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Stability Optimization of Lower-Limb Exoskeleton Robots Based on Fuzzy Sliding Mode Control

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***Abstract*—With the growing application of lower-limb exoskeleton robots in medical rehabilitation and human movement assistance, achieving high-precision trajectory tracking while rejecting external disturbances has become a key issue. Existing control methods often struggle with unmodeled human dynamics and model uncertainties. While sliding mode control (SMC) offers excellent robustness against these challenges, it typically suffers from the chattering phenomenon. Therefore, this paper focuses on the optimization of robust trajectory tracking for lower-limb exoskeleton robots using fuzzy sliding mode control (FSMC). A mathematical model of the driving joints is established by using a brushless DC motor, and the transfer function of the motor's angular position is derived. Subsequently, a sliding mode controller is designed, and simulation experiments are conducted using step signals, walking, and leg-lifting trajectory inputs. Finally, fuzzy logic is introduced to dynamically adjust the switching gain of the SMC, effectively mitigating chattering and enhancing the exoskeleton's tracking accuracy under human-robot interaction disturbances. This study provides a reliable control scheme for the practical application of lower-limb exoskeletons by addressing system robustness and trajectory tracking precision.**

I. INTRODUCTION

Lower-limb exoskeleton robots are increasingly applied in medical rehabilitation, elderly assistance, intelligent lower-limb sports protection equipment, and labor assistance [1]. However, operating in close physical contact with humans introduces complex, unmodeled dynamic disturbances. Traditional Proportional-Integral-Derivative(PID) control struggles to adapt to these rapid gait changes, often resulting in overshoot and response lag [2]. To enhance robustness against these uncertainties, Sliding Mode Control(SMC) has been widely investigated. While SMC guarantees robust tracking, it inherently suffers from the "chattering" phenomenon — high-frequency oscillations caused by discontinuous switching laws. In wearable exoskeletons, chattering excites unmodeled high-frequency dynamics, causes mechanical wear, and severely degrades user comfort and safety[3].

Therefore, designing a controller that maintains high-precision trajectory tracking while effectively suppressing chattering remains a critical challenge. [4] Various optimization strategies have been proposed to address this. For instance, some studies have introduced improved reaching laws to reduce system delay, while others developed adaptive adjustment mechanisms to enhance robustness against parameter variations [5]. Furthermore, integrating fuzzy logic with SMC has shown great potential. Recent literature demonstrates that applying fuzzy rules to continuously approximate the switching gains of SMC is an effective method to mitigate chattering and improve tracking accuracy.

Based on the aforementioned challenges, this paper proposes an FSMC strategy to optimize the trajectory tracking performance of lower-limb exoskeleton robots[6]. Instead of relying on conventional fixed-gain switching laws, fuzzy logic is introduced to dynamically adjust the sliding mode switching gain based on the real-time tracking error and its derivative. This approach effectively smooths the control signal and suppresses chattering without sacrificing the inherent robustness of SMC[7]. The effectiveness of the proposed FSMC in achieving high-precision position tracking under varying gait trajectories is verified through comprehensive mathematical simulations and wearable hardware experiments. This study provides a robust and practically viable trajectory tracking scheme for high-performance lower-limb exoskeletons.

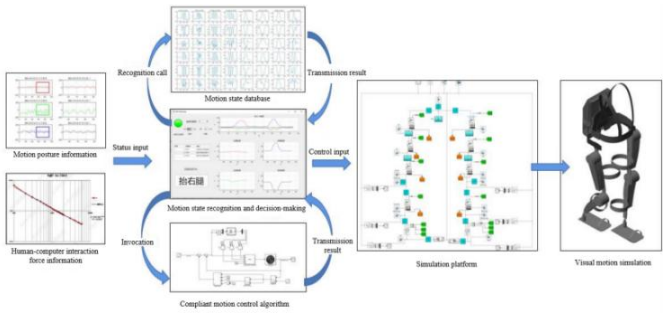
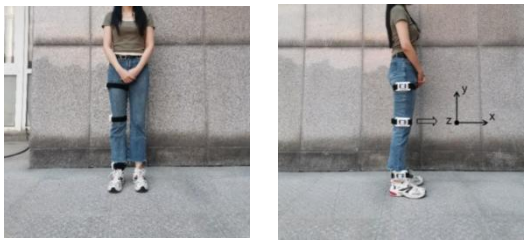


Figure 1. Algorithm of closed-loop control system

II. IMU-BASED MOTION DATA COLLECTION

Real-time acquisition of human motion data is a crucial part of the lower-limb exoskeleton's perception system. Accurate, real-time, and fast acquisition of human body state information is essential for improving the control system's performance. In this paper, the motion data is collected. The sensor numbers are 1-3 from top to bottom. The installation position of the IMU device is shown in Figure 2[7]. The X-axis of the IMU is located in the sagittal plane of the human body, the Y-axis points perpendicularly to the ground and upwards, and the Z-axis is located in the coronal plane of the human body. The IMU is kept vertical through a 3D-printed sensor fixing device.

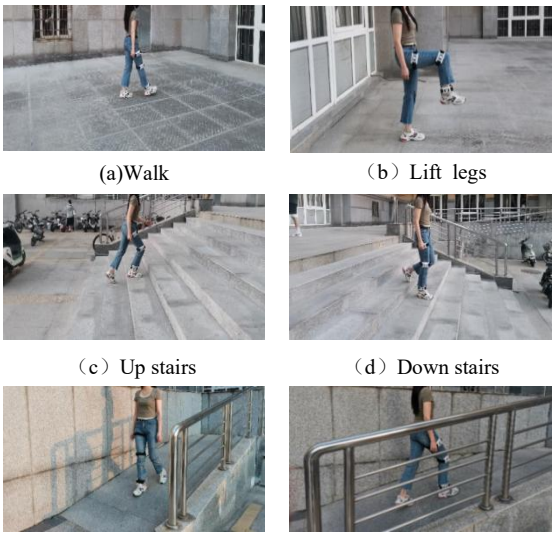
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(a) Front view of sensor layout　　（b）Side view of sens(b) or layout

Figure 2 IMU sensor layout diagram

During data collection, the subject performed six types of motion: walking, leg-lifting, walking down stairs, walking up stairs, downhill, and uphill. Each movement is recorded five times, each lasting three minutes.



(a)Walk　　（b）Lift legs

（c）Up stairs　　（d）Down stairs

（e）Downhill　　（f）Uphill

Figure 3. shows the process diagram of experimental data acquisition

During the movement of the lower limbs of the human body, due to the possible influence of IMU sensors by their own drift, inertial errors, and external environmental factors, the collected raw data may not be precise and stable enough, which in turn leads to deviations in subsequent analysis or control decisions[8]. Therefore, in order to obtain more accurate and reliable motion information, preprocessing the raw data is of vital importance. In this paper, the Kalman filtering method is adopted to filter and reduce the noise of the original signal, which reduces the errors caused by sensor noise, drift and external interference. Then, the motion feature data graphs are extracted[10].

The filtered, high-precision human joint angular trajectories are subsequently exported and utilized as the expected reference trajectories for both the mathematical simulations and hardware tracking experiments. By directly integrating the actual human gait data into the control loop, the practical effectiveness and adaptability of the proposed trajectory tracking controller can be more rigorously validated.

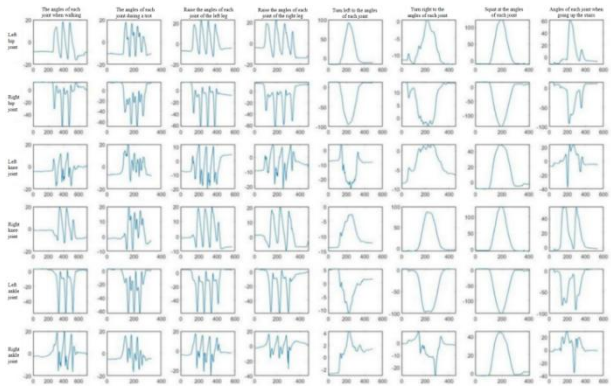


Figure 4 Motion characteristic data graph

All experiments involving human participants in this study were performed in accordance with the Declaration of Helsinki and relevant institutional guidelines and regulations. The experimental protocols were approved by the Institutional Review Board of Jianghan University. Informed consent was obtained from all subjects involved in the study prior to the experiments.

III. Dynamic Model and Control System of Exoskeleton Robot

This section develops the dynamic model and control system of the lower-limb exoskeleton robot, considering the physiological structure of the human lower limb. A multiple degrees of freedom exoskeleton design is proposed, and the robot's dynamics are modeled by Lagrangian mechanics[10].

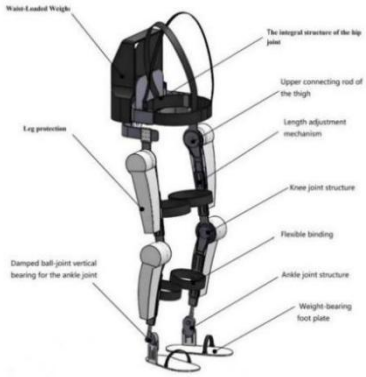


Figure 5 Overall structure diagram of the lower limb exoskeleton

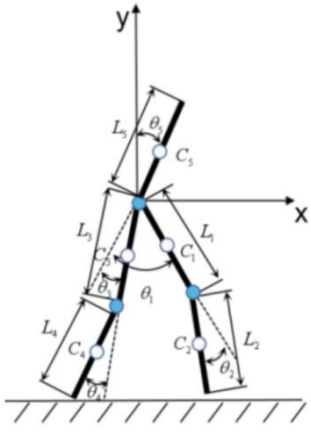


Figure 6. Lagrange five-bar model

where $\theta, \dot{\theta}, \ddot{\theta} \in \mathbb{R}^n$ represent joint position, velocity, and acceleration.$D(\theta), C(\theta, \dot{\theta})$,and$G(\theta)$denote the inertia matrix, Coriolis/centrifugal matrix,and gravity vector,respectively $\tau_f(\dot{\theta})$ denotes joint friction, and τ_{ext} represents external disturbances is the control input.

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + \tau_f(\dot{\theta}) + \tau_{ext} = \tau \tag{1}$$

$$D(\theta) = \begin{bmatrix} m_1 {d_1}^2 + m_2 {L_1}^2 + m_2 {d_2}^2 + 2m_2 L_1 d_1 \cos\theta_2 & -(m_2 L_1 d_2 \cos\theta_2 + m_2 {d_2}^2) \\ -(m_2 L_1 d_2 \cos\theta_2 + m_2 {d_2}^2) & m_2 {d_2}^2 \end{bmatrix} \tag{2}$$

$$C(\theta,\dot{\theta}) = \begin{bmatrix} -2m_2 L_1 d_2 \sin\theta_2\, \dot{\theta}_2 & m_2 L_1 d_2 \sin\theta_2\, \dot{\theta}_2 \\ m_2 L_1 d_2 \sin\theta_2\, \dot{\theta}_2 & 0 \end{bmatrix} \tag{3}$$

$$G(\theta) = \begin{bmatrix} -m_2 g d_2 \sin(\theta_1 - \theta_2) - m_1 g d_1 \sin\theta_1 - m_2 g L_1 \sin\theta_1 \\ m_2 g d_2 \sin(\theta_1 - \theta_2) \end{bmatrix} \tag{4}$$

To facilitate controller design, let $x_1 = \theta$ and $x_2 = \dot{\theta}$.The dynamic model is rewritten into a state-space form:

$$\dot{x}_1 = x_2 \tag{5}$$

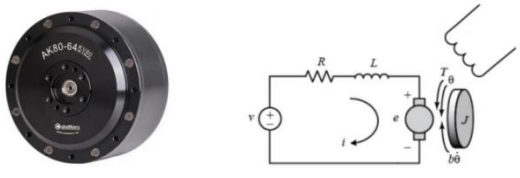
$$\dot{x}_2 = f(x) + b(x)\tau + d(t) \tag{6}$$

where $f(x) = -D^{-1}(x_1)[C(x_1, x_2)x_2 + G(x_1)]$ is the nominal dynamics, and $b(x) = D^{-1}(x_1)$. The term $d(t) = -D^{-1}(x_1)[\tau_f(x_2) + \tau_{ext} + \Delta f(x)]$ represents the lumped unknown disturbances, including parameter variations $\Delta f(x)$. We assume $d(t)$ is bounded. The proposed Fuzzy Sliding Mode Controller (FSMC) is specifically designed to estimate and compensate for this bounded disturbance $d(t)$.

Motors, as the driving core of exoskeleton joints, directlyaffect driving force and control accuracy. A mechanical model of the motor is established to derive its transfer function, which is coupled with the exoskeleton's motion control model for accurate system control and optimization[12]. this paper chooses AK80-64 motor as drive motor,its parameters as show in Table I.

TABLE I. MOTOR PARAMETERS

Serial Number	Basic Data (AK80-64)	
1	Rated Current (A)	20
2	Rated Voltage (V)	48
3	Motor Weight (g)	790
4	Continuous Torque (Nm)	48
5	Dimension (mm)	62*58
6	Number of Pole Pairs	21
7	Winding Resistance (mΩ)	161±5%
8	Winding Inductance(uH)	73.2±10%
9	Back EMF Constant (V/rpm)	0.01
10	Torque Constant (Nm/v)	0.095
11	Speed Constant (rpm/v)	100



(b) Physical diagram of the motor (a) Mechanical model diagram of the motor

Figure 7 Motor model and physical picture

As the driving core of the exoskeleton robot joint, the dynamic response of the motor directly affects the driving force output and control accuracy of the exoskeleton[13]. By establishing the motor transfer function, the electrical and mechanical characteristics of the motor as well as the interaction between the motor and the load can be comprehensively considered, accurately describing the dynamic relationship between the input voltage and the output angular position and angular velocity. Therefore, this paper establishes the transfer function of the motor, providing theoretical support for the subsequent design of PID controllers and sliding mode controllers[13].

$$L_s \frac{di_s}{dt} + i_s R_s + e_s = u_s \tag{7}$$

$$M = K_t i_s \tag{8}$$

$$J\frac{d\omega}{dt} = M - m_c - b\omega \tag{9}$$

Then, the transfer function of the motor angular position to the input voltage is obtained:

$$G_\theta(s) = \frac{K_t}{s(Js + b)(L_s s + R_s) + sK_e K_t} \tag{10}$$

After establishing the dynamic model, a motion simulation system is built based on the lower limb exoskeleton. Then, taking the transfer function of the drive motor of the lower limb exoskeleton robot as the controlled object, the PID control trajectory tracking experiment of the lower limb exoskeleton robot system is carried out based on the MATLAB/Simulink simulation platform to verify the simulation effect of the PID algorithm in motion control.

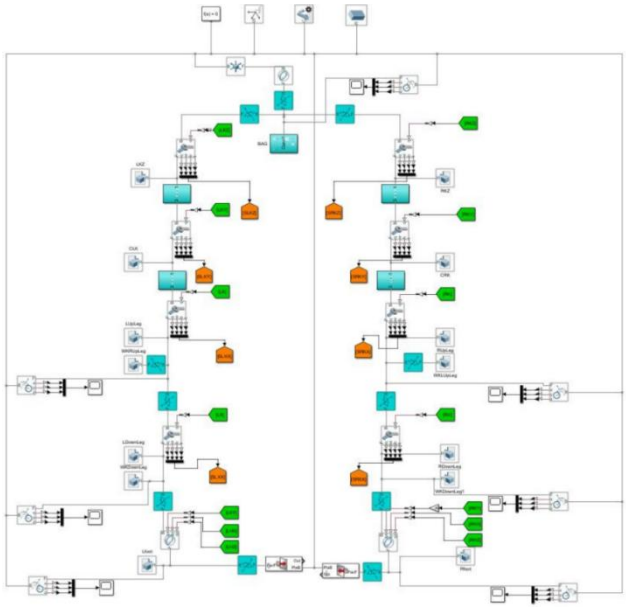


Figure 8. Diagram of the motion simulation system

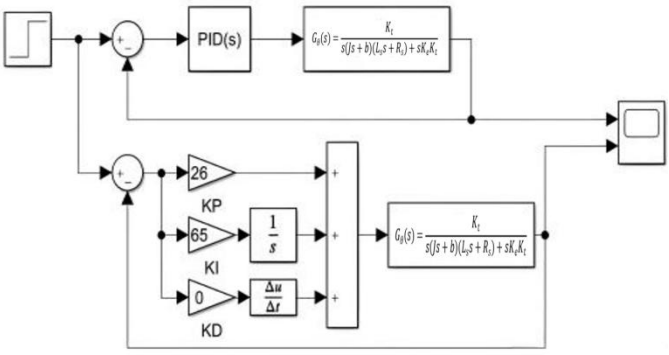


Figure 9. PID control model diagram

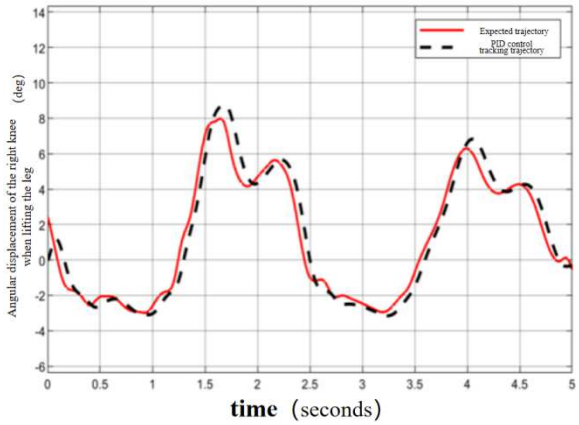


Figure 10. Trajectory tracking curve when lifting the leg

As can be seen from the figure, when tracking the leg-lifting action signal, the PID controller shows a lag phenomenon at some moments with significant dynamic changes, and the tracking curve slightly oscillates. However, the PID control as a whole can effectively follow the input signal. Overall, although the system responds well, further optimization is still needed to enhance its stability and tracking capability.

IV. Simulation and Optimization of Sliding Mode Controller Design

A. Sliding Mode Controller Design and Simulation

The sliding mode control law is designed based on the state-space dynamic model derived in Section III to ensure robust tracking[15]. The equivalent and switching control law is formulated as:

$$\tau = b^{-1}(x)[-f(x) + \ddot{\theta}_d - c\dot{e} - k \cdot \mathrm{sgn}(s)] \tag{11}$$

To strictly guarantee the convergence of the tracking error and demonstrate the finite-time stability of the closed-loop system, a Lyapunov candidate function is defined as:

$$V = \frac{1}{2}s^2 \tag{12}$$

Taking the time derivative of V yields $\dot{V} = s\dot{s}$. By substituting the system dynamics and the proposed control law u into this derivative, we obtain:

$$\dot{V} = s(d(t) - k\mathrm{sgn}(s)) \le |s||d(t)| - k|s| \tag{13}$$

Assuming the external lumped disturbance is bounded by $\|d(t)\| \le D_{\max}$,and selecting the switching gain$k \ge D_{\max} + \eta(where\eta > 0)$,the condition becomes:

$$\dot{V} \le -\eta|s| \le 0 \tag{14}$$

According to Lyapunov's direct method, this ensures that the sliding surface s=0 can be reached in finite time, rigorously proving the stability of the proposed SMC.

Based on the MATLAB/Simulink simulation platform, the sliding mode control trajectory tracking experiment of the lower limb exoskeleton robot system is carried out to verify the simulation effect of the sliding mode controller in motion control. The control signal is calculated by controlling the error between the expected joint Angle and the actual joint Angle, thereby achieving effective control of the lower limb exoskeleton robot system**Error! Reference source not found.**.

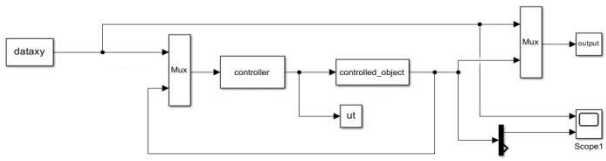


Figure 11. Simulation structure diagram of the sliding mode controller

Taking the step signal as the system input, at 1 second, it is expected that the joint trajectory will change from 0 to 1. The control input ut is calculated through the designed sliding mode control law and applied to the lower limb exoskeleton robot system[17]. Among them, the control input includes the error between the expected Angle and the actual Angle, and the corresponding control signal is generated through the sliding mode controller. The simulation data of step response based on sliding mode control is shown in Figure 11.

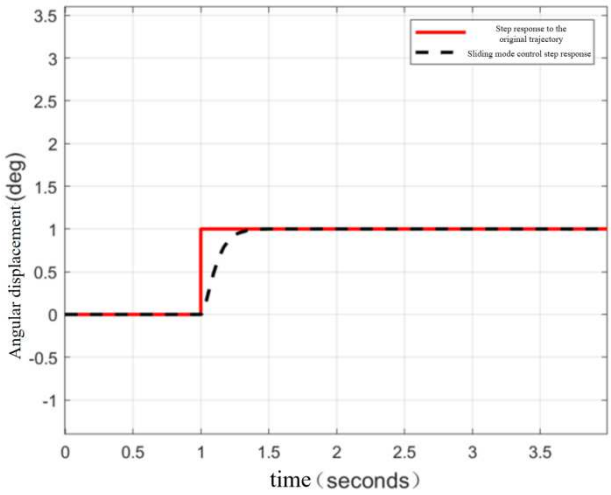


Figure 12. Simulation trajectory of step response

As can be seen from the figure, since the sliding mode controller requires time in the initial stage to quickly bring the system state into the sliding mode surface in order to suppress errors and stabilize the system, within the 1s-1.4s time period, the tracking trajectory based on the sliding mode controller has a certain delay compared to the expected trajectory[19].

Although the sliding mode controller can eventually track the target trajectory, it takes a relatively long time to reach a steady state, showing a certain response delay.

Taking the movement trajectory of the right knee joint of the experimental subject as the control input, the simulation results under the two different states of walking and leg lifting are shown in the figure.

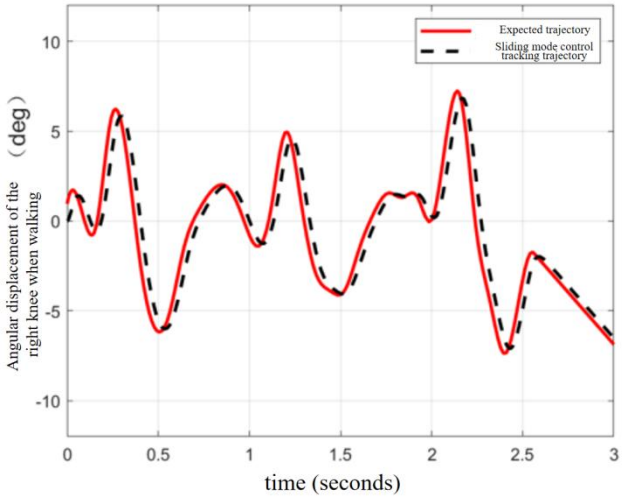


Figure 13 .Trajectory tracking curve when walking

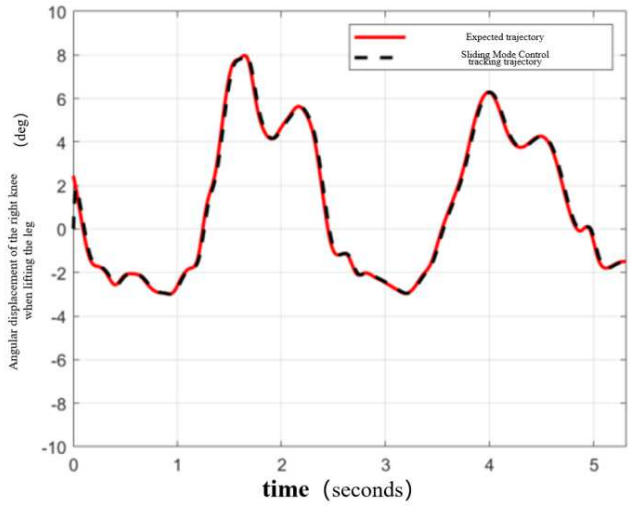


Figure 14 .Trajectory tracking curve when lifting the leg

When walking and lifting the leg, the angular trajectory of the right knee joint shows periodic fluctuations. The control trajectory generated by the sliding mode controller follows the changes of the expected trajectory, presenting a similar dynamic response**Error! Reference source not found.**. It can be seen from the figure that the sliding mode controller has a slight lag in the initial response. Although the system showed some slight delays during the cycle changes, over time, the sliding mode controller gradually reduced the error and approached the expected trajectory, and stabilized near the expected Angle after a period of time.

B. Fuzzy sliding mode control optimization

Sliding mode control can provide good robustness and better tracking effect in the motion control of lower limb exoskeleton robots. However, it will cause delays and oscillations during rapid dynamic changes, especially in the transition stage. To solve these problems, a simulation study on the motion control of lower limb exoskeleton robots is carried out in combination with fuzzy control sliding mode control (FSMC). The sliding mode control law based on fuzzy logic function show as follows,where $\hat{k}_{fuzzy}$ replaces the constant gain k:

$$\tau = b^{-1}(x)[-f(x) + \ddot{\theta}_d - c\dot{e} - \hat{k}_{fuzzy} \cdot sgn(s)] \quad (15)$$

For the Fuzzy Sliding Mode Control (FSMC), the fuzzy logic block is designed to dynamically tune the control gain k(s) in real-time, effectively replacing the conservative fixed gain k to mitigate chattering. To maintain system stability, the fuzzy rule base is bounded such that the dynamic gain satisfies $\kappa(s) \geq D_{\max} + \eta$ .Consequently, the Lyapunov stability condition $\dot{V} = s\dot{s} \leq -\eta|s|$ remains strictly satisfied. This ensures that the FSMC continuous control law successfully reduces chattering without compromising the robust stability demonstrated in the conventional SMC[20].

The design of fuzzy control is highly dependent on the experience of expert control. This article defines the input and output pairs of fuzzy control as seven intervals, which are respectively represented as negative large (NB), negative medium (NM), negative small (NS), near zero (Z), positive small (PS), positive medium (PM), and positive large (PB). The design of the fuzzy rule table is as show in Table Ⅱ:

TABLE Ⅱ. Fuzzy Rule

Serial	$u_f(t)$	S(t)						
Number	$\dot{s}(t)$	NB	NM	NS	Z	PS	PM	PB
1	NB	NB	NB	NB	NB	NM	NS	Z
2	NM	NB	NB	NB	NM	NS	Z	PS
3	NS	NB	NB	NM	NS	Z	PS	PM
4	Z	NB	NM	NS	Z	PS	PM	PB
5	PS	NM	NS	Z	PS	PM	PB	PB
6	PM	NS	Z	PS	PM	PB	PB	PB
7	PB	Z	PS	PM	PB	PB	PB	PB

In the MATLAB/Simulink environment, the fuzzy sliding mode control method is adopted to build the simulation model to verify the effectiveness of this control method in motion control. It mainly includes sliding mode controllers, control objects and fuzzy controllers[18]. Through modular design, closed-loop control is achieved to ensure that the system can maintain stable operation in an uncertain environment.

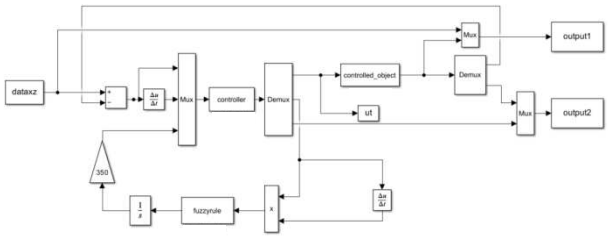


Figure 15. Simulation structure diagram of the fuzzy sliding mode controller

Through simulation experiments on the control performance of different input signals, comparative tests were

carried out using the motion signals under walking actions and leg-lifting actions as inputs.

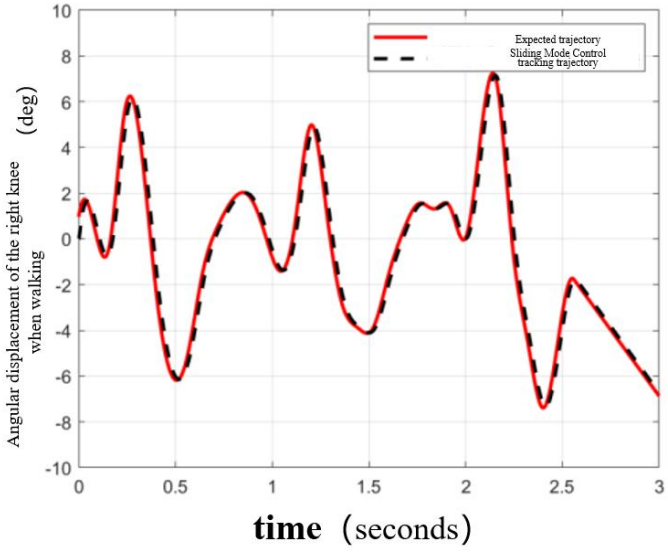


Figure16.Trajectory tracking curve graph during walking

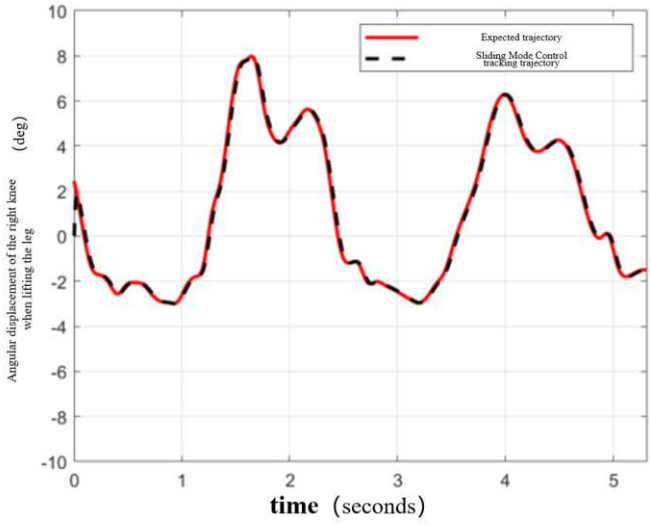


Figure17.Trajectory tracking curve graph when lifting the leg

The results show that in both walking and leg-lifting states, the system can accurately track the Angle trajectory of the knee joint with minimal error and a stable system response. The tracking curve under the walking gait is highly consistent with the expected trajectory, with no obvious overshoot. Moreover, the joint angles can be rapidly adjusted at 0.25 seconds and 0.5 seconds, maintaining the naturalness and stability of the gait. It also demonstrates a good tracking effect under the leg-lifting gait, closely adhering to the target trajectory[19]. Even at the peak position with a large amplitude, the system can quickly adjust and smoothly transition during the trough stage without sudden changes or vibrations.

V. EXPERIMENTAL RESULTS

The drive motor of the lower limb exoskeleton robot is equipped with its own drive board, so the hardware circuit design of the control system is mainly implemented.The function of sending control instructions to the motor and feeding back the motion status includes core components such as the STM32F103RCT6 microcontroller system, power module, and communication module, ensuring the stable operation of the system.The driver board is shown in the figure17 and figure18 .

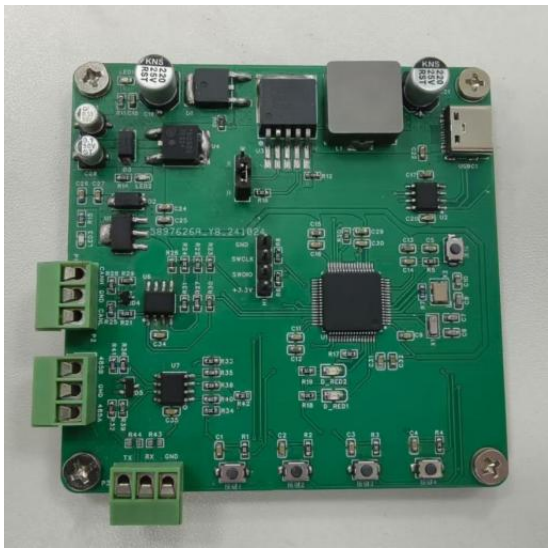


Figure18. Physical picture of the driver board

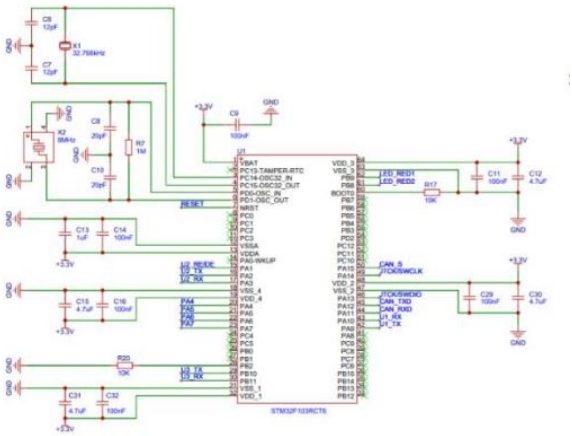


Figure19. Microcontroller System

The drive motor control system of the single joint of the lower limb exoskeleton robot adopts Microsoft Visual Studio as the integrated development environment. The software interacts with hardware devices through computer ports to achieve functions such as data reception and transmission, baud rate matching, and port monitoring, ensuring that the software system can communicate stably with the hardware[23].The interface design of the upper computer of the control system is shown in the figure 19.

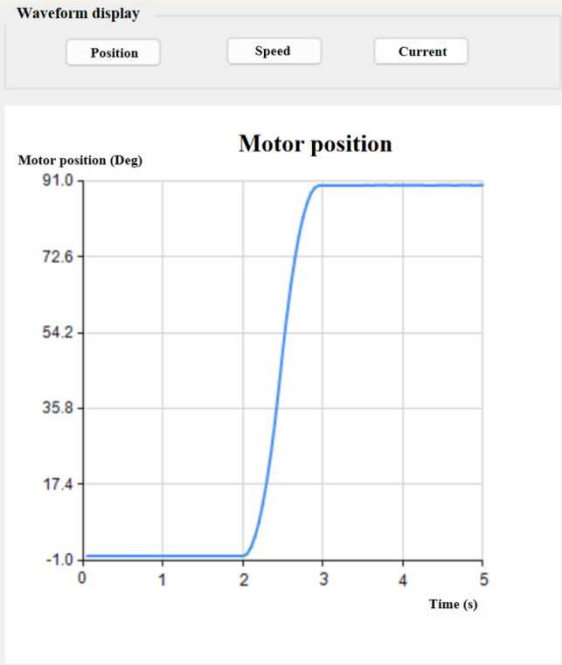


Figure20. The interface of the upper computer for joint motor control

In order to ensure that the motor can operate stably and perform optimally under the predetermined working conditions, the parameters of the T-motor AK80-64 motor are debugged based on serial communication. The hardware connection diagram of the motor drive is shown as follows. The motor interacts with the upper computer through a serial communication interface. The serial communication is achieved through a TTL to USB adapter, which converts the signal names sent by the upper computer into signals that the motor can recognize, thereby enabling some actions or behaviors to be realized on the motor[24].

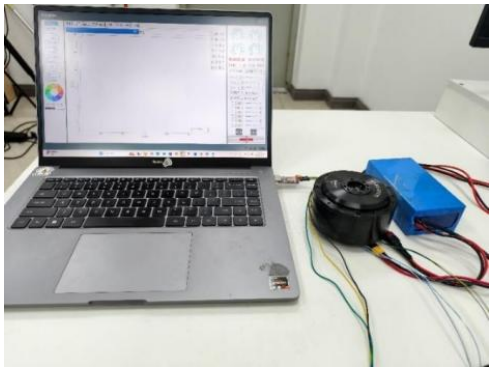


Figure21.Motor parameter debugging

In MIT mode, only one loop can be controlled at a time. Taking position loop control as an example, the expected operation of the motor is achieved Set the position value to 90°.the speed value to 5000ERPM, and the acceleration to 30,000 ERpm. Click the Start button, and the motor position operation waveform is as shown in the following figure.

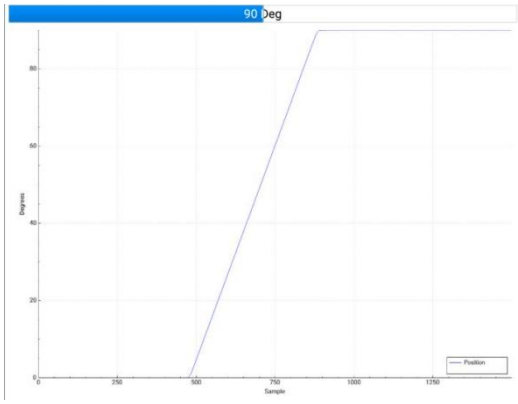


Figure22.Motor position operation waveform diagram

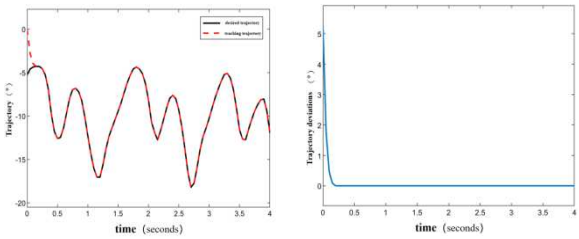
To further verify the stability of the lower limb exoskeleton under fuzzy sliding mode control, after the simulation experiment test, we carried out the experimental platform construction and trajectory tracking control experiment. The experimental platform for the motor drive system of the lower limb exoskeleton robot is shown in the figure.



(a)Bending over for wearing test

(b)The leg is being lifted for the wearing test

Figure 23. Experimental platform for the motor drive system of the lower limb exoskeleton robot



(a) Results of motion trajectory tracking

(b) Motion trajectory tracking error

Figure 24. Tracking curve of knee joint motion trajectory

As can be seen from the figure, the movement trajectory of the knee joint has a relatively large error in the initial stage. This might be due to the fact that the motor set the origin position at the initial moment, while the experimental subject had already started moving before the experiment began, resulting in a deviation between the initial state and the set origin. However, after an adaptation time of 0.25 seconds, the movement trajectory of the joint can follow the expected

trajectory well, demonstrating the good stability and trajectory tracking ability of the control system[25].

VI. Conclusion

This paper focusses on the problem of insufficient stability and trajectory tracking ability in the application of lower limb exoskeleton robot is studied. Firstly, 3 IMU sensors are arranged on the legs to collect six kinds of action data, such as walking, leg lifting, up and down stairs, and Kalman filter is used to process sensor drift and inertia error to ensure data accuracy. Then, combined with the structure of human lower limbs, the multi-degree-of-freedom dynamic equation of exoskeleton is established based on Lagrange dynamics theory. At the same time, the equations of armature potential balance, electromagnetic torque and angular position transfer function of brushless DC motor are derived, and the system model is constructed. Then, PID control and sliding mode control are compared and tested on MATLAB / Simulink platform. It is found that PID has lag oscillation and sliding mode control has response delay. Then, fuzzy control optimization is introduced to obtain fuzzy sliding mode controller. Through simulation and experimental platform verification, the controller can effectively reduce delay and chattering under walking, leg lifting and other actions, so that the joint trajectory can accurately follow the expected trajectory. The experimental hardware platform is built, and the theory is verified by single motor control and wearable motion control experiments. Finally, it provides a reliable control scheme and theoretical and practical basis for the practical application of lower limb exoskeleton robot.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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