module used to calculate the position of each joint. The motion controller card will accept the joint space velocity command and send to the driver, the odometry information was calculated by forward kinematics and encoder then sent it to high-level controller, the high-level controller is designed for mapping, localization and navigation, especially, the path planning node will find the optimized the robot path point according to the mapping information, the trajectory planner module will deal with the path points and generate a interpolated trajectory points for the real robot mobile moving (for example generate the square curve), the joystick control node will used to send manually control command for the low-level controller, the bumper and ultrasonic sensors are programed for the obstacle avoidance function. The program block diagram is shown in Fig. 6.

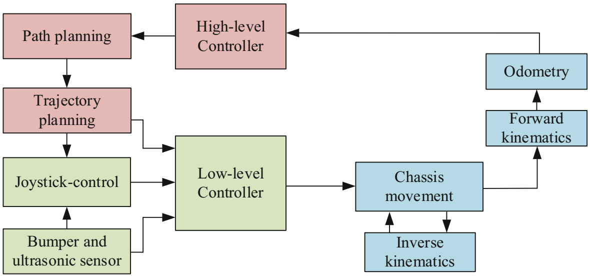


Fig. 6. Software block diagram

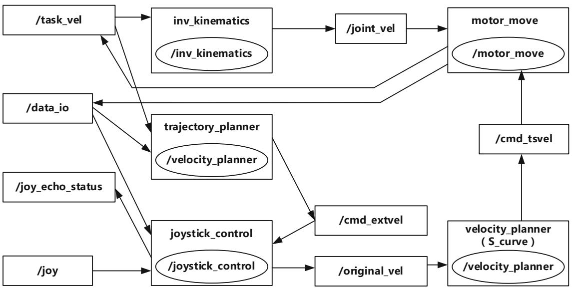


Fig. 7. The block diagram of the software node in ROS

The node information schematics of the programed ROS shown in Fig. 7 (where in this paper, we are not address the localization and navigation function of the omni-directional robot system).

5 Experiment Results

Based on the hardware and software configuration, we developed the prototype of the omni-directional mobile robot, and the robot can achieved motions towards x and y direction and rotate about z axis, that is, the system has three DOF.

When a velocity command has been send from the task space, the joint space velocity will get by using the inverse kinematics. In Fig. 8 we are take two of the caster

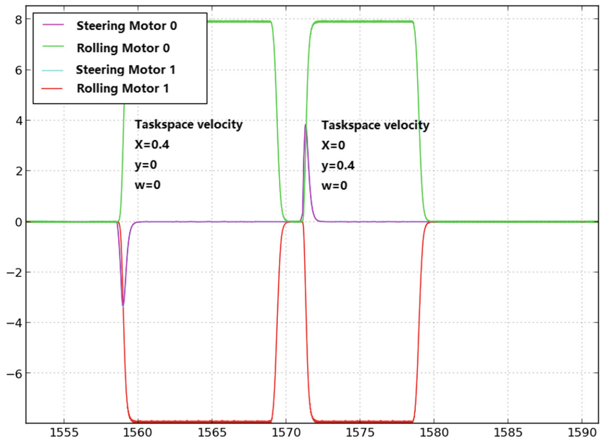


Fig. 8. The robot velocity curve

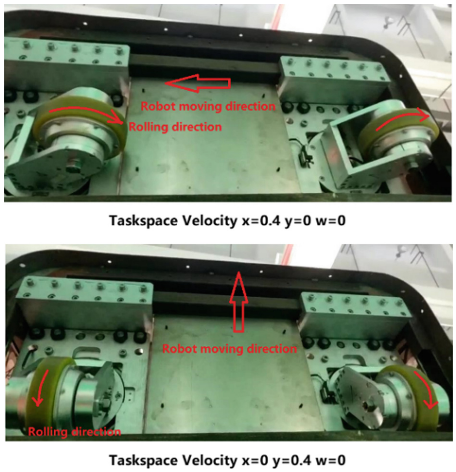


Fig. 9. The robot wheels motion while task space velocity are given

wheels as the example, the velocity are recoded at Steering motor and Rolling motor, it can be see that the Steering velocity only have the value when the robot change their taskspace velocity, and the velocity of the steering motor will be goes to zero after a while. From the robot side we can see that the wheels are goes to the opposite side of the robot velocity direction, which are shown in Fig. 9.

In addition, we are carry out the trajectory following test to analysis the system accuracy, the laser tracker is used to record the actual value of the robot position. The test rig is shown in Fig. 10. The square trajectory are planned for test and the sampling time is set as 0.01 s, the test result is shown in Fig. 11, it can be seen that the maximum of the robot error is about 2.5 cm while width of the square is 70 cm (3.5%). But the

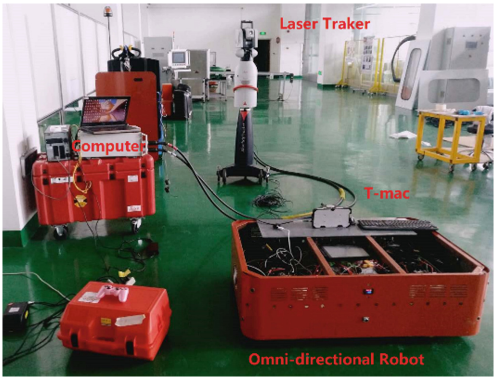
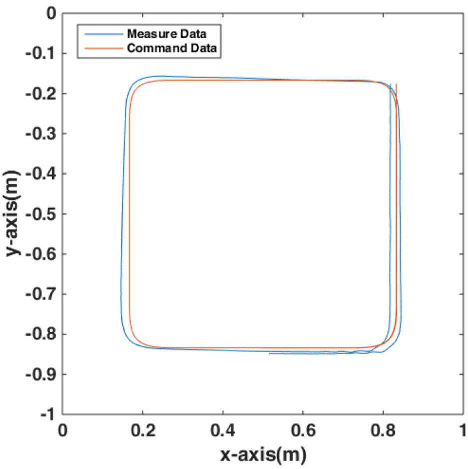
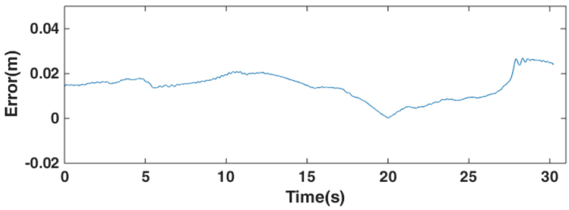


Fig. 10. The robot test rig



(a) The position of robot



(b) Errors between the measured data and command data

Fig. 11. The tested results (a) the position of the robot, (b) the errors between the measured and commanded data.

test result might different when the robot running at different type of the ground due to the different friction force. In this system, we got the accuracy on each motor is about 0.3 mm (the encoder can produce 1024 pulse for each circle).

6 Conclusions

This paper introduced a new mobile robot with two degree of freedom powered caster wheels, and each powered caster wheel is designed with two directly derived motor there are no gear system existed in the wheels so that the system doesn't have errors from the gear system. which will make the system accurate than normal mobile robot system, the prototype of the robot is built, the hardware and software are also developed and the ROS system is used for software building, the experiment is carried out at the developed prototype which is shown that the maximum error of the robot about 2.5 cm at 70 cm squared trajectory following, the error percentage is 3.5%. The designed prototype robot have one problem is that the power cables and the encoder cables of rolling motor have to go through the steering motor, this need to be solve in the future and the localization and navigation system will be also considered in the future.

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