JJMIE

Volume 16, Number 1, January. 2022
ISSN 1995-6665
Pages 31 - 40

Jordan Journal of Mechanical and Industrial Engineering

Gait Control System of Autonomous Mobile Robot Based on PMAC

Guobin Si*, Xiaofeng Jin, Chunxia Wang

College of Mechanical and Electronic Engineering, Jiaozuo University, Jiaozuo 454000, China

Received 14 July 2021 *Accepted 27 December 2021*

Abstract

In the current gait control system of autonomous mobile robot, the stability of robot motion control and the result of gait planning are poor, and the walking compliance and walking efficiency are low, a gait control system of autonomous mobile robot based on PMAC (Programmable Multi-Axis Controller) is designed. Through linear analysis of the control system of the autonomous mobile robot, the dynamic model of the motion control of the autonomous mobile robot is constructed, the walking cycle and key postures of the robot are analyzed, the stable walking gait is planned, and the dynamic model of the robot motion control is combined to reverse the robot correspondence. For the joint rotation angle, the motor rotation angle under the key gait is obtained by using the theory of series and parallel mechanisms, and the cubic spline interpolation method is used to generate a complete gait motion trajectory. According to the architecture, the servo system of the robot and the hardware structure with IMAC (Integrated Multi-Axis Controller) flex motion controller as the core of PMAC motion controller are designed. The software design of modular structure is used to realize the gait control of autonomous mobile robot. The experimental results show that the motion control stability and gait planning results of the proposed method are better, the gait trajectory is smooth and the walking compliance is high, which can effectively improve the walking efficiency of the robot.

Keywords: : PMAC; IMAC flex motion controller; Autonomous mobile robot; Gait control; Cubic spline interpolation method;

1. Introduction

Autonomous mobile robot is an integrated system which integrates environment perception, dynamic decision-making and planning, behavior control and execution. It has a high degree of self-planning, self-organization and self-adaptive ability, which is suitable for working in complex unstructured environment, and can realize object identification, autonomous reasoning, path planning and control functions in complex environment [1]. It brings together the research results of sensor technology, computer technology, mechanical engineering, electronic engineering, automation control engineering, artificial intelligence and other multidisciplinary fields. It is one of the most active areas of scientific and technological development [2]. With the rapid development of computer, network, mechanical and electronic, information, automation and artificial intelligence technology, the research of autonomous mobile robot has entered a new stage, and its application scope has also expanded to various fields of society. It is not only widely used in industry, agriculture, national defense, medical, service and other industries, but also in harmful and dangerous situations such as mine clearance, search and rescue, radiation and space fields [3]. However, the working environment faced by autonomous mobile robots is becoming more and more complex, and higher requirements are put forward for the controller of autonomous mobile robots. Different application fields require the controller to integrate different peripheral devices and application software, and even need to be transplanted between different software and hardware platforms. Therefore, the development of highly open autonomous mobile robot controller has become a research hotspot in this field.

Robot control system is a typical multi axis real-time motion control system, which mainly realizes the coordinated control of various walking robots, tracked robots, bionic robots and robot groups. At present, the research on the control system of robots has also made great progress. Reference [4] uses the natural stimulus algorithm Eagle strategy and particle swarm optimization (ESPSO) technology to design an adaptive control system for a two-wheeled inverted pendulum mobile robot. According to the multi input and multi output characteristics of two wheel inverted pendulum mobile robot, considering the instability of the inverted pendulum system, two loops are proposed in the design. One loop is used to balance the linear displacement, the other loop maintains the required angular motion, so as to realize the function of keeping the balance when the robot moves to the required position. The system has

---

* Corresponding author e-mail: haoxinqing1688@126.com.

the characteristics of nonlinear open-loop instability. Reference [5] designed a three-wheeled omnidirectional mobile robot sliding mode control system based on reduced-order extended state observer (ESO), constructed a dynamic model with unknown friction, and designed a controller. The reduced order ESO is used to estimate the friction compensation effect. According to the second-order sliding mode technology with parameter uncertainty, the other part of the work is controlled. The effectiveness and robustness of the control system in compensating different friction effects are good. However, there are some problems in the system, such as poor stability of robot motion control and gait planning, low walking compliance and walking efficiency.

Aiming at the above problems, an autonomous mobile robot gait control system based on PMAC is designed. Through the dynamic analysis of the motion control of the autonomous mobile robot, the dynamic model of the motion control of the autonomous mobile robot is constructed. The walking cycle and key posture of the robot are analyzed. The stable walking gait is planned, and the corresponding joint angle of the robot is inversely solved. According to the architecture design of the robot's servo system and the hardware structure with the IMAC Flex motion controller in the PMAC motion controller as the core, the software design of the modular structure is adopted to realize the gait planning and motion control of the autonomous mobile robot. The whole control system has good motion control stability, walking flexibility and smooth gait trajectory, which can effectively improve the walking efficiency of the robot.

2. Dynamic Analysis of Autonomous Mobile Robot Motion Control

In the process of autonomous mobile robot motion, its dynamics directly affect the speed, accuracy and efficiency of autonomous mobile robot. In this paper, through the linear analysis of autonomous mobile robot control system, the dynamic model of autonomous mobile robot motion control is constructed, and the analysis of autonomous mobile robot motion control dynamics is realized.

2.1. Linearization analysis of autonomous mobile robot control system

Because of the complex structure and multiple degrees of freedom of autonomous mobile robot, it is necessary to analyze and solve the dynamic equation of the autonomous mobile robot in motion control, and establish the dynamic model of the autonomous mobile robot motion control, so as to provide the basic basis for the control of its motion path and attitude.

The dynamic equation of autonomous mobile robot [6] is:

$$\boldsymbol{E}(\boldsymbol{q})\boldsymbol{R}+\boldsymbol{V}(\boldsymbol{q})+\boldsymbol{G}(\boldsymbol{q})+\boldsymbol{F}(\boldsymbol{q})\delta_s=\delta \qquad (1)$$

In Equation (1), $\boldsymbol{E}(\boldsymbol{q})$ represents the $\alpha\times\beta$ dimensional inertia matrix, $\boldsymbol{R}$ represents the reaction force of the ground against the wheel of the autonomous mobile robot, $\boldsymbol{V}(\boldsymbol{q})$ represents the centripetal force vector, $\boldsymbol{F}(\boldsymbol{q})$ represents the gravity vector, δ_s represents the friction vector, δ represents the bounded unknown interference, and O represents the control force.

In order to prevent the uncertainty from interfering with the motion of the autonomous mobile robot, by adding a suitable state space Equation, the dynamic equation of the autonomous mobile robot is obtained as:

$$Y=\begin{bmatrix}[0_{n\times n}1_{n\times n}]\\ -\boldsymbol{U}^{-1}(\boldsymbol{x})[o(x)+g(x)+f(x)]\end{bmatrix}+\begin{bmatrix}0_{n\times n}\\ \boldsymbol{U}^{-1}(\boldsymbol{x})\end{bmatrix}(\delta-\delta_s) \qquad (2)$$

In Equation (2), $Y=[\boldsymbol{q}\bullet\boldsymbol{R}];1_{n\times n}$ and $0_{n\times n}$ represent the $\alpha\times\beta$ dimensional unit matrix and the zero matrix, respectively, $\boldsymbol{U}(\boldsymbol{x})$ represents the joint vector of the autonomous mobile robot, $o(x)$ represents the $(\alpha-1)$ dimensional gravity term, $g(x)$ represents the $\alpha\times1$ dimensional joint torque, and $f(x)$ represents the reaction force of the wheel axle. Because the centripetal force vector and friction vector mode of the autonomous mobile robot during operation are complex and difficult to calculate, the dynamic equation needs to be simplified as:

$$Y=\boldsymbol{A}_s o(x)+\boldsymbol{P}f(x)+\boldsymbol{U}^{-1}(\boldsymbol{x})\delta-\boldsymbol{P}\boldsymbol{U}^{-1}(\boldsymbol{x})\delta_s \qquad (3)$$

In Equation (3), the choice of $\boldsymbol{P}=\begin{bmatrix}0_{n\times n}\\ 1_{n\times n}\end{bmatrix}$,

$$f(x)=-\boldsymbol{U}^{-1}(\boldsymbol{x})[o(x)+g(x)+f(x)]-[A_{21}A_{22}]$$

, $\boldsymbol{A}_s=\begin{bmatrix}0_{n\times n}1_{n\times n}\\ A_{21}A_{22}\end{bmatrix}$, A_{21} and A_{22} directly affects the stability of $\boldsymbol{A}_s$.

According to Equation (2) and Equation (3), the motion defined control torque of autonomous mobile robot is as follows:

$$\delta=-\boldsymbol{U}(\boldsymbol{x})\hat{f}(x)+\boldsymbol{U}(\boldsymbol{x})\sigma \qquad (4)$$

In Equation (4), $\hat{f}(x)$ represents the estimated value of $f(x)$, and σ represents a new control variable. Through stochastic linear quadratic optimal analysis, the dynamic equation of autonomous mobile robot is transformed into quadratic polynomial dynamic equation, and the linear analysis of autonomous mobile robot dynamic system is realized. The dynamic equation of quadratic polynomial is as follows:

$$Y=\boldsymbol{A}_s o(x)+\boldsymbol{P}\sigma+\overline{f}(x)-\boldsymbol{P}\boldsymbol{U}^{-1}(\boldsymbol{x})\delta_s \qquad (5)$$

In Equation (5), $\overline{f}(x)=f-\hat{f}$ represents estimation error. The linear normalization of the control system of the autonomous mobile robot can effectively optimize the motion performance of the autonomous mobile robot, reduce the interference error and improve the motion stability of the autonomous mobile robot.

2.2. Dynamic model of autonomous mobile robot motion control

When studying the motion control of autonomous mobile robot, its dynamic model is the key point of motion control, but the dynamic model is easily affected by nonholonomic constraints, thus affecting the control parameters [7]. In this paper, the dynamic model of autonomous mobile robot is adopted, and the input value in the control process is set as generalized force rather than velocity. Therefore, the kinematic model of autonomous mobile robot can not be used to study the relationship between motion with nonholonomic constraints and force and torque.

The dynamic model of a general autonomous mobile robot can be described by the following Euler-Lagrange equation:

$$\frac{\mathrm{d}}{\mathrm{dt}}\left[\frac{\partial L}{\partial Y}\right]^{T}-\left[\frac{\partial L}{\partial \boldsymbol{\lambda}}\right]^{T}=\boldsymbol{D}(\boldsymbol{q})\delta-\boldsymbol{B}(\boldsymbol{q})\gamma \tag{6}$$

In Equation (6), $\boldsymbol{\lambda}=[\boldsymbol{\lambda}_1,\boldsymbol{\lambda}_2,\cdots,\boldsymbol{\lambda}_\alpha]^T$ represents the α dimensional generalized coordinates of the autonomous mobile robot control system, L represents the Lagrange function, $\boldsymbol{D}(\boldsymbol{q})\delta$ represents the difference between kinetic energy and potential energy, $\boldsymbol{D}(\boldsymbol{q})$ represents the $\alpha\times\beta$ dimensional input transformation matrix, γ represents the Lagrange multiplier, $\boldsymbol{B}(\boldsymbol{q})$ represents the constraint matrix, and the product $\boldsymbol{B}(\boldsymbol{q})\gamma$ represents the constraint vector. Through the analysis of Euler Lagrange equation, the dynamic model of autonomous mobile robot is constructed as follows:

$$\boldsymbol{E}(\boldsymbol{q})\boldsymbol{R}+\boldsymbol{V}(\boldsymbol{q})\boldsymbol{R}=\boldsymbol{D}(\boldsymbol{q})\delta-\boldsymbol{B}(\boldsymbol{q})\gamma \tag{7}$$

Differentiate both sides of the kinematic model to reduce the interference to the motion control of the autonomous mobile robot, and obtain the dynamic model:

$$\begin{gathered}\boldsymbol{E}(\boldsymbol{q})\left[\boldsymbol{W}(\boldsymbol{q})U(t)+\boldsymbol{w}(\boldsymbol{q})u(t)\right]+\\ \boldsymbol{V}(\boldsymbol{q})\boldsymbol{R}=\boldsymbol{D}(\boldsymbol{q})\delta-\boldsymbol{B}(\boldsymbol{q})\gamma\end{gathered} \tag{8}$$

In Equation (8), $\boldsymbol{W}(\boldsymbol{q})$ represents the friction force of the ground against the wheel, $\boldsymbol{w}(\boldsymbol{q})$ represents the external force received by the autonomous mobile robot, $U(t)$ represents the weight coefficient of the behavior toward the target, and $u(t)$ represents the weight coefficient of the behavior toward obstacle avoidance.

Then both sides are multiplied by $\boldsymbol{A}(\boldsymbol{q})$ at the same time, $\boldsymbol{A}(\boldsymbol{q})\boldsymbol{B}(\boldsymbol{q})\gamma=0$ is set to reduce the control energy consumption, and the Lagrange multiplier γ is eliminated, and the final autonomous mobile robot motion control dynamics model is:

$$\boldsymbol{A}(\boldsymbol{q})\chi\boldsymbol{W}(\boldsymbol{q})+\boldsymbol{A}(\boldsymbol{q})(\chi+\upsilon)u(t)=\boldsymbol{A}(\boldsymbol{q})\rho\delta \tag{9}$$

In Equation (9), $\boldsymbol{A}(\boldsymbol{q})$ represents the total control amount at the time of interpolation, χ represents rolling resistance, υ represents driving force, and ρ represents wheel rolling resistance coefficient.

In conclusion, through the linearization analysis of the control system of the autonomous mobile robot, the dynamic model of the motion control of the autonomous mobile robot is constructed, which provides the basis for the gait planning of the autonomous mobile robot.

3. Gait planning of Autonomous Mobile Robot

Firstly, the walking cycle and key posture of the robot are analyzed, and then the stable walking gait is planned. Combined with the dynamic model of the robot motion control, the corresponding joint angle of the robot is inversely solved. Then, the motor rotation angle under the key gait is obtained by using the theory of series parallel mechanism. Finally, the motor continuous motion trajectory of the complete gait is generated by using cubic spline interpolation method.

3.1. Walking cycle of autonomous mobile robot

A complete cycle movement of an autonomous mobile robot can be divided into two stages, one is the period of double-leg support and the other is the period of single-leg support. During the leg support period, both the front and rear legs are in contact with the ground. This cycle starts from the forefoot foot on the ground to the end of the hind leg toe off the ground [8]. During the single-leg support period, the support leg is stable on the support surface, and the swing leg moves from the back to the front. In the gait planning, it is assumed that the leg support period is instantaneous. In this case, the waist must move forward rapidly. Meanwhile, in order to maintain the dynamic and static stability, the center of gravity of the robot must complete the movement from backward to front leg during the instant leg support period. On the other hand, if the support period of the legs is too long, it will limit the speed of the robot's walking. According to the length of human legs supporting time, when planning gait, it takes about 20% of the whole gait. Analyze the whole biped robot walking cycle composed of the two-leg support period and the single-leg support period from the forward plane.

Assuming that the gait cycle of each step is t , the duration of the leg support period is t_s , r represents the r step, which defines that the right foot is about to leave the ground, and the left heel just touches the ground as the beginning of a complete gait, and the left heel is about to leave the ground, and the cycle ends when the right heel just hits the ground. The gait of the complete cycle is as Figure 1.

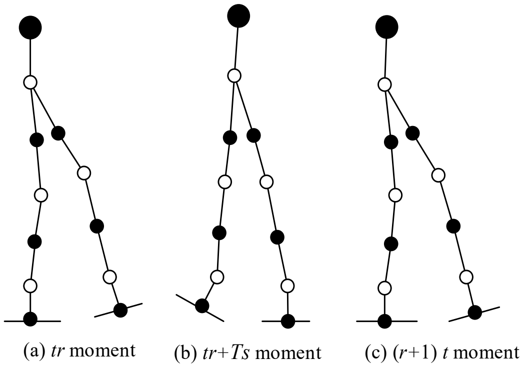

(a) *tr* moment (b) *tr*+*Ts* moment (c) (*r*+1) *t* moment

Figure 1. Gait cycle

3.2. Gait planning of autonomous mobile robots

In the gait planning process of autonomous mobile robot, in order to maintain the stability of the robot in the process of motion, the plantar trajectory is used to ensure the gait planning, that is, the plantar corresponding to the planned gait is located on the stable area. Considering the possible deviation of theoretical gait when applied to the actual physical model, such as the assumption that the robot is an ideal rigid body in theoretical planning, the influence of machining errors of mechanical transmission chain is ignored, and whether these errors are in the control loop, etc. [9]. When drawing gait, we should give full play to the role of the completed physical prototype of the autonomous mobile robot, and combine the theoretical gait with the physical prototype. That is to say, the initial posture of the prototype should be obtained according to the theoretical gait, and then according to the specific influence of the error and other factors on the actual physical prototype, the preliminary posture is adjusted, and then the final gait is determined.

In time, the complete motion of the autonomous mobile robot is divided into three stages. The first stage of gait planning is when the robot starts to walk until one leg is opened and its heel lands on the ground. The second stage is to take a complete gait cycle as the second stage, and the last stage is to take back the hind legs and stand together.

3.3. Inverse solution of forward kinematics of autonomous mobile robot

For the theoretical key gait, it is mainly the planning of the forward plane, therefore, only the inverse kinematics solution is made in this plane. Assuming that the given joint position of the theoretical key gait is known, the position of each joint point corresponding to the reference coordinate system is as follows, right plantar centroid $\left(x_1, z_1\right)$, right ankle joint $\left(x_2, z_2\right)$, right knee joint $\left(x_3, z_3\right)$, left and right hip joints $\left(x_g, z_g\right)$, left knee joint $\left(x_4, z_4\right)$, left ankle joint $\left(x_5, z_5\right)$, left plantar centroid $\left(x_6, z_6\right)$ the relationship between the corresponding joint angle and the position of each joint point is as follows:

$$\begin{aligned} \theta_1 &= \arctan\frac{x_2 - x_1}{z_2 - z_1} \\ \theta_2 &= \arctan\frac{x_3 - x_2}{z_3 - z_2} \\ \theta_3 &= \arctan\frac{x_g - x_3}{z_g - z_3} \\ \theta_4 &= \arctan\frac{x_4 - x_g}{z_4 - z_g} \\ \theta_5 &= \arctan\frac{x_5 - x_4}{z_5 - z_4} \\ \theta_6 &= \arctan\frac{x_6 - x_5}{z_6 - z_5} \end{aligned} \tag{10}$$

According to the above conversion relationship, the rotation angle of the corresponding joint around the y axis along the positive direction of the x axis can be obtained, and the joint rotation angle combined with the characteristics of the autonomous mobile robot transmission chain is converted into the guide rod displacement, and the guide rod displacement is related to the rotation angle on the parallel mechanism fixed platform the changes are related as follows:

$$\begin{aligned} Q_1 &= A_1 + \sqrt{A_1^2 - S_1} \\ Q_2 &= A_2 + \sqrt{A_2^2 - S_2} \end{aligned} \tag{11}$$

In Equation (11), Q_1 and Q_2 respectively represent the coordinate values of the two ball joint connection points on the moving platform in the z direction of the reference coordinate system, which can reflect the movement of the two guide rods. For the inverse solution of the displacement of the guide rod to the angle of the joint motor, it can be obtained by converting the lead of the lead screw and the speed ratio of the planetary reducer.

According to the above steps, the feasible key gait has been inversely resolved into the theoretical rotation angle corresponding to the motor output shaft. These theoretical rotation angles are controlled to act on the motor to judge whether the actual gait matches the planned theoretical gait. If not, adjust the actual gait accordingly. During the adjustment process, judge whether the adjustment is reasonable or not according to the feedback from the plantar until the actual motor output position corresponding to the key posture is finally determined.

3.4. Gait generation of autonomous mobile robot

According to the interpolation method of cubic spline, the discrete displacements of the above joints are fitted out according to the interpolation points to ensure the continuous change of the speed and acceleration of the turning point to produce a group of continuous displacements, and then coordinate together until a complete gait is generated [10].

Cubic spline interpolation is used to fit the joint motor position points corresponding to the above key posture. Suppose the interpolation function is $H(t)=f_i$, the corresponding first-order and second-order derivatives in this interval (t,t_m) are continuous, m represents the key time point, $W_i=(t_m,t_{m+1})$ represents the number of corresponding poses, $h_i=t_{m+1}-t_m$ represents the time interval, then $H(t)$ is expressed as:

$$H(t)=\frac{W_i}{6h_i}(t_{m+1}-t_m)^3+\left(f_i-\frac{Wh_i^2}{6}\right) \tag{12}$$

W_i is determined by the following equation:

$$W_i=\frac{f_{i+1}-f_i}{6h_i}-\frac{f_i-f_{i-1}}{3h_{i-1}} \tag{13}$$

From the initial condition $H'(t)=0$ and the termination condition $H'(t_m)=0$, it can be obtained that:

$$\begin{aligned} c_i&=\frac{f_{i+1}-tf_i}{t_m h_i}\\ b_i&=\frac{6(c_i-tf_i)}{t_m h_i}\end{aligned} \tag{14}$$

In Equation (14), c_i and b_i respectively represent the absolute distance of the two end points in the reference coordinate system.

In the specific fitting, the interpolation function of the first three time points is obtained, and then the cubic spline curve of the corresponding joint in the complete gait from t to t_m can be obtained step by step. Finally, the complete posture of the robot can be obtained through the coupling relationship between the joints.

4. Control System Hardware Design

The control system of autonomous mobile robot is a general designation of the software and hardware parts that control the autonomous mobile robot to complete the expected trajectory [11]. The control system of autonomous mobile robot is an important part to guarantee the performance of autonomous mobile robot, and is the command center of autonomous mobile robot system. Therefore, the control system of autonomous mobile robot must have high reliability, comprehensive function and fast response speed. The hardware part of the control system is the working platform of the autonomous mobile robot control system, which determines the performance of the control system and the scalability of the system.

4.1. Control system hardware composition

As the autonomous mobile robot needs to complete the work such as receiving instructions, adjusting the movement gait and positioning calculation in the work, with a large amount of calculation, therefore, the industrial computer is selected as the upper computer, and the touch screen is equipped to provide a convenient and practical human-computer interaction interface [12, 13]. When the autonomous mobile robot is moving, the positioning accuracy of the control system of the autonomous mobile robot is required to be higher, and the four axis linkage is needed in the moving process. The core of the control system is IMAC Flex motion controller of PMAC motion controller series. The hardware structure of the control system is as Figure 2.

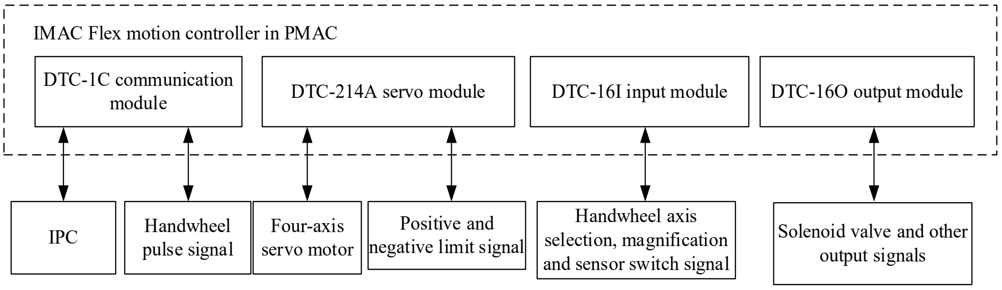


Figure 2. Control system hardware structure

IMAC Flex motion controller includes DTC-1C communication module, DTC-214A servo module, DTC-16I input module and DTC-16O output module. The controller can communicate with IPC through DTC-1C communication module and receive handwheel pulse signal. Four servo motors can be controlled by DTC-214A servo module, and 16 output points and 16 input points can be provided by input and output modules. In addition, PMAC can execute three kinds of commands: Online command, motion program command and PLC program command [14]. PMAC will execute the command immediately after receiving the online command, and will not store it. Motion program command is a group of buffer instructions stored in the buffer and executed by “R” command. Its function is to specify the motion position, motion mode and attribute, program logic control and variable assignment. PLC program command is also a group of buffer instructions, which can be repeated, including operations, logic control and information transmission commands.

The industrial computer has dual network cards, one network card is used to receive commands from the master control system, and the other network card is used to connect with the DTC-1C communication module [15]. After running the upper computer software on the windows platform, it can manually control the operation of the autonomous mobile robot, plan and store the path information of the autonomous mobile robot, and use the information to automatically write the motion program that PMAC can execute, and download it to PMAC to run [16].

The handwheel pulse signal is set to facilitate the staff to manually control the autonomous mobile robot to execute commands and collect key coordinate points in the path. The pulse signal from the handwheel is input to the DTC-1C communication module, and the handwheel axis selection signal and the handwheel override signal are input to the DTC-16I input module. The DTC-16I input module not only receives the axis selection and magnification switch signals of the handwheel, but also receives signals such as emergency stop switch buttons and sensors.

The output signals mainly include: gripping and releasing of fixture, servo power on control and servo alarm clearing.

4.2. Servo system construction

It can be seen from the above system hardware structure that to complete a given motion form, PMAC must output the control information in a certain form to the servo amplifier of the servo system. In this paper, P series AC servo motors and PY2 series servo amplifiers from Japan’s SANYO DENKI Company are selected to construct a servo system for autonomous mobile robots. Since the inertial force, coupling reaction force and gravity load of the autonomous mobile robot change with the change of the motion space, the dynamic control is applied to each joint of the autonomous mobile robot as a separate linear uncoupled servo for closed-loop control [17]. According to the operating characteristics of autonomous mobile robots, both stable motion speed and accurate positioning are required. For autonomous mobile robots, the torque and speed are in the inner loop and the position is in the outer loop. The principle is as Figure 3.

The current closed loop is realized by servo amplifier, which can avoid circuit damage caused by current mutation; The speed closed loop is also realized by the servo amplifier and adopts proportional integral control. The user can adjust the proportional constant and integral constant according to the control requirements of different systems to obtain satisfactory speed closed loop characteristics; The position closed loop is completed by the PMAC motion control card. PMAC adopts the PID control method for the position closed loop. The parameters of the position loop can be adjusted by variables and can be set by the user within a certain range according to the different servo requirements of the system. At the same time, it is also possible to use PMAC to automatically detect the system load for automatic adjustment of PID parameters to complete the parameter tuning.

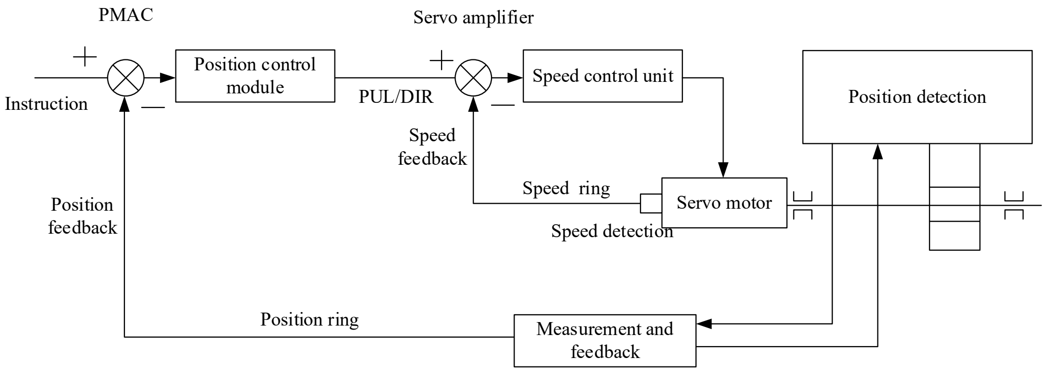


Figure 3. Servo control principle

5. Control System Software Design

This article uses the Windows 2 000 system as the operating system and supports graphical user interfaces. The currently widely used and powerful Visual C++ is selected as the software development tool. The control system software adopts modular structure design and is divided into upper computer human-computer interaction module and lower computer motion control module. The host computer adopts Visual C++6.0 high-level language for development, and communicates through PMAC's PTALK control. It is mainly used for motion trajectory planning, robot dynamic analysis, parameter setting, modification, motion simulation, operating command issuing, intelligent algorithm processing and other management modules. The software of the lower computer adopts PMAC's own language development, and uses its high-speed calculation function to realize autonomous mobile robot kinematics calculation, motion trajectory interpolation calculation, motion servo control, etc. The software structure of the control system is as Figure 4.

The communication function between PC and PMAC belongs to the system software, which is responsible for the communication between hardware. Its realization first loads the dynamic link library PComm32 to obtain its handle, and then calls the function through the entry pointer of the called function to realize the communication between the computer and PMAC. PMAC communication drive function library Pcomm32, as a communication bridge between Windows and PMAC, uses an interrupt mechanism to complete high-real-time tasks such as servo control, trajectory interpolation, and speed processing. When the buffer is cleared, PMAC will send an interrupt request signal. After receiving the signal, the host computer will carry out path planning control for the following trajectory segments, and write the calculated new control data into DPRAM. PMAC will read the data from DPRAM and send it to the servo drive device to complete the gait control of each joint of the autonomous mobile robot.

1. Human-computer interaction module: The main functions completed include initialization system, manual operation, compilation and connection module, teaching module, instruction download and information feedback, etc.
2. Motion control module: It is the core of the autonomous mobile robot control software. Its main functions include kinematics calculation, robot gait path planning, online quick adjustment of position, configuration of system parameters, and PLC program editing, management, system monitoring, etc. Based on the analysis of the linearization of the control system of the autonomous mobile robot, the dynamic model of the motion control of the autonomous mobile robot is established. On this basis, based on the interpolation method of cubic spline, the gait planning of the autonomous mobile robot is generated, and the motion control of the autonomous mobile robot is realized. Obtain information such as the position and pose coordinate sequence of the moving target of the autonomous mobile robot system and the motion trajectory control method, and calculate the angle that each joint needs to rotate through the inverse motion calculation according to the pose matrix of the initial position and the target position. It is transmitted to the PMAC servo control system, and PMAC is set according to some parameters of the user to realize the gait control of the autonomous mobile robot.

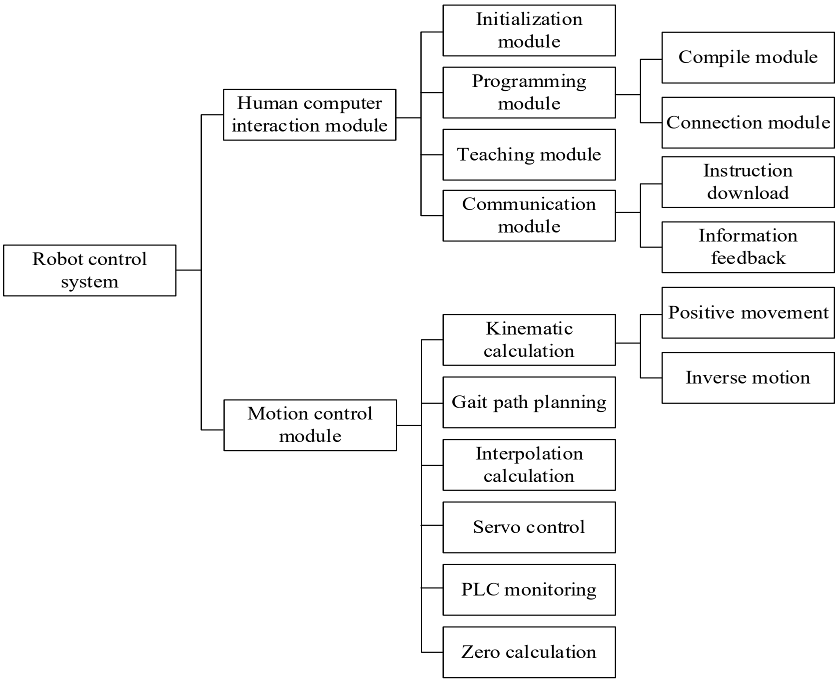


Figure 4. Control system software structure

6. Experimental Simulation and Analysis

6.1. Setting up the experimental environment

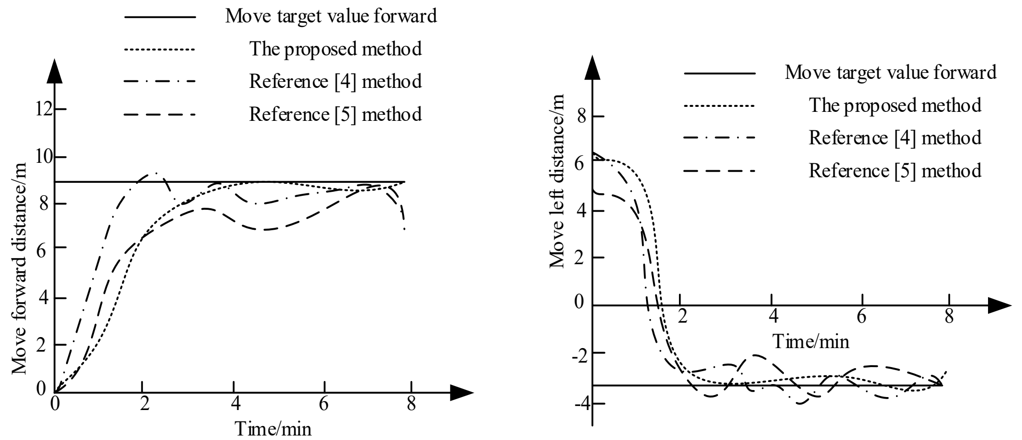
In order to verify the effectiveness of the gait control system of autonomous mobile robot based on PMAC, a computer with Inter Core i5-3470 processor, 8.00 G memory, 600 G hard disk and 64 bit Windows 7 operating system was used in the experiment. In the Visual C++ integrated environment, the C++ language is used to develop an autonomous mobile robot gait control system based on PMAC to realize and verify its performance. The hardware selection and parameter index are as Table 1.

6.2. Stability analysis of robot motion control

In this system, the dynamic model of the motion control of the autonomous mobile robot is established, the kinematics algorithm is imported into the simulation software, and the reference [4] method, the reference [5] method and the proposed method are used to compare the motion in different directions. Stability is an indicator, and the results of experimental analysis are shown in Figure 5.

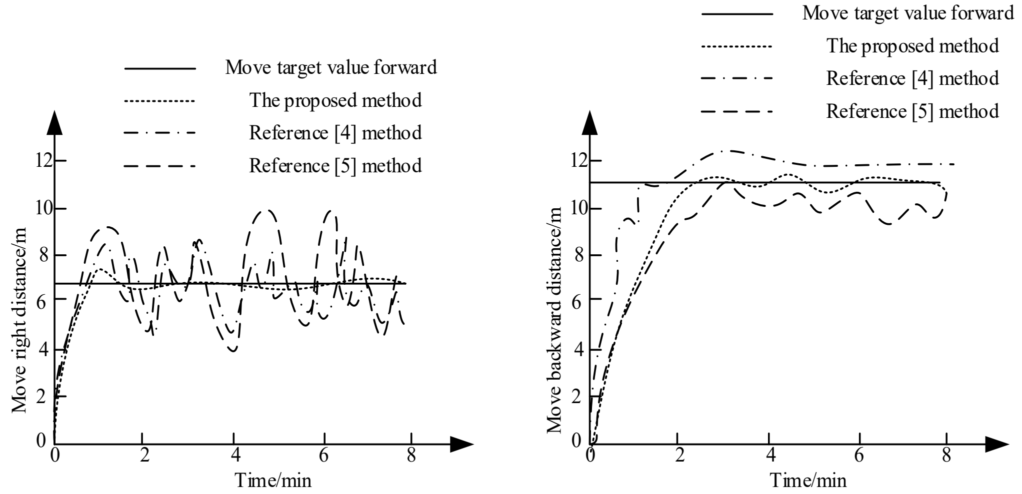
Table 1. Hardware selection and parameter list

Hardware name	Model
Upper computer	Surface Pro2
Lower computer	STM32F103
CO sensor	MICROceLTM
CH$_4$ sensor	MICROpel
H$_2$S sensor	MICROceLTM
Temperature and humidity sensor	SHT15
Inertial navigation module	miniIMU AHRS
Camera	600 lines micro
Human body detection	HC-SR501
Infrared ranging	GP2Y0A02



(a) Move forward the coordinate change curve

(b) Move left the coordinate change curve



(c) Move right the coordinate change curve

(d) Move backward the coordinate change curve

Figure 5. Comparison of robot motion control stability of different methods

It can be seen from Figure 5 that the position of the autonomous mobile robot controlled by the reference [4] method and the reference [5] method oscillates when it moves forward, and when it moves to the left, there is a steady-state error in the position. When moving, the position oscillates and the average value deviates from the target value. The proposed method can effectively avoid the oscillation caused by signal lag and increase the response to small deviations. The reason why the deviation of the leftward movement is slightly larger than the forward deviation is that when the control signal of the leftward movement is small, the inertial device cannot provide sufficient thrust. When the control signal is moved to the right, it is easily affected by the ground, and there are certain fluctuations in the backward movement. However, it is maintained near the target value as a whole. It can be seen that the motion control stability of the autonomous mobile robot using the proposed method is better.

6.3. Gait displacement and walking efficiency analysis of robot

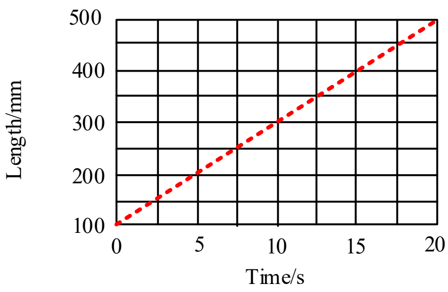
In order to verify the walking compliance of the autonomous mobile robot gait control system based on PMAC, the reference [4] method, the reference [5] method and the proposed method were used to compare the robot gait displacement curves of different methods. The comparison results are as Figure 6.

According to Figure 6, it can be seen that the robot gait trajectory of the proposed method is smoother than that of the reference [4] method and the reference [5] method, and the robot walking compliance of the proposed method is higher than that of the reference [4] method and the reference [5] method. The average speed is used to measure the walking efficiency of autonomous mobile robots, namely:

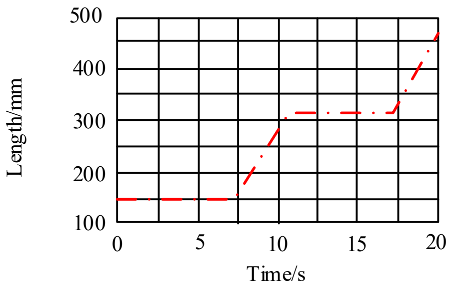
$$\eta = \frac{\mu}{t} \tag{15}$$

In Equation (15), μ represents the step distance, and t represents the gait cycle. Since the step distance μ is 500 mm, the gait period t of the method in reference [4], the method in reference [5] and the proposed method are 7 s, 6 s and 5 s, respectively. According to Equation (15), the average speed of the reference [4] method, the reference [5] method and the proposed method are 71.4 mm/s, 83.8 mm/s and 100 mm/s, respectively. It can be seen that the average gait speed of the proposed method is larger and the walking efficiency is higher.

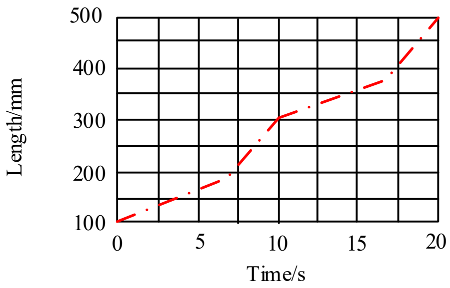
Based on the above comparative analysis, it can be seen that, compared with the robot gait displacement curve and the average gait speed of the reference [4] method and the reference [5] method, the robot gait motion trajectory of the proposed method is smooth and the walking flexibility is better. The average gait speed of the robot is relatively high, and the walking efficiency is relatively high.



(a) Gait displacement of robot in the proposed method



(b) Gait displacement of robot in the reference [4] method



(c) Gait displacement of robot in the reference [5] method

Figure 6. Comparison of robot gait displacement curves of different methods

6.4. Robot gait path planning

In order to further verify the gait path planning effect of the autonomous mobile robot gait control system based on PMAC, the reference [4] method, the reference [5] method and the proposed method are used to compare the planning path of robot gait control system of different methods. The comparison result is as Figure 7.

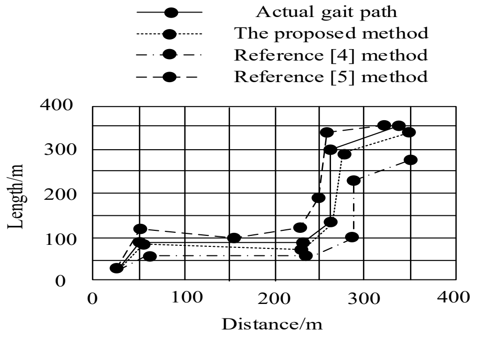


Figure 7. Comparison of robot gait path planning effects of different methods

According to Figure 6, it can be seen that there is a certain deviation between the robot gait path planning of the reference [4] method and the actual gait path, and the robot gait path planning of the reference [5] method has a large deviation from the actual gait path. The robot gait path planning of the proposed method is basically consistent with the actual gait path, and can successfully realize the movement from the starting point to the target point. Therefore, the robot gait path planning effect of the proposed method is better.

7. Conclusions

In this paper, the gait control system of autonomous mobile robot based on PMAC is proposed. The dynamic model of walking gait of autonomous mobile robot is constructed, and the walking period and key posture are calculated, thus the walking gait model of robot is designed. The series mechanism and parallel mechanism are used to control the rotation angle of the motor, and the gait trajectory is planned. Experiments show that this method can improve the walking compliance and walking efficiency of the robot.

However, in the process of gait control of autonomous mobile robot, information feedback such as robot attitude should be added to reduce the influence of machining and installation errors on the performance of control system. Therefore, a complete upper control system will be established in the next research to realize fast offline attitude planning and online real-time gait adjustment.

Acknowledgement

The research is supported by: The 2018 Henan provincial key teacher training program for colleges and universities (No. 2018GGJS268).

Reference

[1] Hutchinson, M.; Liu, C.; Chen, W.H. Information-based search for an atmospheric release using a mobile robot: Algorithm and experiments. IEEE Transactions on Control Systems Technology, 2019, 27(6): 2388-2402.

[2] Vassallo, C.; Olivier, A.; Souères, P.; Crétual, A.; Stasse, O.; Pettre, J. How do walkers behave when crossing the way of a mobile robot that replicates human interaction rules. Gait & Posture, 2018, 60: 188-193.

[3] Kantaros, Y.; Zavlanos, M.M. Distributed intermittent connectivity control of mobile robot networks. IEEE Transactions on Automatic Control, 2018, 62(7): 3109-3121.

[4] Venkatesh, A.; Rao, G.R. An improved adaptive control system for a two wheel inverted pendulum-mobile robot using eagle strategy with a particle swarm optimization. Multimedia Systems, 2018, 5(7): 137-145.

[5] Ren, C.; Li, X.; Yang, X.; Ma, S. Extended state observer based sliding mode control of an omnidirectional mobile robot with friction compensation. IEEE Transactions on Industrial Electronics, 2019, 66(12): 9480-9489.

[6] Lu, Q.; Han, Q.L. Mobile robot networks for environmental monitoring: a cooperative receding horizon temporal logic control approach. IEEE Transactions on Cybernetics, 2018, 49(2): 698-711.

[7] Paull, L.; Seto, M.; Leonard, J.J.; Li, H. Probabilistic cooperative mobile robot area coverage and its application to autonomous seabed mapping. International Journal of Robotics Research, 2018, 37(1): 278-295.

[8] Garrocho, C.T.B.; Da Silva, M.J.; Oliveira, R.A.R. D2D pervasive communication system with out-of-band control autonomous to 5G networks. Wireless Networks, 2020, 26(1): 373-386.

[9] Guo, Q.Y.; Shi, G.L.; Wang, D.M.; He, C.Y.; Hu, J.; Wang, W. Iterative learning based output feedback control for electro-hydraulic loading system of a gait simulator. Mechatronics, 2018, 54: 110-120.

[10] Kuwada, S.; Aota, T.; Uehara, K.; Nara, S. Application of chaos in a recurrent neural network to control in ill-posed problems: a novel autonomous robot arm. Biological Cybernetics, 2018, 112(5): 495-508.

[11] Ye, W.; Liao, C. Method for planning natural gait joint trajectory of embedded intelligent robot. Computer Simulation, 2020, 37(5): 301-305.

[12] Kuang, C.; Zheng, X.Y. Space trajectory planning of electric robot based on unscented kalman filter. Jordan Journal of Mechanical and Industrial Engineering, 2021, 15(1): 29-38.

[13] Ali, M.A.H.; Mailah, M. Path planning and control of mobile robot in road environments using sensor fusion and active force control. IEEE Transactions on Vehicular Technology, 2019, 68(3): 2176-2195.

[14] Kantaros, Y.; Guo, M.; Zavlanos, M.M. Temporal logic task planning and intermittent connectivity control of mobile robot networks. IEEE Transactions on Automatic Control, 2019, 64(10): 4105-4120.

[15] Tonin, L.; Bauer, F.C.; Millán, J.R. The role of the control framework for continuous teleoperation of a brain–machine interface-driven mobile robot. IEEE Transactions on Robotics, 2020, 36(1): 78-91.

[16] Mutawe, S.; Hayajneh, M.; BaniHani, S.; Qaderi, M.A. Simulation of trajectory tracking and motion coordination for heterogeneous multi-robots system. Jordan Journal of Mechanical and Industrial Engineering, 15(4): 337-345.

[17] Zheng, Z.; Zhao, H.; Swanson, A.R.; Weitlauf, A.S.; Warren, Z.E.; Sarkar, N. Design, development, and evaluation of a noninvasive autonomous robot-mediated joint attention intervention system for young children with ASD. IEEE Transactions on Human-Machine Systems, 2018, 48(2): 125-135.