Optimization Method for Inverse Kinematics of Quadruped Robot Based on Improved Longicorn Whisker Algorithm

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Abstract: With the deepening of the enabling development role of robotics related industries, new types of robots have gradually been integrated into many fields of production and life. Due to the advantages of quadruped robots such as strong stability during movement, fast movement speed, high controllability, and strong adaptability to the ground, it has become a research focus in the field of intelligent manufacturing related to robots and humans. The inverse kinematics optimization method for quadruped robots based on the improved Longicorn whisker algorithm is a major breakthrough in the field of robotics. This method utilizes an improved Longicorn beard algorithm to solve complex inverse kinematics problems for quadruped robots. The Longicorn beard algorithm is inspired by the sensory system of insects, which uses their antennae to detect and respond to changes in the environment. An improved version of the algorithm combines a more accurate and effective method to solve inverse kinematics problems. The inverse kinematics optimization method for quadruped robots based on the improved Longicorn whisker algorithm has many advantages over traditional methods. It can quickly and accurately solve complex problems, and is very suitable for use in real-time applications. In addition, this method has strong adaptability and can be used for different types of robots. Overall, the inverse kinematics optimization method for quadruped robots based on the improved Longicorn beard algorithm represents a significant advance in robotics technology. Its potential applications range from industrial automation to medical robotics.

1 INTRODUCTION

In recent years, with the rapid development of high-tech industries such as artificial intelligence, and the continuous exploration and deepening of the role of robotics in the empowerment and development of related industries, new types of robots have gradually been integrated into many fields of national production and life. Emerging disciplines such as robotics have become the main driving force for national development, and more and more countries have started exploring and researching artificial intelligence fields such as robotics, China has also proposed the "Made in China 2025" intelligent manufacturing development strategy, and the transition from traditional technology industries to advanced intelligent manufacturing has become a hot spot and development trend in scientific and technological research (Huang, Wu, et al. 2021).

In the process of research in the field of robotics, the application of mobile robots to various fields of national production and life, such as the service industry and manufacturing industry, not only liberates human resources and improves people's quality of life, but also represents a revolution in production technology. Therefore, research in the field of mobile robots has always been in an important position.

For unstructured terrain, quadruped robots have stronger adaptability than traditional wheeled or tracked vehicles. Therefore, quadruped robots have become a research hotspot in the field of mobile robots. Inverse kinematics solution (IK problem) is one of the key research issues in the kinematics of 12 degree of freedom quadruped robots (Qin, Dong et al. 2021). It is of great significance for the research of trajectory planning, dynamic characteristics analysis, and motion control of mobile robots. Currently, there are algebraic methods, numerical methods, and intelligent optimization algorithms for solving IK problems. Algebraic method has a fast solution speed, but it has strict requirements for robot configuration and is not universal. The numerical solution has strong versatility, but the setting of initial values has

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a significant impact on the convergence effect. In intelligent optimization algorithms, the parallel general network based on RBF neural network and BP neural network solves IK problems faster than algebraic methods, and has strong real-time performance (Biswal, and Mohanty 2021). However, when neural networks are applied to robots with different configurations, it is necessary to retrain the network, resulting in a weak generalization ability. The hybrid genetic algorithm introduces the concepts of exploration and development, using real-coded HGA and binary competition selection operators to evaluate multiple inverse kinematics solutions of articulated and Puma manipulators (Schreiber, and Gosselin 2022). However, genetic algorithms have a complex structure and a large amount of computation, which weakens the real-time performance of IK problem solving. The hybrid algorithm of the multi-directional exploration feedback strategy, Tianniuxu and genetic algorithm, increases the search ability of the algorithm, but also increases the computational complexity of the algorithm when exploring different directions. Artificial bee colony algorithm for solving inverse kinematics problems of redundant robot arms has the characteristics of good robustness and strong global optimization ability (Zhou, Yu et al. 2021). However, this method has a complex structure and weak local optimization ability.

In fact, the Tianniu whisker algorithm (BAS) is an intelligent optimization algorithm based on individuals. Since there is only a single Tianniu during the iteration, it is lower in time and space complexity than the swarm intelligence algorithm, and its efficiency is also higher.

However, traditional BAS has the characteristics of low convergence speed and strong oscillation during the convergence process, which reduces the accuracy of the results and is difficult to meet the real-time and accuracy requirements of the inverse kinematics solution process for a 12 degree of freedom quadruped robot (Zhang, Zhu, et al. 2021).

2 RELATED WORKS

2.1 Current Research Status of Longicorn Whisker Search Algorithm in China

Based on imitating the predatory behavior of longicorn beetles in nature, Jiang Xiangyuan proposed a bionic intelligent optimization algorithm with meta heuristics, high randomness, and fast convergence in 2017, called the Beetle Antennae Search Algorithm (BAS). In nature, the predation of longicorn beetles mainly relies on the antennae distributed on both sides of the head. The odor receptors in the antennae sense the concentration of pheromones emitted by prey in the air (Chandan, Shah, et al. 2021). When the odor receptors sense both sides! When there is a difference in the pheromone concentration of the antennae, the longicorn beetle will move a certain distance towards the side with the higher pheromone concentration, thereby repeatedly approaching the target and finally finding food.

Over time, many researchers have conducted in-depth research on longicorn whisker search algorithms and applied them to multiple research fields such as parameter tuning, power scheduling, neural network pre training, and path planning. In his paper, Associate Professor Jiang Xiangyuan used the proposed longicorn whisker search algorithm to conduct simulation tests on the Michalewicz test function and the Goldstein Price test function from the perspective of convergence and local minimum avoidance (Zohour, Belzile, et al. 2021). The test results show that the longicorn whisker search algorithm can complete accurate numerical optimization after fewer search iterations. Subsequently, Jiang Xiangyuan et al. proposed a BAS-WPT (BAS-Without Parameter Tuning) algorithm that does not require parameter adjustment for the optimized object, and further expanded the Tianniu whisker search algorithm to the field of multi-objective optimization. BAS-WPT algorithm uniformly maps the optimized parameters of different orders of magnitude and different value ranges to the same constraint range by normalizing the optimized parameters, simplifying the time and computational complexity of parameter tuning to a certain extent, and using the penalty function to deal with inequality constraint problems, also improving the optimization ability of the Taurus whisker search algorithm in multi-objective optimization problems (He, Shao, et al. 2021). Dangke et al. 185 further improved the step attenuation strategy in the original longicorn whisker search algorithm and proposed a variable step longicorn whisker search strategy, taking into account the convergence speed and accuracy of the algorithm.

Since its introduction, the Tianniu whisker search algorithm has attracted the attention of many researchers. Due to its advantages such as small computational complexity, strong randomness, rapid convergence, and simple optimization strategies, the Tianniu whisker search algorithm has been applied and recognized in many aspects of the optimization field. Currently, the application of the Tenebrio Tenebrio search algorithm is mostly concentrated in the combination with other algorithms, and few studies have made further improvements on the Tenebrio Tenebrio search algorithm (Ju, 2021. On the basis of detailed and in-depth research, this paper improves the search strategy of the longicorn's whisker search algorithm, and applies it to the obstacle avoidance path planning problem of quadruped robots based on its fast computing characteristics, achieving rapid planning of the running path of quadruped robots in the working environment with obstacles.

2.2 Longhorn Whisker Search Algorithm

As a kind of meta heuristic optimization algorithm, the longicorn whisker search algorithm mainly derives its search strategy from imitating the predatory behavior of longicorn. In nature, longicorn beetles mainly rely on the antennae distributed on both sides of their heads (Biswal, and Mohanty 2021). The odor receptors in the antennae can obtain pheromones scattered in the air. Due to the different distances between the two antennae from food, the odor concentration obtained also varies. When a high odor concentration is detected on one side, the longicorn moves in the direction indicated by that side, thereby continuously updating its position and finally obtaining food (Tholapu, Sudheer et al. 2021). The search behavior of the longicorn whisker search algorithm can be simplified to the geometric model shown in Figure 1. The blue triangle in the figure represents a longicorn, and the two corners on the long side of the triangle represent two longicorn antennae, which are equally spaced on both sides of the longicorn's head (Devi, Jadhav, et al. 2021). The length of the connecting line between the midpoints of the long sides of the front and rear triangles is used as the search step for longicorn movement (Wang 2021). The color depth of the light blue area indicates the strength of the fitness function value, This can graphically represent a conceptual diagram of the search behavior of the longicorn whisker search algorithm.

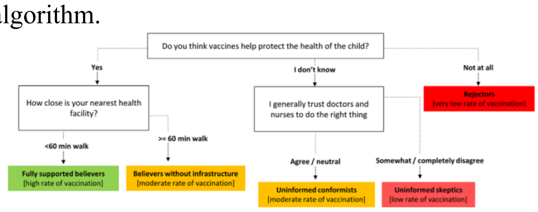

Figure 1: Schematic diagram of optimization of longicorn whisker search algorithm

The search behavior in Figure 1 can be described as follows: At the beginning of the search, the longicorn generates a random head orientation at the current position, and the antennae distributed on both sides of the head perceive the fitness value of their respective positions; When there is a difference in the fitness value between the two sides, the longicorn moves a certain search step towards the side with the high fitness value; When the longicorn moves to the searched position, the single search process ends, and the search step length should be shortened based on the last moving distance. In this way, Taurus continues to advance and eventually converges to a certain value in a certain region (Megalingam, Tantravahi, et al. 2021).

The mathematical model of the longicorn whisker search algorithm is as follows:

2.2.1 Establish a Fitness Evaluation Function

First of all, it is necessary to establish a fitness evaluation function f (x) for the optimization objective, and use the coordinates of the centroid of the head of Tianniu as the independent variable x. The value of the fitness evaluation function varies with the change in the centroid coordinates of the taurus head, and its value should directly reflect the merits of the optimization problem. The function is represented as follows:

$$\min f(x), x \in R^k \tag{1}$$

In the formula, k represents the dimension of the independent variable x, and the optimization goal of the fitness evaluation function is the minimum value of the function.

2.2.2 Generate Random Orientation

Then, a random search direction b needs to be generated, and the normal direction of the random search direction represents the direction of the longicorn.

$$\vec{b} = \frac{rand(k,1)}{\| rand(k,1) \|} \tag{2}$$

Where rand (k, 1) represents a randomly generated k within the range of [- 1,1] × A one-dimensional vector, where the random search direction b is consistent with the dimension of the independent variable x. The purpose of dividing rand (k,1) by its own modulus is to unit the random search direction b, thereby reducing the numerical differences brought about by the search direction.

2.2.3 Generation of left and right fitness values

Subsequently, based on the generated random search direction, the right side of the longicorn is marked as positive in the search direction, and the left side of the longicorn is marked as negative. Then, the fitness values of their respective positions are obtained based on the distance between the left and right tentacles of the longicorn. The coordinates of the tentacles on the left and right sides of the longicorn are shown as follows:

$$x_r = x^{t^{-1}} + d^{t^{-1}}\vec{b}/2, \tag{3}$$

$$x_l = x^{t^{-1}} - d^{t^{-1}}\vec{b}/2 \tag{4}$$

Where, xr and xl represent the coordinates of the right and left tentacles of the centroid of the head of the longicorn bull, respectively, and d 'represents the distance between the left and right tentacles, which is affected by the search step size δ And the size of the search step decreases as the number of iterations increases. The iterative representation of search step length and whisker spacing is as follows:

$$\delta^t = \lambda\delta^{t-1}, \tag{5}$$

$$d_0^t = \partial^t/c \tag{6}$$

Where, λ Represents a constant with a value between [0,1], which represents the search step size δ Attenuation rate of; C is a constant that represents the distance d between the left and right tentacles and the search step length δ The correlation coefficient of. After obtaining the coordinates of the left and right tentacles, it is also necessary to bring xr and xl into the fitness evaluation function to obtain the fitness values f (xr) and f (xl) for their respective positions.

The centroid iteration of Taurus is determined by the search direction b and the search step length 8. These two variable parameters also constitute the core search strategy of the Taurus whisker search algorithm. In the early stage of search, a sufficiently large search step can effectively explore the value range of independent variables, ensuring efficient global search capabilities; When encountering local extremum, it is possible to deviate from the local extremum by virtue of a large search step size and a completely random search direction; In the later stage of the search, due to the continuous attenuation of the step length, the longicorn beetle converges in a certain search area and eventually converges to a certain value.

3 OPTIMIZATION OF INVERSE KINEMATICS OF QUADRUPED ROBOT BASED ON IMPROVED LONGICORN WHISKER ALGORITHM

3.1 Improved Design of Longicorn Whisker Search Algorithm

The Tianniu whisker search algorithm has many advantages such as simple structure, strong randomness, and rapid convergence, but its disadvantages are also relatively obvious. For example, when dealing with large-scale combinatorial optimization and multi-extremum optimization problems, due to the attenuation rate of the search step size and the completely random search direction, there will be problems such as poor search efficiency, non optimal results, and blind search wasting computational resources; At the same time, when dealing with complex nonlinear strongly coupled optimization problems such as obstacle avoidance path planning for robotic arms, it is necessary to comprehensively consider various performance requirements, improve search efficiency, and satisfy the optimality of the solution as much as possible, avoiding the waste of computing resources. Therefore, it is necessary to improve the original Tianniu whisker search algorithm to improve its efficiency in complex optimization problems while retaining its efficient global search and convergence characteristics.

The core strategy of the locally variable step size search mechanism is: during the current iteration process, if the optimal solution of the algorithm is updated, the global search step size will be locked and assigned to the locally variable step size. Relying on the self attenuation of the locally variable step size, the convergence and local optimization of the current iteration will be completed, achieving rapid exploration of the optimal value of the potential optimal region.

This locally variable step size only exists in the locally variable step size search mechanism. This article redesigns the self attenuation of this locally variable step size as follows:

$$\delta_\eta^0 = \delta^t \tag{7}$$

$$\delta_\eta^i = \delta_{\eta\min} + \delta_\eta^{i-1} \cos\left(\frac{\pi}{2} \cdot \frac{i}{m}\right), i \in [0, m] \tag{8}$$

Where, δ Is an independent variable composed of δ' Initialize and then attenuate independently. T represents the number of iterations in the search process of the main program of the Taurus whisker search algorithm, and i represents the number of iterations in the search process of the local variable step size search mechanism, δ "Min is a constant that represents the minimum value of the locally variable step size search mechanism, and m represents the maximum number of iterations of the locally variable step size search mechanism. The selection of its size requires comprehensive consideration of search accuracy and search speed.".

$$x_r = x_{bst}^{i-1} + \delta_\eta^{i-1} \vec{b}/c \tag{9}$$

$$x_l = x_{bst}^{i-1} - \delta_\eta^{i-1} \vec{b}/c \tag{10}$$

Where, x_ Bst ^ i is an iterative model of a locally variable step size search mechanism, which performs iterative updates of data in the local mechanism. When the mechanism exits the iteration and returns to the main program of the Tianniuxu search algorithm, it is necessary to return the optimal solution of the local search results to the main program for storage, so that the algorithm can compare with other local optimal values obtained after the main program search.

The process of an improved longicorn whisker search algorithm with a locally variable step size search mechanism is as follows:

1) The starting condition of the local variable step size search mechanism.

The main program of the algorithm starts, initializes parameters such as search step size and attenuation coefficient, and updates the optimal solution using the optimization strategy of the Tenebrio search algorithm. When the global optimal solution of the algorithm is updated, the program switches to a local variable step size search mechanism.

2) Parameter initialization of local variable step size search mechanism and single search iteration strategy.

Lock the global search step size and assign a value to the local variable step size, and assign the current global optimal solution and its fitness value to the local optimal solution and its fitness value. The single iteration process of local variable step size is as follows: First, generate a new local search direction to guide the local variable step size search; Then, complete a single search iteration with locally variable step size according to Equations (8), (9), and (10), and compare the search results with the local optimal solution; Finally, update the local optimal solution based on the comparison between the search results and the local optimal solution, complete the local variable step size attenuation according to Formula (9), and end the single iteration.

3) After exiting the local variable step size search mechanism, the local optimal solution is stored and returned to the main algorithm program.

The local variable step size search mechanism ends the iteration after m searches, saves the local optimal solution and its fitness value, and returns them to the local optimal solution set in the main program of the algorithm. It serves as a parallel solution set for the optimal solution in the main program of the algorithm, and is used to compare and obtain the global optimal solution after the algorithm finishes searching.

3.2 Kinematic Analysis of Quadruped Robot

Kinematics analysis is the basis for subsequent mechanism dynamics analysis, foot workspace solution, and foot motion trajectory planning. According to motion control requirements, kinematics is decomposed into forward and inverse kinematics analysis. Positive kinematics refers to deriving the posture and position of the foot end position coordinates in the torso coordinate system based on the changes in the rotation angle of each link joint under the condition that the structural dimension parameters of each leg link are known. Inverse kinematics refers to the inverse calculation of the angle of each joint based on the known position coordinates of the foot end relative to the fuselage coordinate system and the position relationship and size of the connecting rod. The specific analysis process is shown in Figure 2. In this process, the force problem during the motion of a quadruped robot can be temporarily ignored, and the research is aimed at the coordinate system relationship between the various links of the legs of the quadruped robot. The analysis of the joint space and foot end motion position of the robot leg structure lays a theoretical foundation for subsequent motion gait planning and motion control, and is of great significance for the research and development of quadruped robots.

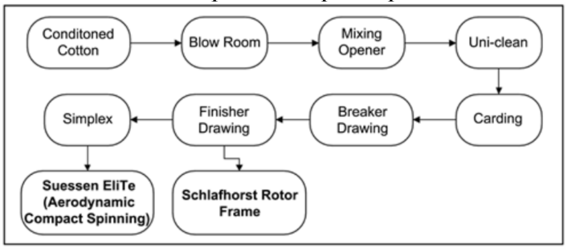

Figure 2: Kinematic Analysis Flow Chart

The four legs adopt the same structural design, so it is possible to configure the joints of the legs according to specified motion requirements. Currently, research on the joint configuration of quadruped robots includes: full knee, front knee back elbow, front elbow back knee, and full elbow. Due to the respective advantages and disadvantages of various joint configurations, their applicable environments vary. The joint configurations of the full knee and full elbow legs have the characteristics of uniform structure, facilitating joint control, Among them, the full knee pose has a wider range of motion space and can achieve strong dynamic stability during movement, so its application is more extensive; The front knee, back elbow, and front elbow, back knee leg joint configurations have a relatively large support area due to the large distance between the front and rear foot ends and the ground, so they have strong static stability. Based on the principles of bionics, most mammals use a full elbow joint configuration. Although its motion stability is still somewhat different from that of the front elbow back knee joint, it has strong controllability and environmental adaptability due to comprehensive consideration of motion stability and speed requirements.

Considering the simplicity and modifiability of structural modeling, this article uses SolidWorks software to design the structure of various parts of the body and legs of a bionic quadruped robot. Models are drawn in three-dimensional drawing software based on the actual dimensions of various accessories, and a virtual prototype of the designed bionic quadruped robot is simulated based on functional module planning and overall design requirements. The assembled three-dimensional model structure is shown in Figure 3 below:

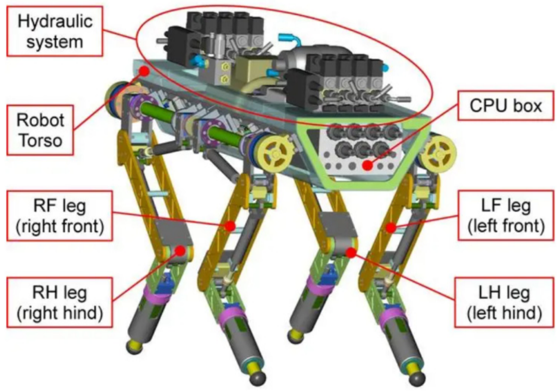

Figure 3: Three-dimensional model diagram of quadruped robot

The forward kinematics of the robot described above can calculate the foot end coordinate position based on the joint rotation angle. However, the actual robot motion control process is to calculate the joint angle control amount based on the planned foot end position coordinates, and set the joint drive according to the control method, thereby achieving the motion control effect for the robot and human. Therefore, in the process of motion control for quadruped robots, it is also necessary to solve the inverse kinematics of the foot ends. According to the definition, inverse kinematics is based on the trajectory equation of the foot end that has been planned, and information such as the posture of the foot end, the position coordinates relative to the fuselage, and the length of each link is known, and then the obtained posture positions are used to inverse deduce the variable values at each joint.

This article takes the left front leg as an example to solve the inverse kinematics of the foot end. The position coordinates of the foot end position coordinate system {4} in the fuselage coordinate system and the designed mechanical structure dimensions are known, and the joint rotation angles at the hip joint, shoulder joint, and knee joint are calculated. Taking a single leg as an example, in order to facilitate joint angle calculation, the base coordinate system to be solved is set as the temporary coordinate system {0} on the shoulder joint coordinate. The motion control of the quadruped robot leg is achieved based on joint angle control. The foot position coordinate system is solved based on the above positive motion:

$$P = [P_x \quad P_y \quad P_z] \tag{1}$$

To solve inverse kinematics, the rotation angle function of each joint can be obtained from the above formula, as shown below:

$$\begin{cases} \theta_1 = -\arctan\left(\frac{P_y}{P_x}\right) - \arctan\left(\frac{L_1}{\sqrt{P_y^2 + P_z^2 - L_1^2}}\right) \\ \theta_z = \arccos\left[\frac{L_z + (P_z^2 + P_z^2 + P_z^2 - L_z^2 - L_z^2 - L_z^2)/2L_z}{\sqrt{P_z^2 + P_z^2 + P_z^2 - L_z^2}}\right] - \arctan\left(\frac{}{\sqrt{P_z^2}}\right) \\ \theta_3 = -\arccos\left(\frac{P_x^2 + P_y^2 + P_z^2 - L_1^2 - L_2^2 - L_3^2}{2L_2L_3}\right) \end{cases} \quad (1)$$

4 RESULTS AND DISCUSSION

Conduct joint control simulation through Solidworks and Matlab/Simulink, associate the modeling system with the control system, simplify the calculation process of model building in the control system, and make the results of the simulation run directly observable. In the imported single leg model, parameter values such as coordinate system conversion calibration, gravity, fixed relationship, linkage, and joint rotation have been given in the system, so additional settings are not allowed. Based on this virtual prototype, a control module is built according to the above planning, and trajectory control and detection of parameters such as the angle and angular velocity of the moving joint are performed through the control, sensor, and detection modules in the Simulink toolbox, The control system shown in Figure 4 is mainly composed of a virtual prototype module, a control module, and a detection module.

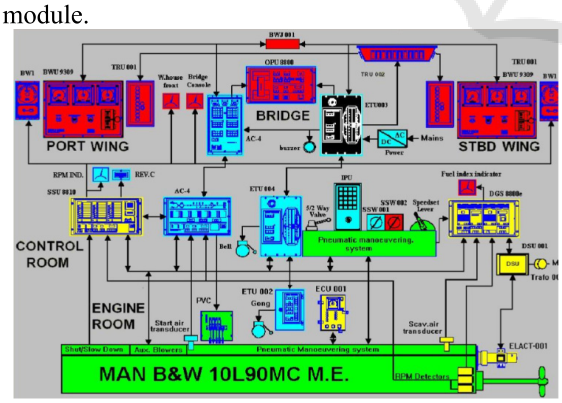

Figure 4: Single Leg Control System Diagram

From the above figure, it can be seen that the foot trajectory planning control is performed on the built single leg control model, and the model is built based on the improved trajectory described above. Inverse kinematics is used to solve the planned trajectory, calculate the joint rotation angle as the input variable of the virtual prototype rotational joint, drive the joint, set the sensor module to collect the angle and angular velocity changes of the rotational joint, and store the data, The feasibility of trajectory planning and motion control is demonstrated by analyzing the change curve.

The sensor detection device is set for the angle and angular velocity of the rotational joint. The change diagram of the rotation angle of the hip and knee joints under the foot end trajectory planning based on the improved trajectory is shown below. Figures 5 and 6 show the driving angle change diagram of the hip and knee joints. Within a motion cycle, the driving angle changes smoothly and does not produce angle mutations, verifying the rationality of trajectory planning.

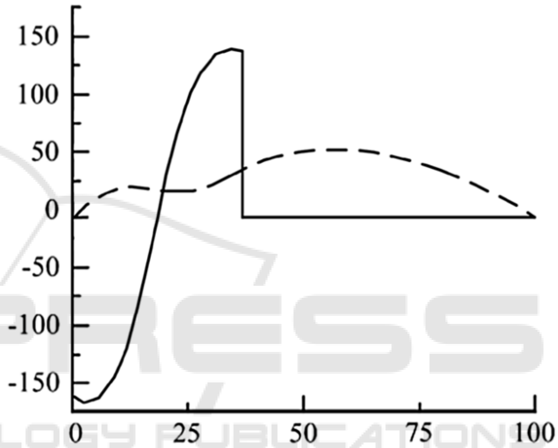

Figure 5: Hip joint drive angle

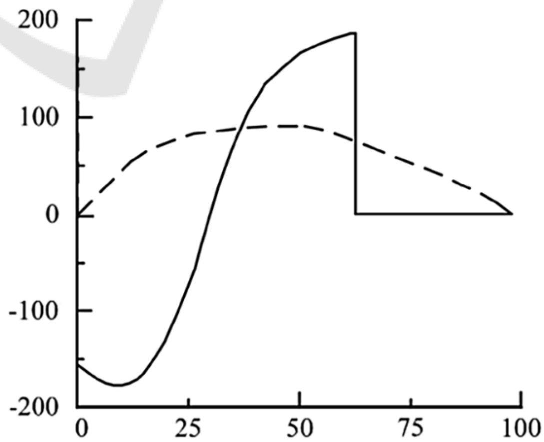

Figure 6: Knee drive angle

For comparison, the two motion modes use the same physical dimensions (see Table 1). The researchers considered the physical properties of the hind legs of 42 cheetahs, Acinonyx Jubatus. In order to evaluate the effectiveness of these two models, we used the kinematics and dynamics equations of the model to simulate running cheetahs, greyhounds, and bobcats (rotary galloping), as well as horses, antelopes, and alpacas (lateral galloping).

Table 1: Physical parameters of the model used

Parameter	MMS	SLIP
Stride length	2.152 m	1, .4834 m
Hopping height	0.31969 m	0.35304 m
Normal effort	16.1752 N .	0N
Tangential stress	- 76.0275 N	- 76.0275 N

According to the analysis of the two control experiments conducted on the physical prototype, it can be seen that the control strategy for the developed quadruped robot is feasible, and the prototype production has certain rationality. In Experiment 1, the quadruped robot has completed the in situ gait movement according to the diagonal gait law, and in Experiment 2, the walking gait experiment has been completed in a laboratory environment without external power supply, The experimental results show that the quadruped robot designed in this paper has a reasonable structure, and the drive and control modules are feasible. Based on the joint simulation theory of the entire machine, a motion control system is built, and the planned foot trajectory is verified using external power supplies and controllers. The experimental results show that the quadruped robot can basically complete the control movement of the planned gait according to design expectations.

5 CONCLUSIONS

Based on the work requirements of quadruped robots and the design concept of functional modular division, this paper completes the design of the overall mechanical system of quadruped robots, and uses Solidworks 3D software to establish a virtual prototype of quadruped robots. Improving the traditional compound cycloid and polynomial trajectory to complete foot end gait and trajectory planning. Simplify the control process, temporarily ignoring the lateral motion of the joint, and only analyzing the rotation of the hip and knee joints. Based on this, a single leg simulation model is established. Based on the principle of zero impact force, the composite cycloid and polynomial trajectory are optimized and analyzed. The composite cycloid is proposed as a fusion trajectory of the lateral trajectory and the octagonal polynomial as a vertical trajectory. This trajectory has transition segments to achieve smooth control of the joint drive function, and has good obstacle surmounting function. Build a control module to simulate the planned foot trajectory, and verify the rationality of gait planning using Simulink.

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