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Fuzzy Adaptive Admittance Control of Hexapod Wheeled-Legged Robot Based on Real-Time Estimation

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Abstract: A fuzzy adaptive admittance control method based on real-time estimation is proposed for the motion of the hexapod wheeled-legged robot in various environments. Firstly, the mechanical structure of the robot is designed, and a control system framework is proposed according to the different motion environments. To address the adaptability issue of the robot foot contact with the ground, a position-based admittance control method is proposed. Secondly, to improve the tracking performance of the robot foot contact force when the ground environment changes, a fuzzy adaptive admittance parameter adjustment method is proposed. Furthermore, to address the problem of sudden changes in the tracking difference of the foot contact force when the ground environment changes, a real-time estimation method is proposed to estimate the dynamic foot contact force. Finally, a simulation experiment is conducted in MATLAB and Simscape to verify the effectiveness of the robot motion control system, admittance control, fuzzy adaptive admittance parameters adjustment, and the real-time estimation method. Through multi-scenario experiments with the robot prototype, the control method demonstrates its effectiveness and adaptability in various environments.

Keywords: hexapod wheeled-legged robot; dynamic foot contact force; fuzzy adaptive; real-time estimation; admittance control

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0 Introduction

The hexapod wheeled-legged robot is a typical combination of wheeled and legged mechanisms in multi-legged robots. It utilizes a wheeled mechanism on flat terrain to achieve rapid motion and employs a wheel-legged composite structure on complex terrain to quickly and stably perform a variety of complex motions, such as obstacle crossing, slope climbing, and ditch crossing[1]. During the actual motion process, when the robot encounters obstacles or changes in the ground environment, it may face the problem of relatively large rigid impacts between the robot foot and the ground, resulting in motion instability and joint deformation[2]. Therefore, it is necessary to endow the robot with ground adaptability.

Admittance control[3] improves the adaptability of the robot to the ground environment through force or position feedback. By mimicking the flexibility and adaptability of an object, admittance control enables the robot to exhibit characteristics similar to spring damping when it contacts the ground, allowing the robot to dynamically adjust its motion trajectory in response to changes in the ground environment. Admittance control can adjust the motion trajectory of the leg based on the tracking difference of the foot contact force, which effectively reduces the rigid impact force, addresses the issue of motion adaptability to complex terrain, and ensures motion stability.

Admittance control is widely used in robotics, including robotic arms and medical robots, to improve their adaptability and operational accuracy. Irawan et al.[4] optimized the compliant motion of robots on complex terrain by adjusting the expected contact force of the feet controlled by admittance on the robot's six legs. Sharifi et al.[5] explored four nonlinear model reference adaptive admittance controllers to achieve the desired flexibility characteristics of the robot admittance model. Kim et al.[6] introduced an energy constraint method into admittance control to enhance the robustness of environmental interaction. Adaptive admittance control methods[7-12] were proposed to enhance the adaptability of robots to changing working environments. Lee et al.[11] proposed a time-dependent genetic method to optimize the parameters of admittance control, enabling the quadruped robot to move stably over irregular terrain. Zhang[12] proposed a position-mode-based admittance control and a ground stiffness identification method based on constrained memory least squares to optimize the performance of admittance control, achieving leg compliance in a quadruped robot during motion. In summary, admittance control has significant advantages in improving the compliance and adaptability of robots when interacting

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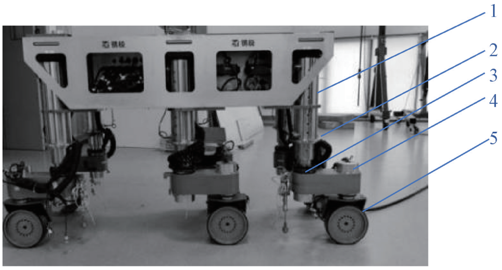
with external environments.

Focusing on the real-time tracking of the foot contact force when the robot encounters environmental changes, we propose a fuzzy adaptive admittance control method. It estimates the dynamic contact forces at the foot in real time and adjusts the admittance parameters of the robot leg to enhance the control system's effectiveness. Aiming at the motion of the hexapod wheeled-legged robot in various environments, a fuzzy adaptive admittance control method based on real-time estimation is proposed. Firstly, the mechanical structure of the robot is designed, and the control system framework is proposed according to the different motion environments. The principle of the position-based admittance control method is analyzed. Secondly, to adapt to the changes in the motion environment and improve the poor tracking effect of foot contact force, a method for adjusting admittance parameters based on fuzzy adaptive control is proposed. Additionally, a real-time estimation method for dynamic foot contact force is proposed to address the problem of sudden changes in the tracking difference of the foot contact force when the ground environment changes. Finally, the control system of the robot is built in MATLAB and Simscape for simulation and experimental verification.

1 Mechanical Structure and Control System of Hexapod Wheeled-Legged Robot

1.1 Robot structural design

The prototype of the hexapod wheeled-legged robot is shown in Fig. 1. It consists of a main body and leg structure with a total of 24 degrees of freedom. To simplify the leg structure, each leg is designed to include a thigh, a thigh joint, a knee joint, a lower leg, and a walking wheel.



1—thigh; 2—thigh joint; 3—knee joint; 4—lower leg; 5—walking wheel.

Fig. 1 Hexapod wheeled-legged robot prototype

The thigh joints and knee joints are equipped with multi-stage servo motors and reducers for precise position control. A gyroscope is mounted at the center of gravity to obtain the robot's angular velocity and attitude angle information. To mitigate the damage caused by impact forces on the mechanical structure and to increase the friction between the foot and the ground, rubber is used for the foot ends of the walking wheels, and pressure sensors are also installed. The mechanical legs of the robot are symmetrically distributed on both sides of the main body, balancing the unevenly applied forces. Aluminum alloy is selected to reduce the inertial forces generated during the robot's motion. The specific structural parameters are shown in Table 1.

Table 1 Structural parameters of hexapod wheeled-legged robot

Parameter	Value	Parameter	Value
Length of thigh/mm	448	Height of main body/mm	18
Length of knee and lower leg/mm	205	Length of main body/mm	1 368
Length of lower leg/mm	189	Width of main body/mm	668
Radius of walking wheel/mm	100	Mass of robot/kg	213

1.2 Motion control system for robot-environment interaction

The ground environment for robot motion is illustrated in Fig. 2. When encountering obstacles or changes in the ground environment, it is necessary to address the issue of motion adaptability between the robot's foot and the ground. Consequently, an admittance control system based on environmental interaction is proposed to ensure the robot's stable motion.

The framework of the robot control system is depicted in Fig. 3, where position control serves as the core component. It governs the robot's motion according to a predefined trajectory and makes dynamic adjustments based on the real-time feedback of the displacement. When encountering ground obstacles, the foot contact force f_e undergoes significant changes. The admittance controller translates the tracking difference of the foot contact force into the displacement x_e, ensuring the robot's smooth passage over the obstacles.

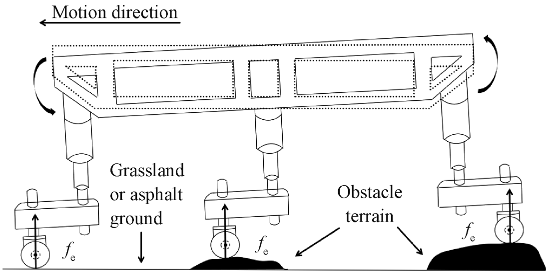


Fig. 2 Hexapod wheeled-legged robot motion on uneven terrain

When changes occur in the ground environment, the fuzzy adaptive control method generates control signals based on variations in environmental contact stiffness and the damping coefficient, adjusting the admittance parameters accordingly. Concurrently, the real-time estimation method, in conjunction with environmental parameters and the robot displacement feedback, estimates the dynamic foot contact force. It further refines the control strategy, enhances the tracking performance of the foot contact force, and ensures the robot's stable motion across diverse environments.

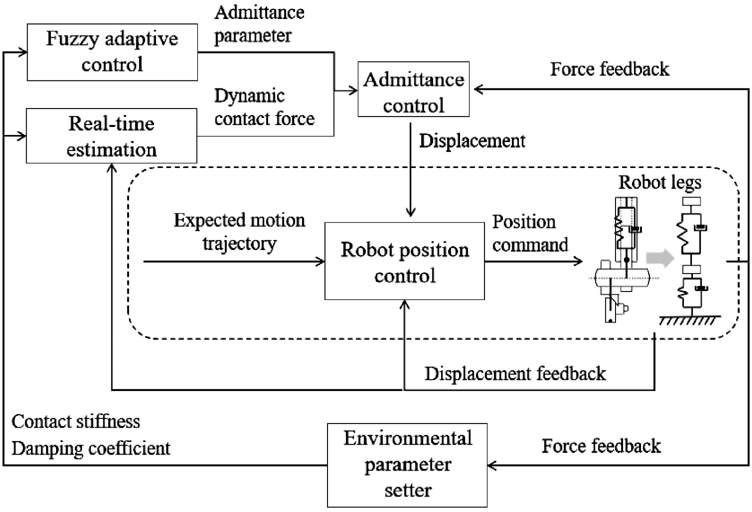


Fig. 3 Robot control system framework

1.3 Position-based admittance control method

The position-based admittance control method converts the difference in the foot contact force tracking into the robot leg displacement. Position control then adjusts the robot leg motion trajectory based on this displacement to reduce the rigid impact force and ensure stable motion. The principle of admittance control is illustrated in Fig. 4. x_e is the actual position; s represents the Laplacian operator; m_d, b_d, and k_d denote the inertia, damping, and stiffness parameters in the admittance model, respectively. These parameters, in turn, represent the system's response to the changes in acceleration, velocity, and position. They are collectively referred to as admittance parameters.

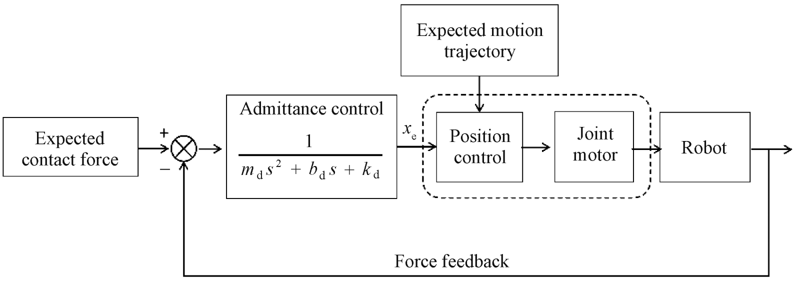


Fig. 4 Admittance control principle

When the robot foot is in contact with the ground, only the thigh joint moves along the leg direction. To simplify the force analysis, the foot contact force is equivalent to the force in the thigh direction. Therefore, the admittance control model along the leg direction is designed as shown in Fig. 5. m_g, b_g, and k_g represent the inertia, damping, and stiffness parameters in the contact model, respectively; f_d is the expected foot contact force; P_r is the position reference point of the thigh joint.

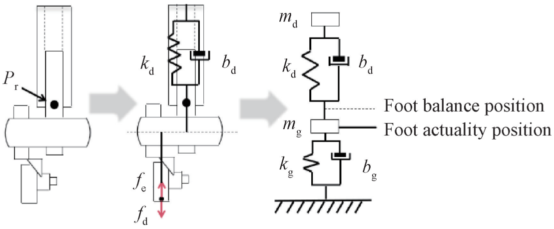


Fig. 5 Single-leg admittance model and ground environment contact model

The position-based admittance model is expressed as

$$f_{\mathrm{d}} - f_{\mathrm{e}} = e_f = m_{\mathrm{d}}(\ddot{x}_{\mathrm{d}} - \ddot{x}_{\mathrm{c}}) + b_{\mathrm{d}}(\dot{x}_{\mathrm{d}} - \dot{x}_{\mathrm{c}}) + k_{\mathrm{d}}(x_{\mathrm{d}} - x_{\mathrm{c}}), \quad (1)$$

where e_f is the difference between the expected foot contact force and the actual foot contact force. x_{d}, $\dot{x}_{\mathrm{d}}$, and $\ddot{x}_{\mathrm{d}}$ represent the expected position, speed, and acceleration generated by the robot according to motion gait, respectively; $\dot{x}_{\mathrm{c}}$ and $\ddot{x}_{\mathrm{c}}$ represent the speed and acceleration, respectively.

2 Fuzzy Adaptive Admittance Control Method Based on Real-Time Estimation

2.1 Fuzzy adaptive adjustment of robot leg admittance parameters

To adapt to changes in the robot motion environment and improve the poor tracking effect of the robot foot contact force, a systematic relationship between the admittance model and the ground environment is established, and a fuzzy adaptive control method is designed to adjust the admittance parameters of the leg in real time according to the ground environmental parameters.

2.1.1 System model of admittance and ground environment

The contact model is equivalent to a spring-damping-mass system, as shown in Fig. 5. The formula for this model is

$$f_{\mathrm{e}} = m_{\mathrm{g}}(\ddot{x}_{\mathrm{e}} - \ddot{x}_{\mathrm{c}}) + b_{\mathrm{g}}(\dot{x}_{\mathrm{e}} - \dot{x}_{\mathrm{c}}) + k_{\mathrm{g}}(x_{\mathrm{e}} - x_{\mathrm{c}}). \quad (2)$$

The process from foot-ground contact to steady state can be modeled as the step response of an equivalent system. In this model, the input is a step force $F_{\mathrm{d}}(s)$ applied in the direction of the thigh, and the output is the actual foot contact force $F_{\mathrm{e}}(s)$. The inertia generated by the foot mass is much smaller than that of the body and leg masses. To simplify the system model, the influence of the foot acceleration on the overall system model is ignored. The overall system model is expressed as

$$\frac{F_{\mathrm{e}}(s)}{F_{\mathrm{d}}(s)} = \frac{b_{\mathrm{d}}b_{\mathrm{g}}s^2 + (b_{\mathrm{g}}k_{\mathrm{d}} + b_{\mathrm{d}}k_{\mathrm{g}})s + k_{\mathrm{d}}k_{\mathrm{g}}}{m_{\mathrm{d}}(b_{\mathrm{d}} + b_{\mathrm{g}})s^3 + [m_{\mathrm{d}}(k_{\mathrm{d}} + k_{\mathrm{g}}) + b_{\mathrm{d}}b_{\mathrm{g}}]s^2 + (b_{\mathrm{g}}k_{\mathrm{d}} + b_{\mathrm{d}}k_{\mathrm{g}})s + k_{\mathrm{d}}k_{\mathrm{g}}}. \quad (3)$$

The admittance parameters of the robot leg can only be estimated, and it is difficult to obtain accurate values. Therefore, a fuzzy adaptive control method is proposed to adjust the admittance parameters in real time according to the changes in the ground environment.

2.1.2 Fuzzy adaptive control method

The fuzzy adaptive control method is designed by using the MATLAB toolbox, and the robot motion environment is set to either grassland ground or asphalt ground. The mathematical expressions for the ground contact stiffness and the damping coefficient in the fuzzy adaptive control method are expressed as

$$\begin{cases} K = E \times A/L, \\ C = \alpha \times \sqrt{KM}, \end{cases} \quad (4)$$

where K represents the ground contact stiffness; C represents the ground contact damping coefficient; E represents the elastic modulus of the ground; A represents the contact area; L represents the effective depth; α is an empirical coefficient estimated based on the type of the ground and experimental data; M represents the equivalent ground mass.

The ground parameters of robot motion environment are obtained through experimental testing and theoretical calculation[13-14], as shown in Table 2.

Table 2 Ground parameters of robot motion environment

Ground	K/(N/mm)	C/(N·s/mm)
Grassland 1	180	6
Grassland 2	300	9
Asphalt ground	16 400	30

Based on the data, the range of K is set to [100, 20 000], and the range of C is set to [0, 60]. According to the dynamic response characteristics of the admittance control model, these parameters include a fast rise time, an adjustment time, a small overshoot, and a shock. The range of the robot leg admittance parameter b_{d} is designed to be [100, 500]. The range of k_{d} is designed to be [0, 60 000]. The range of m_{d} is determined by the robot's mass. The Gaussian function curve is used as the function curve for both input and output. The fuzzy subset of output k_{d} is set to [NL, NM, NS, ZO, PS, PM, PL], with NL, NM, NS, ZO, PS, PM, and PL representing negative large, negative medium, negative small, zero, positive small, positive medium, and positive large, respectively. The fuzzy subset of input K, C and output b_{d} is set to [NL, ZO, PL].

The response characteristics of the system model include a small overshoot and a fast response speed, which lead to a fuzzy control law. When K increases and C decreases, k_{d} increases. When K increases and C increases, b_{d} increases. Additionally, the fuzzy control law needs to be adjusted according to the actual control system. A set of feasible fuzzy control laws has been obtained, as shown in Table 3.

Table 3 Fuzzy control laws for different contact stiffness and damping coefficient

K	C	$k_{\mathrm{d}}/b_{\mathrm{d}}$	K	C	$k_{\mathrm{d}}/b_{\mathrm{d}}$
NL	NL	ZO/NL	ZO	PL	NS/PL
NL	ZO	NS/NL	PL	NL	PL/PL
NL	PL	NL/PL	PL	ZO	PL/PL
ZO	NL	PS/ZO	PL	PL	PS/PL
ZO	ZO	ZO/ZO			

2.2 Real-time estimation of dynamic foot contact force based on environmental interaction

When the ground environment changes, the actual robot foot contact force changes, resulting in a sudden change in the force tracking difference. Therefore, based on environmental parameters, the actual force and position, a real-time estimation method for the dynamic foot contact force is proposed. The force tracking error is analyzed by the admittance control model to establish the relationship between the robot's foot balance position and the environmental contact stiffness. Combined with the real-time estimation method, the real-time estimation equation for the dynamic foot contact force is established.

2.2.1 Foot contact force tracking error analysis in admittance control

To simplify the analysis model, the ground environment model is assumed to be a pure stiffness model. The force tracking error obtained from the admittance model in Eq. (1) can be expressed as

$$\begin{aligned} e_f = {} & m_d[\ddot{x}_d - \ddot{x}_e + (\ddot{f}_d - \ddot{e}_f)/k_g] + \\ & b_d[\dot{x}_d - \dot{x}_e + (\dot{f}_d - \dot{e}_f)/k_g] + \\ & k_d[x_d - x_e + (f_d - e_f)/k_g]. \end{aligned} \tag{5}$$

Supposing that the balance position $x_e(t)$ of the foot and the dynamic contact force $f_d(t)$ exhibit a step change, then $x_e(s) = x_e/s$ and $f_d(s) = f_d/s$. x_e and f_d are unknown constants. Equation (5) is transformed by the Laplace transform, and the result is obtained by applying the final value theorem:

$$e_{ss} = \lim_{s \to 0} s e_f(s) = \frac{k_d[k_g(x_d - x_e) + f_d]}{k_d + k_g}. \tag{6}$$

As can be seen from Eq. (6), the steady-state error of force tracking in the admittance model is not only related to the environmental contact stiffness k_g and the admittance parameter k_d, but also affected by the expected motion trajectory x_d. To ensure that the steady-state error of force tracking in the admittance model is close to zero, it is necessary to ensure that

$$x_d = x_e - f_d/k_g. \tag{7}$$

The foot balance position x_e cannot be measured during robot motion. Therefore, a real-time estimation method is proposed to estimate the contact stiffness and foot balance position in the ground environment in real time. This allows for the robot's dynamic foot contact force to be obtained when the ground environment changes.

2.2.2 Real-time estimation method of dynamic foot contact force

The real-time estimation method utilizes ground environment parameters to update the prediction of the foot balance position and environmental contact stiffness in real time. It then obtains the dynamic robot foot contact force. The estimates of the environmental contact stiffness k_g, foot balance position x_e, and foot contact force f_e are set as $\hat{k}_g$, $\hat{x}_e$ and $\hat{f}_e$. The intermediate variables are defined as

$$\boldsymbol{\phi} = \begin{bmatrix} \hat{k}_g - k_g \\ \hat{k}_g \hat{x}_e - k_g x_e \end{bmatrix}. \tag{8}$$

Based on the prediction error $\hat{f}_e - f_e$, a control strategy is designed to dynamically adjust $\hat{k}_g$ and $\hat{x}_e$. When $t \to \infty$ $\hat{f}_e \to f_e$ is obtained. Therefore, when $\hat{f}_e = f_e$, substituting the admittance model from Eq. (1) to eliminate $x_d - x_c$ yields

$$m_d \ddot{e} + b_d \dot{e} + (k_d + \hat{k}_g) e = 0, \tag{9}$$

where $e = f_d - f_e$. If Eq. (9) has a solution, then when $\hat{f}_e \to f_e$, $f_e \to f_d$ is obtained.

The update rates of $\hat{k}_g$ and $\hat{x}_e$ are designed to ensure that when $\hat{f}_e \to f_e$, $f_e \to f_d$ is obtained. Consequently, the corresponding Lyapunov function V is designed as

$$V = \boldsymbol{\phi}^{\mathrm{T}} \boldsymbol{P} \boldsymbol{\phi}, \tag{10}$$

where $\boldsymbol{P}$ denotes a pre-defined 2×2 positive definite matrix, and

$$\dot{\boldsymbol{\phi}} = -\boldsymbol{P}^{-1} \begin{bmatrix} -x \\ 1 \end{bmatrix} (\hat{f}_e - f_e). \tag{11}$$

Taking the derivative of Eq. (10) and then substituting Eq. (11) into the result yields

$$\dot{V} = 2\boldsymbol{\phi}^{\mathrm{T}} \boldsymbol{P} \dot{\boldsymbol{\phi}} = -2(\hat{f}_e - f_e)^2 \leqslant 0. \tag{12}$$

It follows that the system is stable, and when $\hat{f}_e \to f_e$, $f_e \to f_d$ is obtained, the real-time estimation equation for the dynamic contact force of the robot foot is finally obtained by combining Eqs. (11) and (8):

$$f_d = \hat{f}_e = \hat{k}_g(\hat{x}_e - x_c). \tag{13}$$

The relationship between $\hat{k}_g$ and $\hat{x}_e$ is

$$\begin{cases} \dot{\hat{k}}_g = \alpha x_c[\hat{k}_g(\hat{x}_e - x_c) - f_e], \\ \dot{\hat{x}}_e = -(\alpha x_c \hat{x}_e + \beta)[\hat{k}_g(\hat{x}_e - x_c) - f_e]/\hat{k}_g, \end{cases} \tag{14}$$

where α and β are parameters in the positive definite matrix $\boldsymbol{P}$. The parameter values can be obtained by the Runge-Kutta method.

The actual foot contact force changes when the robot's motion environment changes. Therefore, the dynamic foot contact force obtained through the real-time estimation equation can adjust the tracking difference of the foot force in real time, ensuring the motion stability of the leg admittance control.

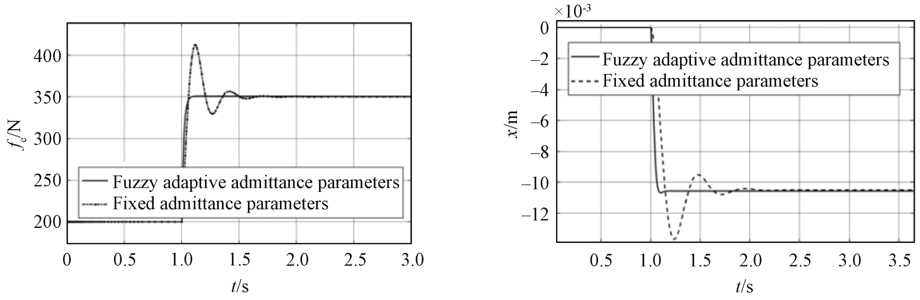
3 Simulation Experiment Verification of Hexapod Wheeled-Legged Robot

The simulation experiment of the hexapod wheeled-legged robot is conducted in MATLAB and Simscape.

The three-dimensional model is created in SOLIDWORKS, converted into the URDF, and imported into Simscape. The fuzzy adaptive admittance control system based on real-time estimation is developed in MATLAB/Simulink. The control system is connected to the three-dimensional model of the robot, and the ground environment models with different contact stiffness and the damping coefficient are built.

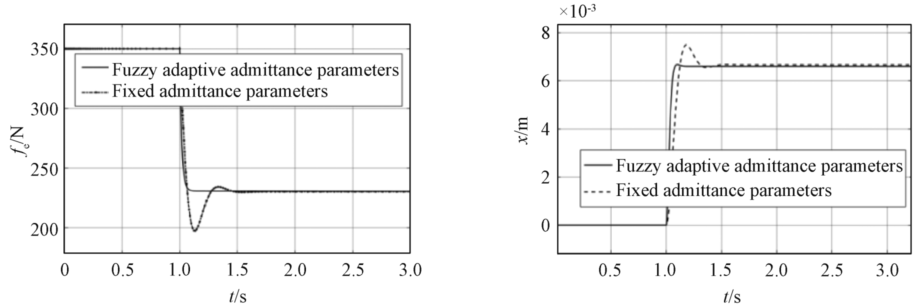
3.1 Fuzzy adaptive admittance parameter adjustment simulation

When the robot motion environment changes, the leg admittance parameters are obtained by a fuzzy adaptive method based on the ground contact stiffness and the damping coefficient. The foot contact force f_e tracking curve and the corresponding leg displacement x variation curve are shown in Figs. 6 and 7, where t is time.



(a) (b)

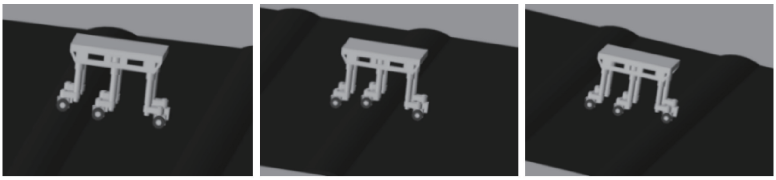
Fig. 6 Environment changes from grassland to asphalt ground: (a) foot contact force variation curve; (b) leg displacement variation curve



(a) (b)

Fig. 7 Environment changes from asphalt ground to grassland: (a) foot contact force variation curve; (b) leg displacement variation curve

The motion state of the hexapod wheeled-legged robot on the obstacle terrain is shown in Fig. 8. The robot's legs can promptly adjust when passing the obstacle while the robot maintains a horizontal body posture, ensuring stable motion performance.



(a) (b) (c)

Fig. 8 Motion of robot on obstacle terrain: (a) front legs passing obstacles; (b) middle legs passing obstacles; (c) rear legs passing obstacles

The simulation results of the robot encountering a ground obstacle are depicted in Figs. 9 to 15. Figure 9 demonstrates a significant increase in the foot contact force when the robot's leg passes a ground obstacle. The admittance control simultaneously adjusts the motion trajectory of the robot's leg based on the contact force. The corresponding displacement x, velocity v, and acceleration a are shown in Figs. 10, 11, and 12, respectively.

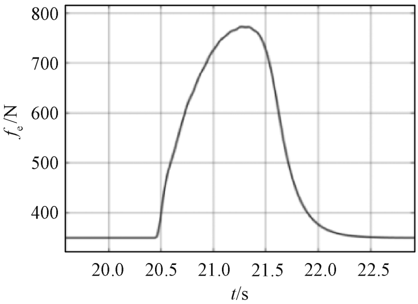


Fig. 9 Foot contact force variation curve

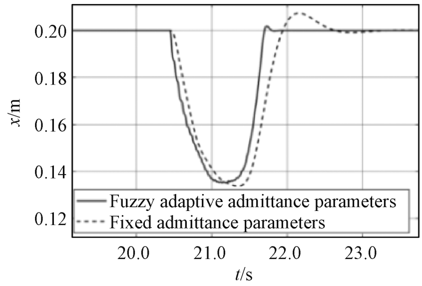


Fig. 10 Leg motion position variation curve

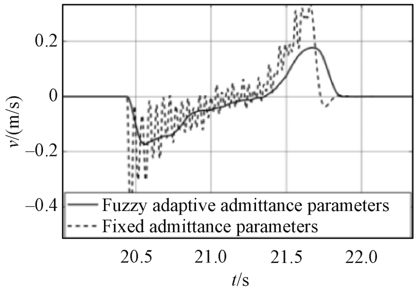


Fig. 11 Leg motion velocity variation curve

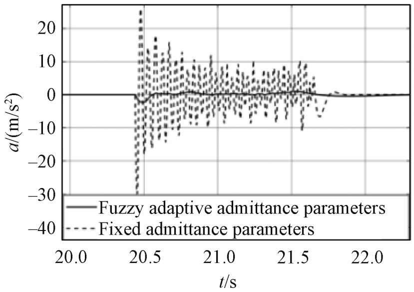


Fig. 12 Leg motion acceleration variation curve

The analysis results indicate that, compared to the fixed admittance parameters control method, the fuzzy adaptive admittance parameter control method can respond more rapidly to environmental changes, resulting in smoother displacement, velocity, and acceleration curves with significantly reduced fluctuation amplitudes.

The simulation results of the robot pitch angle θ and angular velocity ω are shown in Figs. 13 and 14. Compared with the method using fixed admittance parameters, the fuzzy adaptive admittance parameter method exhibits smaller curve fluctuation amplitudes and demonstrates better motion stability when the robot's leg passes a ground obstacle. This validates the effectiveness of the fuzzy adaptive admittance control method in enhancing the robot's motion stability.

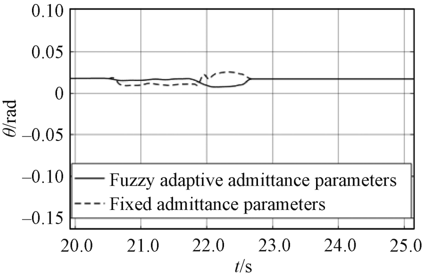


Fig. 13 Robot pitch angle

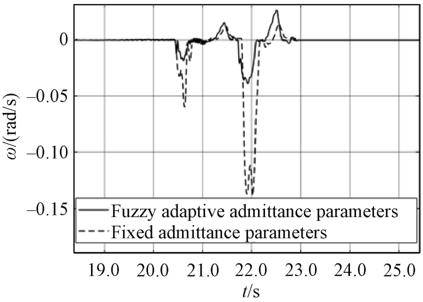
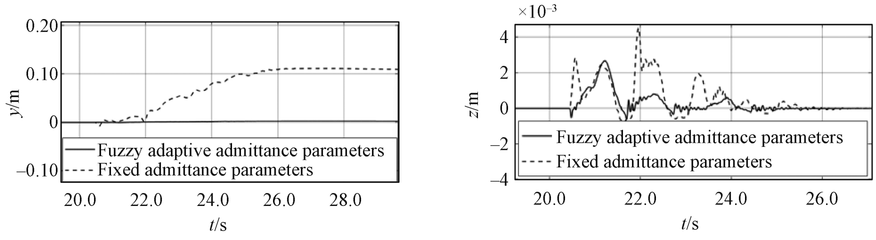


Fig. 14 Robot pitch angular velocity

When the robot passes a ground obstacle, it moves in a straight line along the X-axis direction. The motion position errors y and z in the Y-axis and Z-axis directions are shown in Fig. 15.



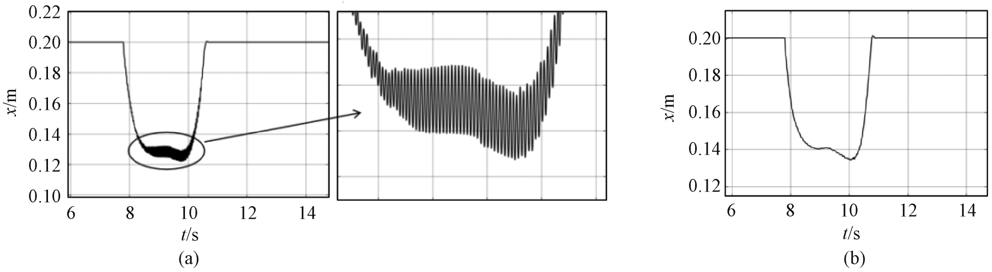
(a) (b)

Fig. 15 Robot motion position errors: (a) Y-axis direction; (b) Z-axis direction

As shown in Fig. 15, the robot controlled by the fuzzy adaptive admittance parameter method exhibits position errors approaching zero in the Y-axis direction and maintains position errors within the range of −1 to 3 mm in the Z-direction. In contrast, the fixed admittance parameter method results in position errors of up to 0.11 m in the Y-axis direction and maintains position errors within the range of −1 to 5 mm in the Z-axis direction. This further confirms the effectiveness and superiority of the fuzzy adaptive admittance control method in complex dynamic environments.

3.2 Real-time estimation simulation of dynamic foot contact force

Based on the ground environment parameters, the actual foot contact force and position, and the dynamic foot contact force are obtained through a real-time estimation method. The difference in the foot contact force tracking is adjusted in real time. When the motion environment changes and the robot encounters a protruding ground obstacle, the admittance model enables the robot to control the thigh to pass the ground obstacle. The tracking curve of the motion trajectory of the reference point is shown in Fig. 16.



(a)

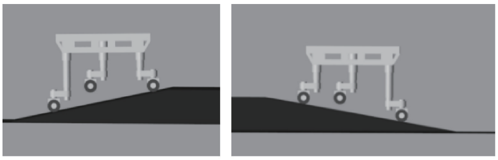
(b)

Fig. 16 Trajectory curves of thigh position reference point: (a) before optimization; (b) after optimization

From the information presented in Fig. 16, it can be inferred that when the robot's motion environment changes, the actual foot contact force alters, leading to oscillations in the thigh motion trajectory controlled by admittance. By establishing a real-time dynamic foot contact force equation through a real-time estimation method and adjusting the tracking difference of the foot contact force in real time, the control performance of the system is effectively enhanced.

3.3 Simulation of motion control on a grassy slope

To prevent slight changes in the robot foot contact force from causing vibrations in the motion trajectory of the thigh, the admittance control is triggered when the foot contact force exceeds 50 N. On a grassy slope, a slope gait is designed to ensure the stability of the motion. By adjusting the height of each leg, the robot maintains its body in a horizontal position while moving on the slope. Additionally, the motion along the x-axis direction is processed in segments to ensure that the legs are adjusted in time when the body enters the slope. The motion state is shown in Fig. 17, while the displacements D along each axis are illustrated in Fig. 18. The motion information is detailed in Table 4.



(a)

(b)

Fig. 17 Motion of robot on a grassy slope: (a) uphill motion process; (b) downhill motion process

Based on Figs. 17 and 18, as well as Table 4, the robot performs an uphill gait from 9 s to 18 s and a downhill gait from 21 s to 30 s. The motion displacement curves of each segment are smooth, with small fluctuations in the Y-axis and Z-axis directions. These results indicate that the robot exhibits good stability on a grassy slope.

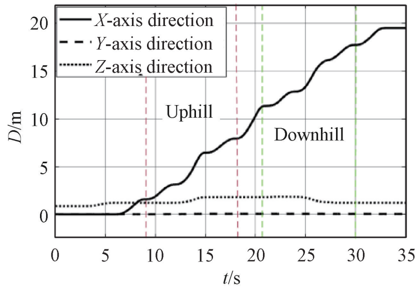


Fig. 18 Displacement curve of robot center mass along X-, Y- and Z-axis directions

Table 4 Motion information on a grassy slope

Parameter	Value
Motion time/s	30
X-axis direction displacement/m	18
Y-axis direction fluctuation/m	0.021
Z-axis direction fluctuation/m	0.011

3.4 Experimental motion tests of hexapod wheeled-legged robot prototype

The fuzzy adaptive admittance control system based on real-time estimation is developed for the prototype of the hexapod wheeled-legged robot. The ground parameters for the robot motion are presented in Table 2, and the robot motion in grassland and asphalt ground is depicted in Fig. 19. As shown in the figure, the robot can stably climb slopes and pass obstacles on both grass and asphalt surfaces, demonstrating the control system's adaptability to varied environments.

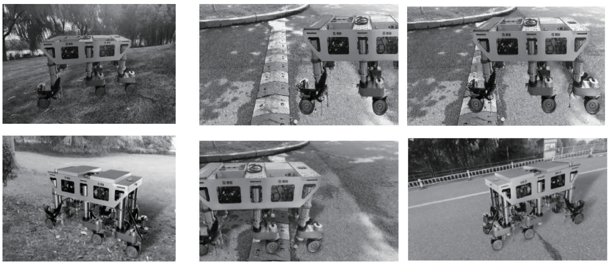

(a) (b)

Fig. 19 Motion behaviors of hexapod wheeled-legged robot prototype: (a) grassland ground; (b) asphalt ground

The experimental results of the robot passing a protruding obstacle on the asphalt ground are shown in Figs. 20 – 24. During the process of passing the protruding obstacle, the foot contact force significantly increases. The admittance controller adjusts the leg displacement in real-time according to the tracking difference of the foot contact force to maintain stable motion. The experimental data indicate that the robot position error in the Y-axis direction is maintained within a range of -30 to 50 mm, and the position error in the Z-axis direction is kept within a range of -4 to 8 mm. Additionally, the fluctuations in the robot pitch angle and angular velocity are small, demonstrating that the robot can maintain stable motion when passing the protruding obstacle and essentially maintain a straight-line motion trajectory. This confirms the robustness of the fuzzy adaptive admittance control method based on real-time estimation in various motion environments and further proves the superiority and effectiveness of the control method in ensuring the robot's motion stability and adaptability.

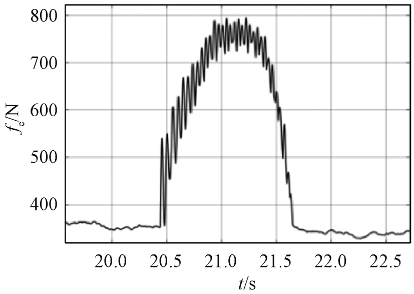


Fig. 20 Foot contact force variation curve

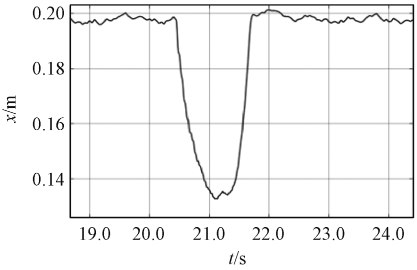


Fig. 21 Leg motion position variation curve

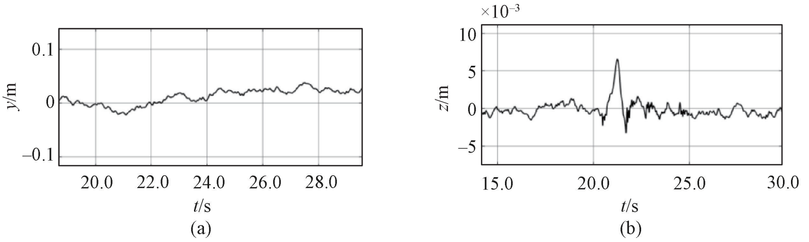


Fig. 22 Robot motion position errors: (a) Y-axis direction; (b) Z-axis direction

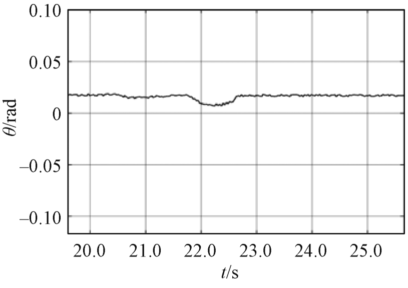


Fig. 23 Robot pitch angle

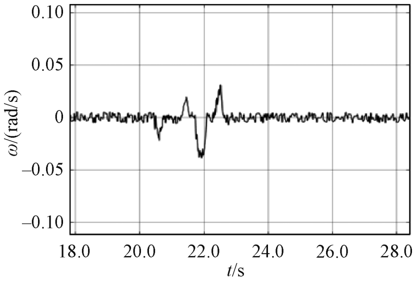


Fig. 24 Robot pitch angular velocity

4 Conclusions

To address the issues of poor foot force tracking and sudden changes in force tracking differences when the environment changes, a fuzzy adaptive admittance control method based on real-time estimation is designed. The fuzzy adaptive admittance control method based on real-time estimation achieves stable motion for the hexapod wheeled-legged robot in various ground environments.

1) The mechanical structure of the robot is

designed, and an environment-interactive admittance control system framework is proposed to address motion adaptability issues between the robot foot and the ground as the environment changes. Additionally, the principle of position-based admittance control is analyzed.

2) By establishing a systematic relationship between the admittance model and the ground environment, and utilizing the environmental parameters, actual foot contact force, and position information, the robot leg admittance parameters and dynamic foot contact force are adjusted in real time to improve the tracking effect of foot contact force.

3) Different motion environments are constructed to conduct a simulation experiment on the motion control system of the hexapod wheeled-legged robot. The control system is implemented on a robot prototype for experimental validation in various environments.

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基于实时估计的六足轮腿式机器人模糊自适应导纳控制

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摘　要：针对六足轮腿式机器人在多种环境的运动情况，提出基于实时估计的模糊自适应导纳控制算法。首先，设计机器人的机械结构，并根据不同运动环境，提出控制系统框架。针对机器人足端与地面接触的适应能力问题，提出基于位置的导纳控制方法。其次，为解决地面环境改变时机器人足端接触力跟踪效果不佳与足端力跟踪差值突变的问题，提出基于模糊自适应的导纳参数调整方法与实时估计算法估计动态足端接触力。最后，在 MATLAB 和 Simscape 环境中进行仿真实验，验证机器人运动控制系统、导纳控制、基于模糊自适应的导纳参数调整及实时估计算法的有效性。并通过机器人样机的多场景实验，验证了控制算法在不同环境下的有效性与适应性。

关键词：六足轮腿式机器人；动态足端接触力；模糊自适应；实时估计；导纳控制