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Mechanical Design and Control System of an Omni-directional Mobile Robot for Material Conveying

Tianran Peng, Jun Qian*, Bin Zi, Jiakui Liu, Xingwei Wang

School of Mechanical and Automotive Engineering, Hefei University of Technology, Hefei230009, China

* Corresponding author. Tel.: +86-13956931219. E-mail address: qianjun@hfut.edu.cn

Abstract

This paper presents the mechanical design and control system of a material conveying mobile robot. The robot uses a four-wheel driven chassis and has omni-directional mobility. The mechanical system based on four Mecanum wheels is designed with a damping suspension mechanism. A Siemens S7-1217C PLC with extended modules is used as the lower-layer controller, while a laptop computer is used as the upper-layer controller. The control algorithm for the motion modes of the robot is developed, and the motion control performance is tested with a hand box based on its three-axis potentiometer inside. At last, the visual navigation algorithm based on Hough Transform is designed and an experimental confirmation is completed.

Keywords: Omni-directional mobile robot; Mechanical design; Control system; Machine vision

1. Introduction

Automatic Guided Vehicles (AGVs) are widely used in production line, but they rely on fixed trajectory. Material conveying mobile robots are intelligent moving platforms which are used to convey materials by automatic navigation. Material conveying mobile robots are widely used for flexible manufacturing systems, intelligent factories, automated storages and logistic systems.

Amazon Company improved the labor productivity greatly in its automated multi-layered storehouse by deploying a large number of Kiva robots [1]. Adept company in United States produced an automatic material transfer vehicle called Lynx which is applied to manufacturing, storage and medical industries. KUKA’s omniRob is an indoor conveying platform with indoor autonomous navigation and omni-directional mobile capabilities.

Nowadays in China, there are many companies producing AGVs for production lines of automobile, electric power, pharmaceutical and other industries, e.g. Siasun AGV. There are also some large intelligent vehicles, which can carry heavy loads [2].

Most current mainstream smart conveying mobile platforms use simple differential motion with two driving wheels, while KUKA omniRob uses many Mecanum wheels. To navigate, Kiva detects the grid information on the ground by visual sensors. Siasun AGV uses the ground magnetic stripe navigation. For Lynx and omniRob, autonomous navigation is realized by using laser radars. OmniRob has a big capacity and advanced technology, but is expensive.

This paper presents an omni-directional mobile robot, which can move flexibly in a narrow space. It can also carry materials in production line to create business value. The robot adopts open and modular architecture, which makes modification, maintenance and upgrade easy. There is a touch screen used as the man-computer interaction, so it can be used as a platform for education and scientific research in colleges and universities.
2. Mechanical system design

This robot mechanical system needs to have functions of omni-directional mobility, fixed point transfer and resisting vibration. The mechanical design includes overall structure design and dampened suspension mechanism design.

2.1. Overall structure design

The overall structure of the robot adopts three-layer structure including Chassis Layer, Controller Layer and Transfer Layer. The layers connect with each other by bolt fastening, and are easy to disassemble.

- Chassis Layer
  Chassis Layer consists of the chassis, Mecanum wheels, damping suspension mechanism, motors, battery and power supply circuit. Mecanum wheels connect with the motors through the harmonic reducers which have the reduction ratio of 50. Maxon RE 40 DC servo motors are selected to drive the wheels. A DC 48V lithium-ion battery is used as the power supply. The nominal speed of the robot is about 1m/s.

- Controller Layer
  Controller Layer is modularly designed and assembled by structural sections so that it is easy to change and upgrade the robot. The PLC with its extension module and the motor drives are installed on the framework of Controller Layer. A touch screen is embedded on the backboard as the human-computer interaction interface.

- Transfer Layer
  Transfer Layer includes two electric cylinders which are placed on the front and rear of the robot. One electrical transport roller is installed on the electric cylinders horizontally. The electric cylinders and electrical transport roller can realize the function of lifting and moving cargos.

The robot overall structure is shown in Fig. 1.

2.2. Damping suspension design

The four wheels should always keep touching the ground. The rolls of Mecanum wheel touch the ground discontinuously, so that they make noise and vibration. So it is necessary to design a good damping suspension. Generally, only springs are used on mobile robots as the damping suspension mechanism, while some robots also have unidirectional dampers [3,4]. The vertical damping mechanism is designed using springs and hydraulic buffers, while the independent suspension consists of guide pillars and linear bearings. This design makes sure that the wheelbase won’t be changed, so that the robot could go reposefully. Fig. 2 shows the damping mechanism on each wheel.

Fig. 2. (a) The schematic plot of damping mechanism; (b) 3D model of damping mechanism.

2.3. Kinematics analysis

Four Mecanum wheels are used as the mobile mechanism of the robot. The surface of a Mecanum wheel is covered by a number of free rolls with an angle of ±45° to provide lateral friction. Fig. 3 shows a classic form, which can realize omni-directional mobility [5]. Eq. (1) is the forward kinematics equation, while Eq. (2) is the backward kinematics equation.

In Eqs. (1) and (2), $v_x$ and $v_y$ are the forward and lateral velocities of the robot, $\theta_i$ is the revolving speeds of each wheel ($i=1,2,3,4$), $\omega$ is the angular velocity of the robot around its center, $r$ is the wheel radius, $l$ is the center distance between the front and rear wheels, $b$ is the center distance between the left and right wheels.

3. Control system design

3.1. Hardware design of control system

In order to achieve complex functions such as autonomous navigation and omni-directional mobility, the control system adopts two-layer control structure.

PLC is suitable to be the lower-layer controller for its flexible field wiring, ease to extend, and strong anti-jamming capability. Siemens S7-1217C CPU module is suitable to be the lower-layer controller of the robot. To meet the
requirements of control, digital input/output modules (DI/DQ) and analog input/output modules (AI/AQ) are added. A touch screen is used as the human-computer interaction interface. After configuration and debugging, the touch screen can read and write the data in PLC, and displays the running status of the robot. This function makes the robot become a good platform for educational demonstration.

Four Elmo CEL-10/100 DC servo motor drives are used to control the driving motors. Avago HEDL 5540 encoders are used for getting the revolving speeds of four wheels and sending signals to the drives and PLC simultaneously. Two stepper motor drives are used to control the electric cylinders with stepper motors inside. The electric transport roller is controlled by one stepper motor drive.

In order to realize manual operation and debugging, a hand box is designed based on a Caldaro joystick. The angle signal of each axis is measured by the three-axis potentiometer of joystick and used as the input signal of manual mode.

A Microsoft Kinect camera is used as the image acquisition device for visual navigation.

A laptop is used as the upper-layer controller to process a large amount of data and computation of image processing.

Fig. 4 shows the hardware structure of control system.

3.2. PLC programming

The configuration, programming and simulation are completed with the TIA POTAL V13 SP1 software. The program includes main program, hardware interrupt program, and several subprograms for manual, automatic and other modes. When PLC receives the input signals or navigation instructions, it calculates the revolving speed of each wheel according to Eq. (2), and outputs analog and pulse signals to control the coordinated actions of motors. The interrupt response is designed for multiple interrupt events.

3.3. Ethernet communication

The upper and lower layer controllers communicate through the Ethernet by using the OPC (OLE for Process Control) standard [6]. OPC is the embedded process control standard that allows data exchanging between PLC application and field devices. The PLC is the server while the laptop is the client in OPC communication. By using SIMATIC NET software to configure the PC station and OPC Server, and using Visual Studio 2010 to create applications to access OPC Server, the upper-layer controller could read and write the data in the RAM of PLC.

4. Visual navigation

In this paper, a Kinect camera is used to detect the white line on the ground for visual navigation [7]. Using Visual Studio 2010 program to call OpenCV function library, the laptop completes the noise variance sharpening, image segmentation, etc. Then it detects both sides of the white line on the ground and generates the navigation line with the improved Hough Transform.

The laptop calculates the distance and angle deviation between the actual position and navigation line. Then using the robot’s omni-directional mobile ability, the laptop calculates the speeds of each wheel using angle control PID algorithm and distance control PID algorithm [8]. The PLC receives the revolving speed data from the laptop through Ethernet and outputs digital and analog signals to the servo drives. The robot will track the white line and adjust its path.

5. Experiments

5.1. Damping suspension test

The robot is shown in Fig. 5. On the smooth marble floor, the robot's vertical vibration is tested by an acceleration sensor. In Figs. 6 and 7, it’s easy to find out that the largest vibration occurs when the robot brakes in 0.2m/s. The vertical acceleration is 0.045g, while the vertical amplitude is 7mm. Figs. 6 and 7 show that the robot runs very stably in constant speed. It is beneficial for the camera and laser radar. According to the experiment results, uniform motion should be used as much as possible in the speed control to insure the stability of the robot motion.
5.2. PID debugging of the drive

The Elmo CEL - 10/100 DC servo drive has a built-in PID controller. The speed command is the input of PID controller, while the encoder signal is the feedback. \( K_p \) should be increased from 2 till the maximum overshoot is between 20% to 25%. \( K_i \) equals \( K_p \) divided by the rise time. Fig. 8 shows the velocity command of the motor changing from -3323r/min to 3323r/min when \( K_i \) is 5 and \( K_i \) is 100. During the time between the two vertical black lines in Fig. 8, the maximum velocity is 4020r/min, while the steady-state velocity is 3319r/min. So the maximum overshoot is 21.12%, and the relative error in steady state is -0.12%.

![Fig.8. Velocities in PID debugging.](image)

5.3. Movement on straight line

The robot has been tested its straight-line movement on smooth marble floor in 8 directions. Since the lateral errors of the lines and the robot are too small to measure, they are measured once per meter. The data are recorded in table 1. The table shows that the mean of lateral errors is less than 1cm in one meter, so the robot could run on a straight line accurately.

![Fig.9. View of visual navigation test.](image)

![Fig.10. Process of visual navigation.](image)

### Table 1. Lateral errors measured per meter on straight lines.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Distance (m)</th>
<th>Mean (cm)</th>
<th>Variance (cm²)</th>
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<tr>
<td></td>
<td>0~1</td>
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<td>2~3</td>
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<td>-0.3</td>
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5.4. Visual navigation test

The view of visual navigation test is shown in Fig. 9. The starting angle deviation is -19.00°, while the starting distance deviation is 0.18m. Fig. 10 shows the process of visual navigation. The steady state deviation is -0.57° and 0.03m. The control algorithm and the parameter setting should be improved to increase the control precision.

6. Conclusions

This paper presented an omni-directional mobile robot with four Mecanum wheels and damping suspension. The robot’s mechanical system and control system were designed with multilayer and modular structure, which made the robot easy to be transformed and upgraded. The visual navigation was designed based on improved Hough Transform and PID algorithm. The experiments proved that the robot could move omni-directionally and stably with high precision. The robot is integrated in the automatic production line to convey materials. Meanwhile, it is a mobile platform for education and scientific research.

Acknowledgements

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