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Research on adaptive motion planning of complex terrain for space hexapod motion robot based on reinforcement learning

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ABSTRACT

Hexapod robot has wide application prospect in complex environment because of its high stability and flexibility. However, it is often difficult for traditional steering gear control methods to maintain accurate and stable motion in dynamic or irregular space environments. In this paper, a motion control method of hexapod robot based on negative feedback control of steering gear is proposed. By introducing an external sensor Angle sensor, the actual Angle of steering gear is obtained in real time, and the PWM control signal is dynamically adjusted according to the Angle deviation. This negative feedback mechanism can effectively eliminate the error accumulation of the steering gear and achieve higher precision control, so as to ensure the smooth operation of the robot in the complex space environment. The experimental results show that the proposed control method significantly improves the stability and motion accuracy of the hexapod robot in varied terrain, which lays a foundation for the performance of the hexapod robot in practical applications in the future.

KEYWORDS

Hexapod robot; Steering gear control; Negative feedback; Precision control; Kinematic stability

1 Introduction

Hexapod robot shows strong stability and adaptability in complex environment because of its unique structure and movement mode. Compared with four-legged or wheeled robots, six-legged robots perform better on irregular ground or in changeable environments, especially when dealing with complex terrain obstacles, with high reliability and passability[1]. Therefore, hexapod robots are widely used in military reconnaissance, disaster relief, environmental monitoring and other fields. However, the stability and precise movement of the hexapod robot are often limited by its control system, especially the steering gear control part.

The traditional steering gear control usually adjusts the position of the steering gear through the pulse width modulation (PWM) signal, but the accuracy and response speed of this control mode are limited, especially in the complex space environment, it is easy to appear position deviation and motion instability[2]. In order to overcome this problem, in recent years, the negative feedback control of the steering gear has gradually become an effective means to improve the accuracy and stability. Negative feedback control monitors the motion state of the steering gear in real time and adjusts the control input according to the feedback information, so that the steering gear can self-correct according to the changes of the external environment and ensure its smooth movement in the dynamic environment.

The aim of this study is to improve the motion accuracy and stability of a hexapod robot by introducing a negative feedback mechanism in the control of the steering gear. Specifically, this research obtains the Angle information of the steering gear in real time through the Angle sensor, and adjusts the PWM signal according to the feedback data, so as to achieve accurate control and motion stability. The experimental results show that the hexapod robot with negative feedback control can maintain higher motion accuracy in complex terrain and dynamic environment, and significantly improve the motion instability under traditional control methods. The research in this paper provides a new solution for the motion control of hexapod robot, which has important theoretical significance and practical application value.

2 System framework design

In order to realize the smooth operation of hexapod robot in complex environment, a control algorithm framework based on the negative feedback of steering gear is proposed in this paper. The framework is based on CAN bus communication between each actuator, ensuring efficient coordination and information transfer. At the same time, the MCU of the main platform obtains the spatial attitude data of the robot by connecting the gyroscope, which provides an important motion reference for the precise control of the steering gear. The whole frame design includes four main modules: target Angle setting, space attitude perception, feedback data acquisition and PID control[3].

In this framework, the target Angle of each steering gear of the robot is set by the control system of the main platform. Each steering gear communicates with the main platform through the CAN bus to transmit its current Angle and motion status in real time. In order to ensure the precise movement of the steering gear, the gyroscope sensor monitors the robot's spatial attitude in real time and feeds it back to the MCU of the main platform. The MCU calculates the motion error according to the space attitude information and the moving target of the steering gear, and compensates the error with PID control algorithm, and adjusts the PWM signal in real time, so as to ensure the accurate control and the stability of the motion of each steering gear.

PID control algorithm plays an important role in this process, by adjusting the control output in real time, to ensure that the steering gear can respond in time and correct the attitude deviation during the execution of motion. The control system can continuously optimize and adjust the signal according to the feedback data of each steering gear, avoid the position drift caused by load changes or external interference, and improve the smooth operation ability of the hexapod robot in the dynamic environment.

The control framework has a high degree of flexibility and expansibility, and through the communication mechanism of CAN bus, it ensures efficient cooperation between multiple steering gear, and can handle various movement challenges encountered by robots in complex terrain. The design of the whole system optimizes the real-time and precision of the control algorithm, and provides a solid theoretical foundation and technical support for the stable motion of the hexapod robot in practical application.

3 Hardware design

In the control system of hexapod robot steering gear, the key is the negative feedback mechanism and precise control of steering gear, and the efficient cooperation between steering gear is realized through CAN bus communication. The hardware design of the steering gear includes many main components: Angle sensor, motor, motor drive module, H-bridge circuit, single-chip microcomputer control system, and CAN bus communication module[4]. These components work closely together to achieve accurate control and real-time feedback of the steering gear Angle.

3.1 Angle Sensor

The Angle feedback of the steering gear is provided by the Angle sensor integrated in the steering gear, which outputs an analog voltage signal proportional to the Angle of the steering gear. The signal is processed by analog to digital conversion (ADC) module and transmitted to single chip microcomputer for real-time acquisition and analysis. The selection of Angle sensor directly affects the accuracy of steering gear control, so it is necessary to choose a sensor with fast response speed, high precision and stable output. Common Angle sensors such as rotary transformers or optical encoders can be used for this purpose, and the specific selection needs to be optimized according to the actual application scenario.

3.2 MCU Control System

STM32G030F6P6 is selected as the core control unit in the single chip microcomputer of the steering gear, which is responsible for collecting and processing the analog voltage signal output by the Angle sensor. The MCU converts the analog signal to the digital signal through the built-in ADC module, and calculates the deviation value according to the error between the set target Angle and the actual Angle. Then, the single chip microcomputer processes the deviation value by PID control algorithm, dynamically adjusts the duty cycle of PWM signal to control the motor drive of the steering gear.

3.3 Motor and Motor Drive Module

The power of the steering gear comes from the motor, which is responsible for rotating the shaft of the steering gear to adjust the attitude of the robot. The motor is controlled by the motor drive module, which receives the PWM signal sent by the MCU and controls the speed and direction of the motor by adjusting the current size and direction. The motor drive module adopts the integrated H-bridge circuit structure, so that the control signal can flexibly control the positive and negative rotation of the motor, so that the steering gear can accurately reach the target Angle.

3.4 H Bridge Circuit

The H bridge circuit integrated in the steering gear is a common circuit structure used for the forward and reverse control of the motor. The selection of DRV8833 can realize the forward rotation, reverse and stop of the motor according to the control of PWM signal. The advantage of the H-bridge is that it can operate at a higher current and can precisely control the operating state of the motor[5]. Through the H-bridge circuit, the motor can be accurately rotated in a given direction, while avoiding hardware damage caused by changes in direction.

3.5 CAN Bus Communication Module

In order to realize efficient cooperation and information sharing between the steering gear, the steering gear control system adopts CAN bus communication protocol. Each steering gear is equipped with a CAN bus communication module for data exchange with the main platform and other steering gear. Through the CAN bus, the single chip microcomputer can receive the status information of other steering gear in real time (such as current position, motion state, etc.), and coordinate and optimize according to these data.

4 System software design

In the control system of six-legged robot steering gear, the core function of software design is the real-time acquisition and processing of steering gear Angle to ensure that the robot can accurately execute the motion command. The whole system collects data through single chip microcomputer, and uses Kalman filter algorithm to process the Angle signal of steering gear, so as to improve the accuracy and stability of Angle measurement.

4.1 Data Acquisition and Filtering

The Angle of the steering gear is obtained by the Angle sensor, which outputs an analog voltage signal, which has a linear relationship with the actual Angle. Because the sensor may be affected by noise during operation, the Angle value of the sensor output is not exactly equal to the actual Angle. The measured Angle value contains the real Angle and the noise part, usually expressed as the measured value plus noise. The Angle of the steering gear outputs an analog voltage signal through the Angle sensor. There is noise v_k between the signal and the actual Angle θ, so the collected Angle

$$\theta_k \text{ is:} \theta_k = \theta_k + v_k \quad (1)$$

The Kalman filter makes the system maintain high accuracy even when the measurement noise is large by constantly revising and updating the state estimation.

It can extract the effective part of the signal from the noise, thus reducing the interference to the control system and improving the motion accuracy of the steering gear.

4.2 Platform Angle

Angular velocity is the rate at which the Angle changes, and what we need is the actual Angle value. To obtain the Angle from the angular velocity, it is necessary to integrate the angular velocity data output by the gyroscope.

If the robot's attitude at some point is θ_x, θ_y, θ_z, representing the rotation Angle around the X, Y, and Z axes, respectively, then the amount of Angle change can be calculated from the angular velocity in a small time interval Δt:

$$\Delta\theta_x = \omega_x * \Delta t \quad (2)$$

$$\Delta\theta_y = \omega_y * \Delta t \quad (3)$$

$$\Delta\theta_z = \omega_z * \Delta t \quad (4)$$

By integrating these angular velocity data, we can get the Angle change of the robot over a period of time. If we know the initial Angle $\theta_x(0)$, $\theta_y(0)$, $\theta_z(0)$, we can calculate the Angle at time t by the following formula:

$$\theta_x(t) = \theta_x(0) + \int \omega_x \, dt \quad (5)$$

$$\theta_y(t) = \theta_y(0) + \int \omega_y \, dt \quad (6)$$

$$\theta_z(t) = \theta_z(0) + \int \omega_z \, dt \quad (7)$$

In practice, the discrete time step is used to integrate, that is, the Angle change is calculated by multiplying the angular velocity and the time step Δt for each time period.

$$\theta_x(t+\Delta t) = \theta_x(t) + \omega_x * \Delta t \quad (8)$$

$$\theta_y(t+\Delta t) = \theta_y(t) + \omega_y * \Delta t \quad (9)$$

$$\theta_z(t+\Delta t) = \theta_z(t) + \omega_z * \Delta t \quad (10)$$

However, the Angle value obtained by the gyroscope integration will accumulate errors over time. This error is mainly due to the zero bias of the gyroscope, noise and other environmental factors. After a long time of use, these errors may lead to a large drift of the Angle value, affecting the accuracy of the robot movement.

In order to reduce this drift, the following methods are usually used to compensate:

Sensor fusion: Data from the gyroscope is combined with other sensors (such as accelerometers, magnetometers, etc.) to estimate more accurate angles through sensor fusion algorithms (such as extended Kalman filtering, complementary filtering, etc.). Periodic calibration: In some application scenarios, gyroscope drift can be reduced by periodic calibration, or corrected using a known reference Angle, such as the water level.

4.3 Steering Gear Angle Correction During Walking

Each leg is usually controlled by multiple steering engines, with common shoulder, hip, and knee Angle controls. Suppose that each leg has two degrees of freedom: the thigh (θ_1) and the calf (θ_2), which are controlled by the steering gear.

θ_1: thigh joint Angle

θ_2: Angle of lower leg joint

The movement of each leg is usually periodic, that is, the Angle of the steering gear is changed at a certain time interval, resulting in periodic movement. We divide the movement of the legs into two stages: "swing" and "support".

In gait planning, we need to calculate the target Angle of each steering gear at each point in time. Usually sine wave or cosine wave is used to describe the motion of the leg, which can ensure the smoothness of the motion.

Assuming that the swing and support process of each leg of the robot can be represented by a periodic function, the gait period is T, and the target Angle $\theta\_1(t)$ and $\theta\_2(t)$ of each steering gear can be controlled by the following sine function:

$$\theta\_1(t) = \theta\_1\_max * \sin(2\pi * t / T + \varphi\_1) \tag{11}$$

$$\theta\_2(t) = \theta\_2\_max * \cos(2\pi * t / T + \varphi\_2) \tag{12}$$

In order for a hexapod to move forward, we need to coordinate the movements of all six legs so that they make "swinging" and "supporting" movements in turn. The gait of each leg should be coordinated according to the overall direction of the robot. In order for the robot to move forward, the direction of motion of the swinging leg will usually be towards the front of the robot. Suppose we have six legs (L1, L2, L3, L4, L5, L6), and each leg's gait alternates at a certain time interval. Assuming that the robot's current direction of travel is θ_f, the target Angle of each leg must not only satisfy its own periodic change, but also take into account the overall attitude change of the robot.

The displacement X and Y of the robot in each direction can be comprehensively calculated by the gait of each leg, and the specific process is as follows:

Displacement X in the forward direction:

Forward weight of all swinging legsLateral displacement:

$$X(t) = \Sigma\ (L\_x * \cos(\theta\_f)) \tag{13}$$

Lateral components of all swinging legs:

$$Y(t) = \Sigma\ (L\_y * \sin(\theta\_f)) \tag{14}$$

In order for the robot to move forward, we need to control both the overall gait of the robot and the independent movement of each leg. Assuming that the total motion of the robot is composed of the motions of each leg, defining the forward velocity $V\_x(t)$ of the robot at each point in time can be described by the following formula: $V\_x(t) = \Sigma\ (L\_v * \cos(\theta\_f))$ # the velocity components of all swinging legs

Combined with gait planning and steering gear control, the robot can steadily move forward according to the predetermined gait.

In practical applications, we usually use PID controller to precisely control the Angle change of the steering gear. The input of PID controller is the error between the target Angle and the current Angle, and the output is the control signal to adjust the steering gear.

PID controller formula:

$$u(t) = Kp * e(t) + Ki * \int e(t)\, dt + Kd * (de(t) / dt) \tag{15}$$

5 Test experiments

5.1 System Test Environment

Figure 1 Robot model photo

5.2 Motion Process Planning

The figure above shows the distribution of the feet of a hexapod robot in three-dimensional space. In order to realize this model, according to the design concept of hexapod robot, the spatial coordinates of each foot are randomly generated, and the positions on different heights (Z-axis) are displayed graphically. The position of each foot is evenly distributed in a circular area, simulating the support foot of a hexapod robot.

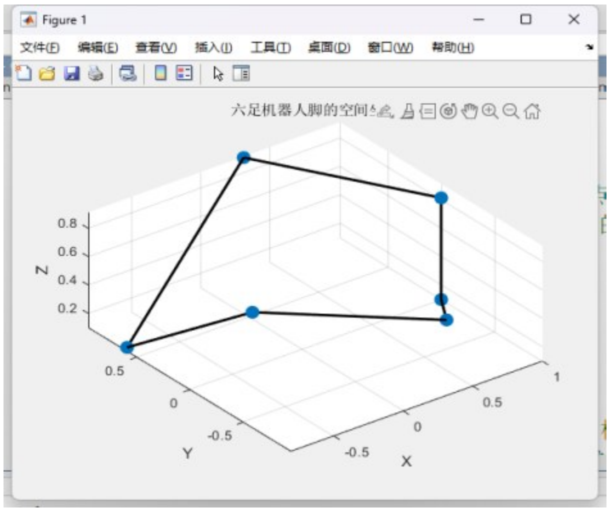

Figure 2 Gait diagram of a hexapod robot

In this model:

X-axis and Y-axis: The position of the feet is determined by evenly distributed on the plane, assuming that the six feet are evenly arranged in a circle with a radius of 1, which can ensure the balance and stability of the robot.

Z-axis: The height of each foot (Z-axis coordinate) is simulated by generating random numbers to show the changes of the robot's feet at different heights, making the model show the effect of ups and downs. This design can simulate the change of support point of hexapod robot when walking on uneven ground in real environment.

This model not only reflects the static support structure of the hexapod robot, but also provides a basis for the subsequent dynamic gait analysis. The position and height of each foot determine the stability and motion attitude of the robot, so the modeling of spatial coordinate points is of great significance for the research of control algorithm, motion planning and plantar-mechanics of hexapod robots.

Through the model in the figure, we can intuitively understand how the six-legged robot distributes its center of gravity under different support conditions and how to adapt to the requirements of complex terrain.

5.3 Experimental Description of Whether the Steering Gear is Fed Back

The core of steering gear feedback control is to monitor the position and Angle change of steering gear in real time during the robot movement, and adjust it by feedback mechanism. The steering gear is usually equipped with an Angle sensor, which can detect the deviation between the actual Angle of the steering gear and the set Angle in real time. Through this feedback mechanism, the control system can constantly adjust the drive current of the steering gear to ensure that the steering gear moves precisely at the desired Angle, thereby avoiding excessive vibration caused by motion errors or inertia.

In the absence of steering gear feedback, the steering gear can only be controlled simply according to the preset PWM signal, and there is no real-time adjustment and correction mechanism. When the steering gear is subjected to external force or inertia during movement, the Angle of the steering gear may deviate from the expected value, resulting in excessive vibration and unstable motion performance.

In the absence of steering gear feedback control, the steering gear can only execute the predetermined control instructions. The amplitude and duration of the drive current of the steering gear is determined by the control signal, but it cannot sense and adjust its own motion state in real time. In the process of robot leg movement, especially in rapid rotation or external load changes, the inertia effect and load changes of the steering gear may cause vibration. Inertia effect refers to the excessive movement of the steering gear due to the inertia of the motor and mechanical system when it changes the motion state. The change of load may cause the speed and position of the steering gear to fluctuate, resulting in greater vibration.

Without steering gear feedback, the steering gear Angle control can only be based on the input signal, but there is no feedback information to correct the gap between the actual Angle of the steering gear and the set Angle. In the process of robot movement, if the Angle of the steering gear deviates, it cannot be corrected immediately, resulting in continuous accumulation of errors. When these errors reach a certain extent, the steering gear will vibrate violently, affecting the stability and motion accuracy of the robot.

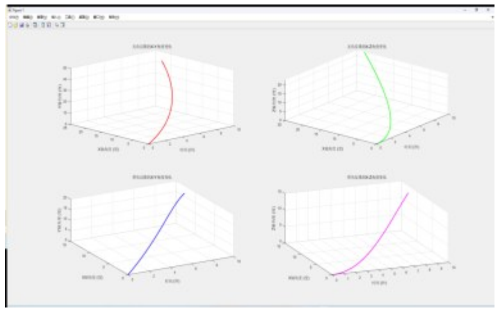

Figure 3 Six-legged robot trajectory diagram group

6 Conclusion

In the experiment of hexapod robot, the servo feedback control can significantly reduce vibration mainly in the following aspects: First, the feedback control can monitor and adjust the Angle change of the steering gear in real time, avoiding vibration caused by inertia, load change and control error; Secondly, the feedback control can effectively restrain the shock and overshoot, and keep the steady motion of the steering gear. Finally, the feedback control optimizes the drive current and load regulation of the steering gear, reduces mechanical friction and damping effects, and makes the robot move more smoothly. Therefore, the servo feedback can not only improve the motion accuracy of the robot, but also effectively improve its stability and reduce vibration.

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References

[1] Liang Guangqiang,Xue Wenchao,Quan Hongwei,et al.Design of Hexapod Robot Walking Mechanism[J].Equipment Manufacturing Technology, 2025,(01):31-34+43.

[2] Cui Bing,Li Guang,Hu Feiyang,et al.Motion Planning Method Based on Adaptive Parameters under Kinetic Dynamics Constraints[J/OL].Control and Decision,1-9[2025-04-16].

[3] Zhang Shilin, Zhang Binbin. Adhesion and Mobility Control Methods for Hexapod Robots under Weak Gravity[J]. Shanghai Space(Bilingual), 2024,41(05):136-144+177.

[4] Wang Yifan. Research on Navigation Methods for Wheeled Robots in Complex Terrain Based on Hierarchical Reinforcement Learning[D]. Jilin University,2024.

[5] Qiao Haiye, Wu Qinghui, Wang Lijuan. Research on Adaptive Environmental Motion Planning for Hexapod Robots Based on Rhythmic Gait[J]. China Equipment Engineering,2024,(03):35-38.