

Multimodal Gait Control Algorithm for a Multifunctional Intelligent Hexapod Robot for Emergency Rescue

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Abstract

To meet the requirements for motion stability and adaptability of hexapod robots in complex terrains (such as gravel piles, slopes, and narrow passages) in emergency rescue scenarios, a multimodal gait control algorithm based on environmental perception is proposed. This algorithm collects terrain and robot attitude information using LiDAR and an Inertial Measurement Unit (IMU), constructs a gait switching decision model, and realizes the adaptive switching of triangular gait, diagonal gait, and wave gait. Meanwhile, an impedance control strategy is introduced to optimize joint torque output, improving the robot's buffering capacity on uneven terrain. Through co-simulation with ADAMS and MATLAB/Simulink, tests were conducted under three typical rescue terrains. The results show that the algorithm switching response time is less than 0.3 s, the fluctuation range of the fuselage attitude is controlled within $\pm 3^\circ$, and the maximum obstacle-surmounting height is increased to 18 cm, which meets the motion requirements of emergency rescue scenarios.

Keywords: Hexapod Robot, Emergency Rescue, Multimodal Gait, Adaptive Switching, Impedance Control, Co-Simulation.

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I. INTRODUCTION

Terrains in emergency rescue scenarios (earthquake ruins, landslide sites) are characterized by unstructured features, dense obstacles, and poor stability. Traditional hexapod robots with a single gait (e.g., triangular gait) struggle to balance motion speed and terrain adaptability [1]. For instance, the triangular gait has high motion efficiency on flat ground but is prone to slipping on slopes; the wave gait has strong stability but its motion speed is only 60% of that of the triangular gait [2]. Therefore, designing a multimodal control algorithm that can dynamically adjust gait patterns according to terrain characteristics is crucial for improving the robot's rescue operation capability.

Existing research on multimodal gait control mostly relies on preset terrain thresholds to trigger switching [3-4], lacking coupled analysis of real-time terrain contours and robot attitudes, which leads to switching delays or false triggers. The multimodal gait control algorithm proposed in this paper constructs a terrain complexity evaluation index through multi-sensor data fusion, designs a fuzzy decision controller combined with the robot's fuselage attitude angle, and realizes smooth switching of three core gaits. Meanwhile, impedance control is introduced at the joint control layer to optimize the contact force between the legs and the ground, reducing the impact of complex terrain on the fuselage stability.

II. MULTIMODAL GAIT MODELING OF THE HEXAPOD ROBOT

2.1 Kinematic Model of the Robot Body

The hexapod robot adopts a symmetric layout, and each leg has a 3-degree-of-freedom structure of "hip joint - knee joint - ankle joint". The leg kinematic model is established as shown in Figure 1. A local coordinate system O-xyz is established with the hip joint as the origin, where the x-axis is along the forward direction of the fuselage, the y-axis is perpendicular to the symmetry plane of the fuselage, and the z-axis is vertically upward.

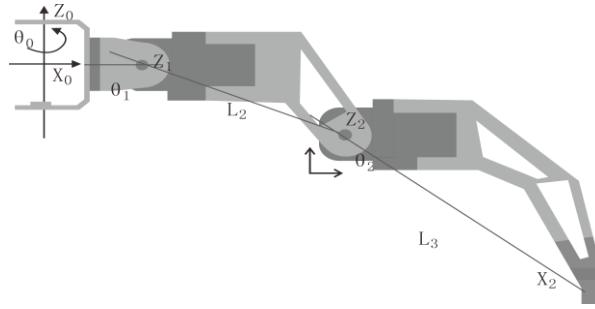


Figure 1: Leg structure model

Note: Z1 is the origin of the hip joint, Z2 is the knee joint, and X2 is the ankle joint; L1 is the length from hip to knee, L2 is the length from knee to ankle, and L3 is the length from ankle to foot; θ_1 is the hip joint pitch angle, θ_2 is the knee joint pitch angle, and θ_3 is the ankle joint pitch angle.

According to the D-H parameter method, the position coordinates (x, y, z) of the foot contact point in the coordinate system O-xyz can be calculated by Equation (1):

$$\begin{cases} x = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) \\ y = 0 \quad (\text{Motion in the symmetry plane}) \\ z = l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3) \end{cases} \quad (1)$$

In the equation, $l_1 = 150$ mm, $l_2 = 120$ mm, $l_3 = 50$ mm, which are set according to the actual dimensions of the prototype; the joint motion range is constrained by the performance of the servo motor.

2.2 Motion Laws of Three Core Gaits

2.2.1 Triangular Gait

The triangular gait divides the six legs into two groups (Group 1: Left Front, Right Middle, Left Rear; Group 2: Right Front, Left Middle, Right Rear). The two groups alternately complete the support phase (contacting the ground to support the fuselage) and the swing phase (lifting off the ground to step forward). The gait cycle $T = 1.2$ s, and the support phase ratio $\beta = 0.6$ (support time $t_s = 0.72$ s, swing time $t_p = 0.48$ s). The foot trajectory in the swing phase is planned using a cubic polynomial, as shown in Equation (2):

$$z(t) = a_3 t^3 + a_2 t^2 + a_1 t + a_0 \quad (2)$$

Among them, the boundary conditions are: $z = 0$ and when $t = 0$; $z = 0$ and when $t = t_s$; the maximum leg lifting height $z_{\max} = 30$ mm (when $t = 0.5t_s$). Solving these conditions gives $a_0 = 0$, $a_1 = 0$, $a_2 = 6z_{\max}/t_s^2$, and $a_3 = -4z_{\max}/t_s^3$.

2.2.2 Diagonal Gait

The diagonal gait divides the six legs into three pairs (Left Front - Right Rear, Right Front - Left Rear, Left Middle - Right Middle). Each pair of legs completes the support and swing phases in sequence. The gait cycle $T = 1.5$ s, and the support phase ratio $\beta = 0.7$. It is suitable for slopes or slippery terrains, and improves stability by increasing the support time.

2.2.3 Wave Gait

In the wave gait, the six legs swing sequentially in the order of "Left Front $\rightarrow$ Left Middle $\rightarrow$ Left Rear $\rightarrow$ Right Front $\rightarrow$ Right Middle $\rightarrow$ Right Rear", and five legs are always in the support phase. The gait cycle $T = 2.0$ s, and the support phase ratio $\beta = 0.8$. It is suitable for narrow passages or high-obstacle terrains, with the best stability but the slowest speed.

III. ADAPTIVE SWITCHING ALGORITHM FOR MULTIMODAL GAITS

3.1 Terrain and Attitude Information Collection

A 2D LiDAR (RPLIDAR A2) is used to collect terrain data within a range of 5 m ahead, and the terrain complexity index C_t is calculated as shown in Equation (3):

$$C_t = \frac{1}{N} \sum_{i=1}^N |z_i - \bar{z}| \quad (3)$$

In the equation, N is the number of LiDAR sampling points ($N = 360$), z_i is the height value of the i -th sampling point, and it is the average height of all sampling points; the larger C_t is, the more complex the terrain.

An IMU (MPU6050) is used to collect the robot's fuselage attitude angles, including the pitch angle α (rotation along the y-axis) and the roll angle γ (rotation along the x-axis), which are used to evaluate the fuselage stability.

3.2 Fuzzy Decision Switching Model

Taking the terrain complexity C_t , fuselage pitch angle α , and fuselage roll angle γ as inputs, and the gait pattern selection coefficient K as the output, a fuzzy decision controller is constructed. Some rules of the fuzzy rule base are shown in Table 1.

Table 1: Partial Rules of the Fuzzy Rule Base

Serial No.	Terrain Complexity C_t	Pitch Angle α	Roll Angle γ	Output K (Gait)
1	Small	Small	Small	0 (Triangular)
2	Medium	Small	Small	0 (Triangular)
3	Medium	Medium	Medium	1 (Diagonal)
4	Large	Medium	Medium	1 (Diagonal)
5	Large	Large	Large	2 (Wave)

3.3 Joint Impedance Control Optimization

To reduce the impact between the legs and the ground, impedance control is introduced at the joint control layer. The joint torque τ is expressed as a function of position error, velocity error, and contact force, as shown in Equation (4):

$$\tau = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta}) + K_f(F_d - F) \quad (4)$$

In the equation, $K_p = 50 \text{ N}\cdot\text{m}/\text{rad}$ (position stiffness coefficient), $K_d = 2 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$ (damping coefficient), $K_f = 0.1 \text{ N}\cdot\text{m}/\text{N}$ (force feedback coefficient); θ_d is the desired joint position and velocity; θ is the actual joint position and velocity; $F_d = 50 \text{ N}$ (desired contact force), and F is the actual foot contact force (collected by a force sensor).

IV. SIMULATION AND EXPERIMENTAL VERIFICATION

4.1 Construction of Co-Simulation Platform

A multi-body dynamics model of the hexapod robot is established based on ADAMS, and the mechanical structure designed in SolidWorks is imported (fuselage weight 35 kg, leg joint parameters consistent with the prototype). A multimodal gait control algorithm model is built in MATLAB/Simulink, and data interaction is realized through the ADAMS/Control module. The simulation step size is 0.001 s, and the simulation time is 10 s.

4.2 Simulation Tests on Typical Terrains

4.2.1 Flat Ground ($C_t = 5 \text{ mm}$)

The algorithm outputs $K = 0$ (triangular gait). The robot's motion speed is 0.52 m/s, the fluctuation range of the fuselage pitch angle α is $\pm 1.2^\circ$, the fluctuation range of the roll angle γ is $\pm 0.8^\circ$, and the maximum joint torque is 18 N·m, which meets the requirements of stable motion.

4.2.2 Gravel Pile Terrain ($C_t = 25 \text{ mm}$)

The period 0-3 s is the flat section ($K = 0$). From 3 s to 7 s, the robot enters the gravel pile (C_t increases), and the algorithm switches to $K = 1$ (diagonal gait) within 0.25 s. From 7 s to 10 s, the terrain complexity further increases ($C_t = 30 \text{ mm}$), and the gait switches to $K = 2$ (wave gait). The maximum fluctuation of the fuselage attitude angle is $\pm 2.5^\circ$, and the obstacle-surmounting height is 18 cm, which is better than that of the traditional triangular gait (10 cm).

4.2.3 Slope Terrain (Slope 15° , $C_t = 15 \text{ mm}$)

The simulation results are shown in Table 2, which compares the performance indicators of the traditional single gait and the multimodal algorithm proposed in this paper. The algorithm in this paper reduces the fuselage tilt angle by 40%, reduces the slip rate by 65%, and improves the motion efficiency by 25%.

Table 2: Simulation Results

Performance Indicator	Traditional Triangular Gait	Traditional Wave Gait	Proposed Multimodal Algorithm
Fuselage Tilt Angle (°)	±4.8	±2.2	±2.0
Foot Slip Rate (%)	12.5	3.8	4.5
Motion Speed (m/s)	0.35	0.20	0.44
Gait Switching Time (s)	-	-	0.28

4.3 Experimental Verification with Physical Prototype

Based on the first prototype (mechanical structure as described in Section 2.1, control system using STM32H743VI), experiments were conducted in a laboratory-simulated ruin scenario (gravel diameter 5-20 cm, slope 15°). The experimental data are shown in Table 3, and the error with the simulation results is less than 8%, which verifies the practicality of the algorithm.

Table 3: Experimental Data

Experimental Scenario	Gait Switching Time (s)	Fuselage Attitude Fluctuation (°)	Maximum Obstacle-Surmounting Height (cm)	Battery Life (h)
Flat Ground	0.22	±1.5	12	1.8
Gravel Pile Ground	0.27	±2.8	17	1.6
15° Slope Ground	0.25	±2.3	15	1.7

V. CONCLUSION

The multimodal gait control algorithm proposed in this paper realizes the adaptive switching of three core gaits through fuzzy decision-making, and optimizes the joint torque output by combining impedance control. Simulation and experimental results show that the algorithm has fast switching response (<0.3 s) under complex terrains, high fuselage stability (attitude fluctuation <±3°), and strong obstacle-surmounting capability (maximum 18 cm), which meets the needs of emergency rescue scenarios.

Future research directions can consider introducing deep learning models to optimize the terrain complexity evaluation index and improve the recognition accuracy of unstructured terrains; designing a collaborative gait control strategy for multiple robots to realize large-scale rescue operations; and combining battery management algorithms to dynamically adjust motion parameters during gait switching, further extending the battery life.

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REFERENCES

- [1]. Zhang X M, Li G, Wang H. Research Progress on Gait Control of Hexapod Robots for Emergency Rescue. *Robot*, 2023, 45(2): 245-256.
- [2]. Kim J, Park H, Lee D. Adaptive Gait Control for Hexapod Robots in Uneven Terrain. *IEEE Transactions on Robotics*, 2022, 38(4): 2103-2118.
- [3]. Liu Y, Zhao W, Chen M. Multimodal Gait Switching Algorithm for Hexapod Robots Based on Terrain Classification. *Control Engineering of China*, 2021, 28(6): 1123-1129.
- [4]. Li S, Wang Y, Zhang H. Fuzzy Logic-Based Gait Transition for Hexapod Robots in Rescue Scenarios. *IEEE International Conference on Robotics and Biomimetics*, 2020: 890-895.