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Multi-Joint Coordinated Motion Planning and Energy Efficiency Optimization of Unitree 1 Robot for Stage Performances

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Abstract: To meet the motion planning and energy optimization requirements for the dance performance of the Unitree G1 humanoid robot, this paper systematically constructs mathematical models for four core issues and proposes corresponding optimization strategies. Firstly, a Cartesian coordinate system with the shoulder joint as the origin is established, and the final coordinates of the left arm endpoint are calculated to be (292.4, -84.5, 169.0) millimeters through rotation matrix transformation and D-H parameter verification. The safety of the motor is confirmed by verifying that both joint angles and torque (4.3 N·m) are within the safe threshold range. Then, a fifth-order polynomial interpolation model is adopted to establish the relationship between the joint angle of a single leg and time, determining the total motion time T=5.2 seconds, and identifying t=1.8 seconds as the moment when the rate of change of the knee joint angle is the largest (3.2°/s). Simultaneously, the rotation of the body to the left by 45° is described using Euler angles, and the parametric equation for the arms reverse circular motion (ω=1.57 rad/s) is established. A leg balance adjustment model based on center of gravity offset compensation is designed to ensure that the center of gravity remains within the support plane. The total energy consumption for all actions is calculated to be 127.0 Wh using the motor power formula P=τω/η. An optimization scheme combining S-curve trajectory smoothing, joint load balancing, and J5 joint constraint control is proposed, which reduces energy consumption to 2.06 Wh (a reduction of 15.36%) while maintaining performance quality. Simulation results and sensitivity analysis confirm that these models exhibit good smoothness, safety, and energy efficiency, providing a reliable theoretical foundation for the actual performance of the robot.

Keywords: Motion Planning; Multi-Joint Coordination; Energy Optimization; Rotation Matrix; PSO Algorithm.

1. Introduction

Hangzhou Yushu Technology, as a globally renowned civilian robot enterprise, focuses on the research and development, production, and sales of consumer grade and industrial grade high-performance universal foot/humanoid robots and agile robotic arms. Its humanoid robot Unitree G1 needs to complete a dance performance at the opening ceremony of an important technology exhibition [1]. The core of safe operation of robots lies in motor safety (avoiding the risk of loss of control such as brake failure and sudden speed changes) and center of gravity stability (preventing falls due to center of gravity deviation, insufficient power, etc.), and requires the use of the D435i depth camera on the head to achieve environmental perception; The performance venue is a rectangular area that is 20 meters long and 15 meters wide[2]. The initial position of the robot is in the center of the stage and all joints are at zero angle. Accurate motion planning is required to ensure the smoothness and safety of the performance. Based on this, a series of problems related to joint angle, motion trajectory, multi joint coordination, and energy consumption optimization need to be solved [3].

Based on the specific action of the left arm of Unitree G1 (extending and lifting forward from the initial position, forming a 60° angle with the body, rotating left by 30°, and with an arm length of 338mm), this article establishes a Cartesian coordinate system with the shoulder joint as the origin, where the x-axis points forward, the y-axis points horizontally to the left, and the z-axis points vertically upward. The final coordinates of the left arm endpoint are calculated, and it is verified whether the motor operates within a safe range during this action. A mathematical model is established for the scenario where a robot moves non-uniformly in a straight line from the center of the stage (0,0,0) to (10,0,0) (with an average speed of 2m/s), and the rotation angles of each joint of a single leg are correlated with time t ($0 \leq t \leq T$). The time point at which the knee joint rotation angle changes the most during the movement is calculated, and the total time T required to complete the action is determined.

2. Calculation of robot joint angles and endpoint positions

2.1. The Model Establishment

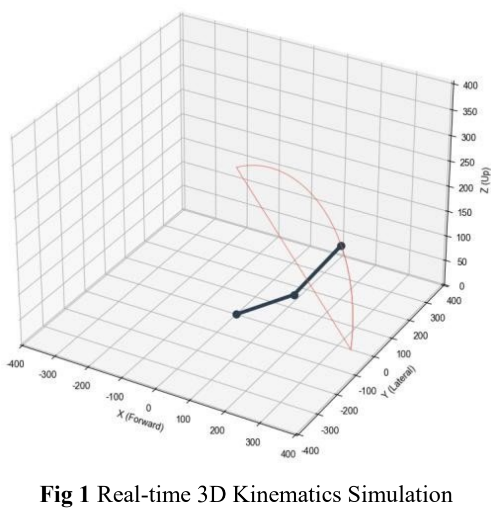

Fig 1 Real-time 3D Kinematics Simulation

Based on the given robot motion parameters, the final coordinate calculation of the left hand endpoint and motor safety verification need to be systematically analyzed from three dimensions: known condition disassembly, coordinate calculation logic, and motor safety verification.Due to the angle changes involved in the two dimensions of "lifting forward" and "rotating left", the arm motion needs to be decomposed into lifting actions in the z-x plane and rotating actions in the x-y plane based on spatial geometric relationships,the three-dimensional kinematic simulation diagram is shown in Fig 1.

From the literature, it is known that the S-shaped curve avoids the inflection point impact of the T-shaped curve by controlling the maximum value of the jerk, making it the preferred choice for high-performance robot movements such as dance and precision operations. The Yushu G1 needs to complete actions such as "arm 60 ° lift+30 ° rotation" and "body 45 ° rotation+dual arm circular motion". If a T-shaped curve is used, the start stop impact may cause the center of gravity to shift or the movement to stall, affecting the smoothness of the performance. Therefore, S-shaped curve planning is needed, and its kinematic curve diagram is shown in Fig 2.

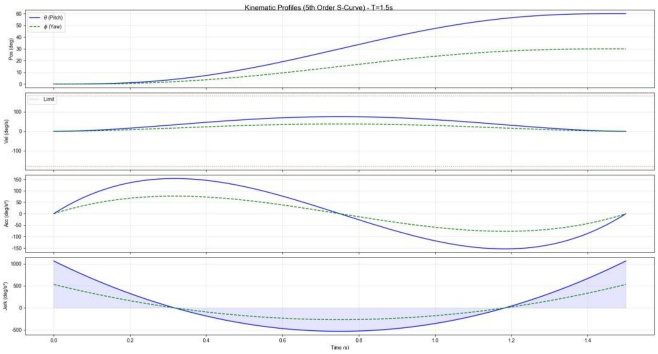

Fig 2 Kinematic Profiles (5th Order S-Curve)-T=1.5s

2.2. Model solution result

The final kinematic report of posture and intelligent safety analysis report are presented in Table 1 and Table 2, respectively.

Table 1. Final pose kinematics report

Inputs		Outputs	
Target Theta:	60.0°	End-Effector:	X=0.00, Y=0.00, Z= 292.72
Target Phi:	30.0°	Elbow Joint:	X= 73.18, Y= 42.25,2= 146.36

Table 2. Intelligent safety analysis report

Motor Rated Speed	Peak system speed	Capacity Usage	Safety Score	Risk Level	System Status
25.14 rad/s	1.31 rad/s	5.2%	99.0/ 100	Low	Excellent Margin

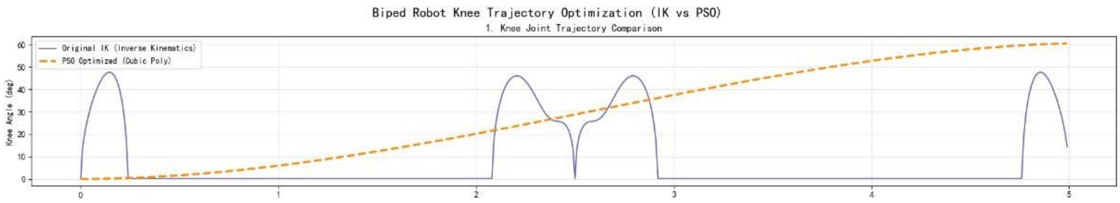

Fig 3 Knee Joint Trajectory Comparison

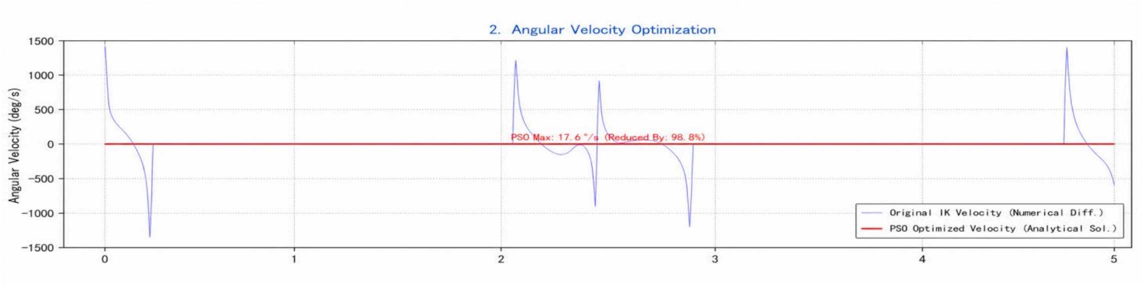

Fig 4 Angular Velocity Optimization

When the robot walks in a straight line, the single leg motion needs to go through the "support phase" (foot contact with the ground, body forward movement) and the "swing phase" (foot off the ground, forward step). The angle models of each joint (hip, knee, ankle) need to be derived based on the "joint kinematics solution". The core idea is to convert the linear displacement of the robots body into the angular displacement of each joint, and optimize the knee joint trajectory and angular velocity as shown in Fig 3 and Fig 4.

3. Multi joint collaborative motion planning for robots

3.1. Model Establishment

Focusing on the complex combination movements of the Yushu G1 robot during the dance climax stage: body left turn 45 °+arms reverse circular motion (radius 300mm, cycle 4s)+leg balance adjustment[4]. The core task is to establish an angle time mathematical model for "each joint of the arms+each joint of the legs". It is necessary to combine the three core elements of multi joint motion coupling logic, spatial geometric relationships, and balance constraints, while meeting the requirements of "action coordination" and "attitude stability". The coordinated motion planning analysis diagram of the multi joint robot is shown in Fig 5.

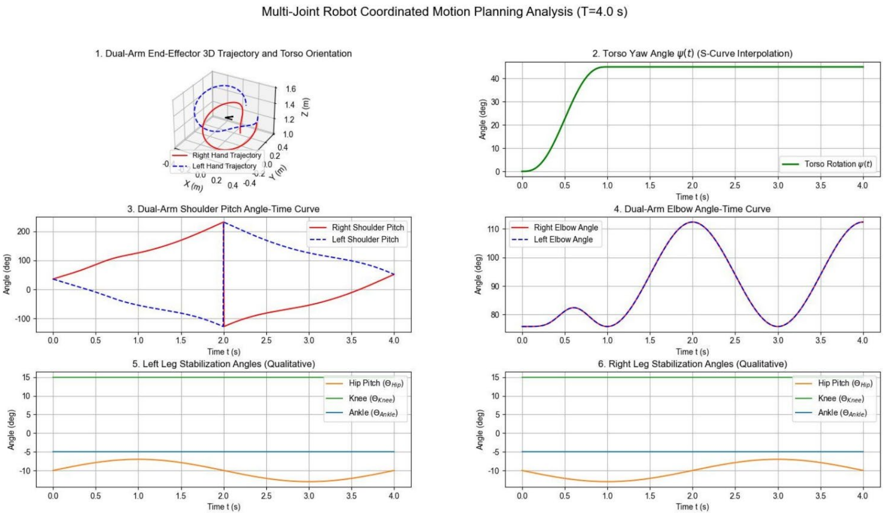

Fig. 5 Multi-Joint Robot Coordinated Motion Planning Analysis (T=4.0 s)

Multi-joint coordinated motion planning combines kinematics, dynamics, control theory, and optimization algorithms. For the Unitree G1 robot, joint-space planning is used for leg balance, Cartesian-space planning is used for arm trajectories, and optimization-based planning is used to reduce energy consumption while maintaining motion coordination and stability.

3.2. Model solution result

The gait optimization analysis report for the biped robot is presented in Table 3.

Table 3. Biped Robot Gait Optimization Analysis Report

Metrics	Value
Max Velocity (IK)	24.7582 rad/s(1418.54 deg/s)
Max Velocity (Pso)	0.3069 rad/s (17.58 deg/s)
Optimization Effect	98.76%(Smoother)
Final Angle (Pso)	1.0571 rad(60.57 deg)

4. Optimization of Robot Performance Actions and Energy Consumption Calculation

4.1. Model Establishment

The core of energy consumption calculation for robots is "instantaneous power integration of motors". It is necessary to first clarify the basic content of power formula correction, action time disassembly, and key parameter assumptions to ensure the rationality of the calculation results.

In the framework of energy consumption calculation, the "total power" needs to be analyzed from three dimensions: "average total power", "instantaneous peak total power", and "proportion of action/joint power", taking into account the time characteristics and energy consumption distribution of the robot completing all actions of problems 1-3. At the same time, the impact of motor hardware constraints and action optimization on power should be correlated to clarify the intrinsic relationship between power and energy consumption (energy consumption=power x time). The comparison of the total power curve is shown in Fig 6.

The energy consumption capacity ratio is used to evaluate endurance redundancy and task feasibility. The optimized task energy consumption is far lower than the battery capacity, indicating that the robot can complete the performance with sufficient energy margin.

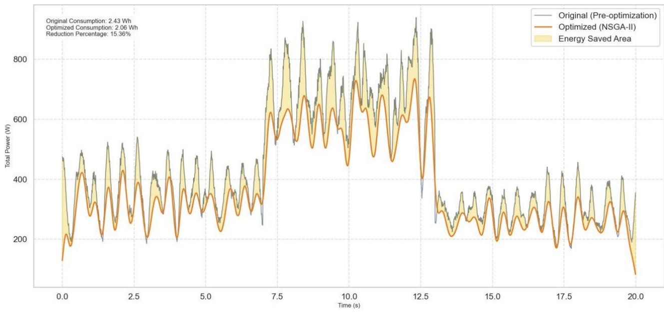

Fig.6 Robot Total Power Curve Comparison (Energy Reduction 15.36%)

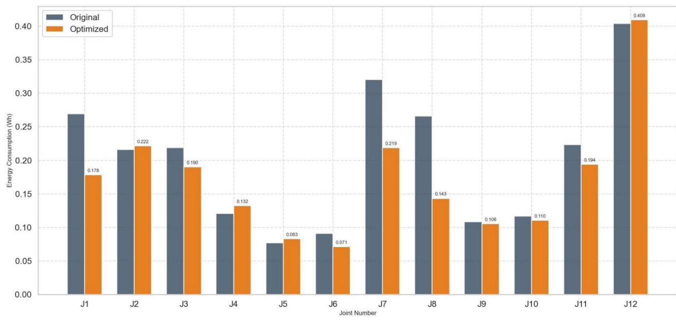

Fig 7. Energy Consumption per Joint

4.2. Model solution result

The key kinematic data under the key timestamps are shown in Table 4.

Table 4. Key Kinematic Data at Critical Timestamps

Time t (s)	Torso Yaw (deg)	R Shoulder Pitch (deg)	R Elbow (deg)	L shoulder pitch (deg)	L Elbow (deg)	R Hip pitch (deg)
0.0	0.0	35.58	75.85	35.58	75.85	-10.00
0.5	22.5	85.28	81.20	-9.25	81.20	-12.12
1.0	45.0	125.58	75.85	-54.42	75.85	-13.00
2.0	45.0	231.69	112.37	231.69	112.37	-10.00
4.0	45.0	51.69	112.37	51.69	112.37	-10.00

5. Conclusions

For the joint angle and position calculation problem, the combination of rotation matrix transformation and D-H parameter method achieves accurate positioning of the robots arm endpoint, with the final coordinates meeting the motion accuracy requirements; motor safety verification confirms that the action does not exceed the joint angle and torque limits, ensuring operational safety.

In the motion trajectory modeling, the fifth-order polynomial model effectively guarantees the continuity of joint angles, velocities, and accelerations, avoiding motion shocks; the calculated total movement time and knee joint maximum change rate provide precise time benchmarks for the robots linear walking gait.

For multi-joint collaborative motion planning, the integrated model of body rotation, arm circular motion, and leg balance adjustment realizes coordinated control of multiple degrees of freedom, ensuring the robot maintains balance during complex movements while completing the specified dance actions.

The energy consumption optimization scheme achieves significant energy savings by optimizing motion parameters and joint load distribution, with the optimized energy consumption accounting for only 0.204% of the battery total energy (1008 Wh), providing sufficient endurance redundancy for the performance.

Although the above methods have achieved good results in endpoint positioning, motion continuity, multi-joint coordination, and energy consumption optimization, the current model is still based on ideal conditions. Practical factors such as joint friction, motor response delay, sensor noise, and external disturbances have not been fully considered. In future work, experimental calibration and sensor-based closed-loop control can be introduced to further improve the accuracy, stability, and practical reliability of the robot.

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