Application of SMC-PID algorithm for anti-roll control for human-carrying robot

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ABSTRACT

The paper presents the application of the PID sliding control algorithm in anti-roll control for robots transporting people up and down stairs. Robots transporting people moving on complex terrain need to be analyzed and controlled to prevent rolling during the movement to ensure the robot's operation is effective and brings safety to the user. When the robot moves, the anti-roll control process is performed by controlling the position of the human transport mechanism with a linear actuator, which is an electric cylinder. The sliding control algorithm with the PID sliding surface is applied to control the response of the linear electric cylinder according to the change in the slope of the stairs to ensure the robot's anti-roll process by shifting the user's center of gravity. The simulation results of the application of the sliding mode controller to anti-roll control for robots are performed on Matlab Simulink software. The position of the anti-roll mechanism changes linearly according to the slope of the stairs, thereby showing the effectiveness of the controller for the anti-roll control process for robots. Simulation shows the effectiveness of the proposed algorithm, which helps the design and manufacturing process of human-carrying robots become more efficient.

Keywords: Human carry robots; Anti-roll control; PID-Sliding control

1. INTRODUCTION

Robots for transporting people with lower limb health problems are researched and manufactured to support users in community integration. For robots transporting people that can move up and down stairs, the center of gravity of the robot tends to shift according to the slope of the stairs, which makes the robot very susceptible to tipping over. The position and mass of the person sitting on the robot are among the factors that create a tipping moment. The more the seat position is offset towards the bottom of the stairs, the greater the tipping moment is for the robot. Controlling the seat position on the robot can limit the risk of the robot tipping over when moving up the stairs. The response of the actuator that controls the seat position has a great influence on the anti-tipping process. An actuator with an inaccurate response can easily cause imbalance when the robot moves up and down the stairs, so a control algorithm is needed to help improve the actuator's response.

Anti-roll control for robots will control the robot's center of gravity to be balanced with the slope of the terrain when the robot moves on the stairs. The user's center of gravity is controlled to readjust the robot's center of gravity to be balanced with the operating environment. Current studies control the robot's center of gravity by controlling the user's position as a counterweight to ensure the force balance factor. Research on anti-roll control of human transport robots in the current dynamic state is still limited. Currently, studies perform anti-roll control through mechanical systems that control the user's center of gravity. Research [1] uses a PD controller combined with closed-loop control to compensate for gravity when the posture angle changes. This robot is designed with an inverted pendulum shape that can climb stairs, and the center of gravity is controlled through a mechanical mechanism connecting the chair and two wheels to create a sliding mechanism to control the center of gravity balance. In a study [2], an X-shaped lifting mechanism was applied, and a PID control algorithm was used in combination with the IMU sensor signal to adjust the center of gravity position of the robot. Another study [3] used a fuzzy controller to control the center of gravity and adjust the tilt of the robot when climbing stairs. The control system is based on dynamic analysis of the relationship between the center of gravity position and the tilt angle through two linear actuators. The study has not been applied to a real model, and the controller parameters have not been optimized. The fuzzy control algorithm used to control the stability of a two-wheeled robot was studied in [4]. The study combined fuzzy controllers to test the robot control process in the plane state and on the stairs and achieve some objective results. However, the study was only performed in simulation. The high-order sliding controller was used in the study [5] to synchronize the moving parts of the stair-climbing robot to limit tipping over. In the study [6], the sliding control algorithm combined with the neural network solved the uncertain parameters of the multivariable system in the electric wheelchair robot. The robot was stabilized when running on rough terrains. In the study [7], the second-order sliding controller was applied to the two-wheeled electric wheelchair robot. The system controlled the input and output velocities of the robot to be linearized. The control system response ensured the autonomy of the wheelchair to meet the desired trajectory.

From the above studies, it can be seen that the application of control algorithms to control robot systems is one of the decisive factors for the success of the robot's operation. Although many studies have been conducted, current studies are still limited in adapting to the slope of the stairs and the response of the system. The sliding controller is a controller with powerful features in the field of control systems with nonlinear feedback, has high efficiency and stability, and is sustainable against impact disturbances [8]. However, the oscillation phenomenon in this algorithm will affect the quality of the control system. In the study [9], the SMC-PD algorithm is used to track the nonlinear trajectory of the robot. The study has demonstrated the effectiveness of the algorithm compared to the basic SMC algorithm. The sliding control algorithm with PI sliding surface is used in the control of the shock absorber-body-spring system in the study [10]. The study shows that the chattering phenomenon in the sliding controller is also limited. Research [11] used the PID sliding control algorithm to control the mobile robot trajectory. The chattering phenomenon in the sliding controller was also limited. The stability of the controller was proven with the impact of disturbances. Next, research [12-14] also overcame the limitations and improved the efficiency of the sliding controller by constructing a sliding surface in the form of a PID equation. Studies have shown that the sliding control algorithm with a sliding surface in the form of a PID equation gives a good response. The system is stable with disturbances and reduces the chattering phenomenon of the basic sliding controller, so in this study, the SMC-PID control algorithm is used in the anti-roll control process for the human transport robot.

2. DYNAMIC MODEL OF ANTI-ROLL CONTROL MECHANISM FOR HUMAN TRANSPORT ROBOTS

The robot is studied with the ability to move up and down stairs with the structure shown in figure 1. The dynamic equation of the robot is considered during the movement on the stairs. The kinematic model of the anti-roll mechanism is built based on the movement process of the seat mounted on the robot framing. Suppose the user's center of gravity is fixed right in the middle of the seat. The robot's original coordinate system is considered at the position in front of the robot's crawler.

Consider the coordinate system as shown in figure 2, assuming the center of gravity position of the robot G_R and the center of gravity position of the sitting object G_n; the distance from the center of the robot frame to the origin is L_0; the angle with the belt surface is β; The distance from the chair rotation axis to the seat center of gravity is b; the distance from the rotation axis to the belt surface is c; the initial angle of the chair center of gravity is α_0; δ is the fixed angle of the chair rotation axis and the coordinate system; L_1 is the distance from the passive wheel to the chair rotation axis; l_{Rx}, l_{Ry} are the coordinates of the robot frame center of gravity; l_{nx}, l_{ny} are the coordinates of the seat center of gravity. The center of gravity of the robot frame $G_R[l_{Rx}, l_{Ry}]$ and of the seat G_n $[l_{nx}, l_{ny}]$ are designed as follows.

$$\begin{cases} l_{Rx} = L_0\cos(\beta+\theta) \\ l_{Ry} = L_0\sin(\beta+\theta) \end{cases} \Rightarrow \begin{cases} \dot{l}_{Rx} = -L_0\dot{\theta}\sin(\beta+\theta) \\ \dot{l}_{Ry} = L_0\dot{\theta}\cos(\beta+\theta) \end{cases} \tag{1}$$

$$\begin{cases} l_{nx} = L_1\cos(\theta+\delta) - b\cos(\alpha_0) \\ l_{ny} = L_1\sin(\theta+\delta) + b\sin(\alpha_0) \end{cases} \Rightarrow \begin{cases} \dot{l}_{nx} = -L_1\dot{\theta}\sin(\theta+\delta) + b\dot{\alpha}_0\sin(\alpha_0) \\ \dot{l}_{ny} = L_1\dot{\theta}\cos(\theta+\delta) + b\dot{\alpha}_0\cos(\alpha_0) \end{cases} \tag{2}$$

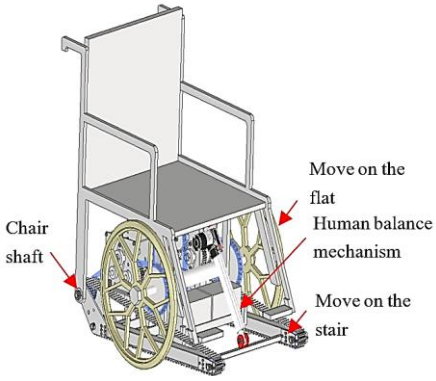

Figure 1. *Human transport robot structure.*

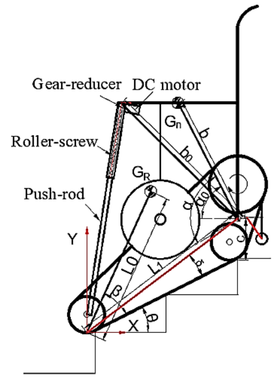

Figure 2. *Dynamic model of mechanism human transport robot.*

Assume the mass of the robot is m_R and mn is the mass of the user on the robot. Consider the kinetic energy equation of the robot moving on a staircase with a slope of θ.

$$\sum T = T_R + T_n = \frac{1}{2}m_R V_R^2 + \frac{1}{2}m_n V_n^2 \tag{3}$$

Where T_R is the kinetic energy of the robot frame, T_n is the kinetic energy of the seat, V_R is the displacement velocity of the robot, and Vn is the displacement velocity of the human transport device. The velocity equation is calculated based on the movement of the center coordinates along the x and y axes set up as shown in figure 2, we have:

$$\begin{aligned} V_R^2 &= \dot{x}_R^2 + \dot{y}_R^2 = \dot{l}_{Rx}^2 + \dot{l}_{Ry}^2 \\ V_n^2 &= \dot{x}_n^2 + \dot{y}_n^2 = \dot{l}_{nx}^2 + \dot{l}_{ny}^2 \end{aligned} \tag{4}$$

The state of the robot operating on the stairs has many changes, so we only consider the case where the robot is in the state when climbing the stairs. We replace formulas (1) and (2) into expression (4) to get:

$$V_R^2 = (-L_0\dot{\theta}\sin(\beta+\theta))^2 + (L_0\dot{\theta}\cos(\beta+\theta))^2 = L_0^2\dot{\theta}^2 \tag{5}$$

$$\begin{aligned} V_n^2 &= (-L_1\dot{\theta}\sin(\theta+\delta) + b\dot{\alpha}_0\sin(\alpha_0))^2 + (L_1\dot{\theta}\cos(\theta+\delta) + b\dot{\alpha}_0\cos(\alpha_0))^2 \\ &= L_1^2\dot{\theta}^2 + b^2\dot{\alpha}_0^2 + 2L_1 b\dot{\theta}\dot{\alpha}_0\cos(\alpha_0+\theta+\delta) \end{aligned} \tag{6}$$

Substituting formulas (5) and (6) into expression (3), the formula is as follows:

$$\sum T = \frac{1}{2}m_R L_0^2\dot{\theta}^2 + \frac{1}{2}m_n L_1^2\dot{\theta}^2 + \frac{1}{2}m_n b^2\dot{\alpha}_0^2 + m_n L_1 b\dot{\theta}\dot{\alpha}_0\cos(\alpha_0+\theta+\delta) \tag{7}$$

The total potential energy of the system is determined as follows:

$$\sum P = P_n + P_R = m_R g L_0\sin(\beta+\theta) + m_n g(L_1\sin(\theta+\delta) + b\sin(\alpha_0)) \tag{8}$$

Where P_n and P_R are the potential energy at the center of gravity of the seat and the center of gravity of the robot, the Lagrange equation of the system is of the form:

$$L = \sum T - \sum P = \frac{1}{2} m_R L_0^2 \dot{\theta}^2 + \frac{1}{2} m_n L_1^2 \dot{\theta}^2 + \frac{1}{2} m_n b^2 \dot{\alpha}_0^2 + m_n L_1 b \dot{\theta} \dot{\alpha}_0 \cos(\alpha_0 + \theta + \delta) - m_R g L_0 \sin(\beta + \theta) - m_n g (L_1 \sin(\theta + \delta) + b \sin(\alpha_0)) \tag{9}$$

$$\frac{\partial L}{\partial \dot{\alpha}_0} = m_n b^2 \dot{\alpha}_0 + m_n L_1 b \dot{\theta} \cos(\theta + \alpha_0 + \delta) \tag{10}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}_0}\right) = m_n b^2 \ddot{\alpha}_0 + m_n L_1 b \ddot{\theta} \cos(\theta + \alpha_0 + \delta) - m_n L_1 b \dot{\theta} (\dot{\theta} + \dot{\alpha}_0) \sin(\theta + \alpha_0 + \delta) \tag{11}$$

$$\frac{\partial L}{\partial \alpha_0} = -m_n L_1 b \dot{\theta} \dot{\alpha}_0 \sin(\theta + \alpha_0 + \delta) - b m_n g \cos(\alpha_0) \tag{12}$$

The anti-roll system for the robot when moving on stairs is controlled based on the slope of the stairs θ, and the position of the user object is determined based on the chair rotation angle α. These two quantities are determined by the IMU tilt angle sensor. The energy of the system will be conserved with the moments of the system. The dynamic equation of the anti-roll control mechanism of the robot is:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}_0}\right) - \frac{\partial L}{\partial \alpha_0} = M_M \tag{13}$$

Substituting formulas (11) and (12) into expression (13), the formula is as follows:

$$\begin{aligned} & m_n b^2 \ddot{\alpha}_0 + m_n L_1 b \ddot{\theta} \cos(\theta + \alpha_0 + \delta) - m_n L_1 b \dot{\theta} (\dot{\theta} + \dot{\alpha}_0) \sin(\theta + \alpha_0 + \delta) \\ & \quad + m_n L_1 b \dot{\theta} \dot{\alpha}_0 \sin(\theta + \alpha_0 + \delta) + m_n g b \cos(\alpha_0) = M_M \\ & \Leftrightarrow m_n b^2 \ddot{\alpha}_0 + m_n L_1 b \ddot{\theta} \cos(\theta + \alpha_0 + \delta) - m_n L_1 b \dot{\theta}^2 \sin(\theta + \alpha_0 + \delta) + m_n g b \cos(\alpha_0) = M_M \end{aligned} \tag{14}$$

Where: M_M is the torque generated from the electric cylinder acting on the seat.

Considering the moment of resistance of the seat system affecting the seat rotation angle, the formula is as follows:

$$m_n b^2 \ddot{\alpha}_0 + m_n L_1 b \ddot{\theta} \cos(\theta + \alpha_0 + \delta) - m_n L_1 b \dot{\theta}^2 \sin(\theta + \alpha_0 + \delta) + m_n g b \cos(\alpha_0) = M_M - f_r \dot{\alpha}_0 \tag{15}$$

Where: f_r is the moment coefficient of the chair, M_M is the moment generated from the electric cylinder, and this is also an important component in the process of controlling the robot's center of gravity.

3. BUILDING ANTI-ROLL CONTROL ALGORITHM

Consider the equation with the chair rotation angle parameter α_0, the anti-roll control algorithm for the system is based on equation (15). Given $x_1 = \alpha_0$, $x_2 = \dot{\alpha}_0$, $y = \alpha_0 = x_1$, $u = M_M$, the state equation is represented as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \dfrac{1}{m_n b^2}\left(u - f_r x_2 - m_n L_1 b \ddot{\theta} \cos(\theta + x_1 + \delta) + m_n L_1 b \dot{\theta}^2 \sin(\theta + x_1 + \delta) - m_n g b \cos(x_1)\right) \end{cases} \tag{16}$$

Based on the sliding control algorithm, it has the advantages of not being affected by noise and having high stability for the system. To overcome the chattering disadvantage of the basic sliding control algorithm, in this study, the sliding control algorithm with the sliding surface in the form of a PID equation combined with the tanh(s) function is applied to the anti-roll control process for the human transport robot. The sliding surface of the controller is constructed as follows:

$$s(t)=\dot{e}(t)+re(t)+r_1\int_0^t e(t)dt \qquad (17)$$

Where e(t) = y (t) – y_0(t) is the error between the output response and the desired signal. y(t) is the output signal, y0(t) is the desired signal. The coefficients r, r1 are chosen as positive constants of the sliding function. These coefficients are chosen so that the system moves quickly toward the sliding surface, ensuring that the characteristic polynomial $s^2+rs+r_1=0$ is a Hurwitz polynomial. This is equivalent to the characteristic equation $s^2+rs+r_1=0$ having solutions with negative real parts.

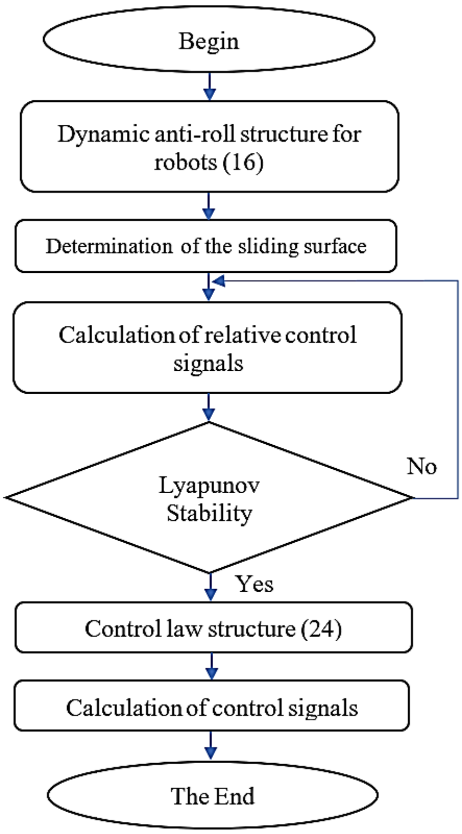

Figure 3. *Control algorithm flow chart.*

Substituting the equation e(t) into equation (17), the formulas are as follows:

$$s(t)=\dot{y}(t)-\dot{y}_0(t)+r(y(t)-y_0(t))+r_1\int_0^t y(t)-y_0(t)dt \qquad (18)$$

$$\dot{s}(t)=\dot{x}_2(t)-\ddot{y}_0(t)+r(x_2(t)-\dot{y}_0(t))+r_1(x_1(t)-y_0(t)) \qquad (19)$$

According to Lyapunov stability theory, the positive definite function T is chosen so that:

$$T=\frac{1}{2}s^2 \qquad (20)$$

$$\Rightarrow \dot{T}=s(t)\dot{s}(t) \qquad (21)$$

To determine $\dot{T}$ the negative value, substituting $\dot{s}=-ksign\left(s(t)\right)$ for $\dot{T}$, the formula is as follows:

$$\dot{T}=-s(t)ksgn(s(t)) \qquad (22)$$

With k being a positive constant chosen in advance so that, in any case $s\dot{s}<0$ when $s\neq 0$ is always satisfied. The sign function has very large oscillations in the sliding surface, so the tanh function will be replaced for the sign function to reduce the oscillation phenomenon as well as the control gain to infinity. The tanh(s) function has a smoother slope and avoids the control gain going to infinity.

With $\dot{s}=-ksgn\left(s\left(t\right)\right)$ is replaced by $\dot{s}=-k\tanh\left(s\left(t\right)\right)$, From equations (19), and (22), the formula is as follows:

$$\begin{aligned}-k\tanh(s(t)) &= \dot{x}_2(t)-\ddot{y}_0(t)+r(x_2(t)-\dot{y}_0(t))+r_1(x_1(t)-\dot{y}_0(t))\\ &=\frac{1}{m_n b^2}\left(u(t)-f_r x_2-m_n L_1 b\ddot{\theta}\cos(\theta+x_1+\delta)+m_n L_1 b\dot{\theta}^2\sin(\theta+x_1+\delta)-m_n gb\cos(x_1)\right)\\ &\quad-\ddot{y}_0(t)+r(x_2(t)-\dot{y}_0(t))+r_1(x_1(t)-\dot{y}_0(t))\end{aligned} \quad (23)$$

The sliding control law of the system can be designed as follows:

$$\begin{aligned}u(t) &= m_n L_1 b\ddot{\theta}\cos(\theta+x_1+\delta) - m_n L_1 b\dot{\theta}^2\sin(\theta+x_1+\delta)+m_n gb\cos(\alpha_0)+f_r x_2\\ &\quad+m_n b^2\left[\ddot{y}_0(t)-r(x_2(t)-\dot{y}_0(t))-r_1(x_1(t)-\dot{y}_0(t))-k\tanh(s(t))\right]\end{aligned} \quad (24)$$

4. EXPERIMENTAL RESULTS

The simulation diagram of the PID sliding controller to control anti-rolling for human transport robots through a linear actuator implemented in Matlab/Simulink is presented as follows:

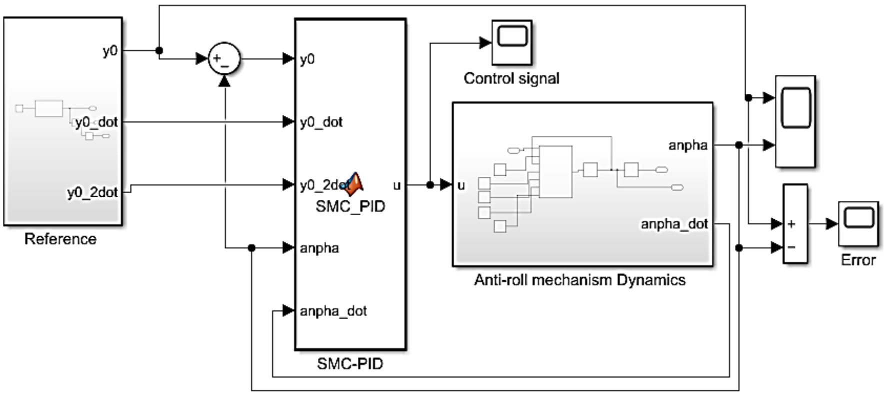

Figure 4. *Simulation diagram of anti-overturn PID sliding controller for robot.*

The parameters of the anti-roll control system for the human transport robot and the sliding controller used in the simulation are presented in table 1.

Table 1. *Simulation parameters of robot anti-rollover control system.*

Symbol	Legend	Value	Unit
m_n	User mass	50 - 70	kg
b	Distance from center of gravity to seat pivot	200	mm
l_1	Distance from chair swivel joint to the driven wheel	700	mm
δ	The angle of elevation of the rotary joint relative to the driven wheel	15	Degree
θ	Tilt angle	30 - 45	Degree
f_r	Friction Coefficient	0.05	Nm
K	Positive constant	1.5	
r, r_1	Coefficients in the PID sliding surface	15; 290	

The simulation of anti-roll control for a human transport robot is performed with a PID sliding mode controller. The tanh(s) function replaces the sgn(s) function in the control law. The results show that the response of the anti-roll mechanism converges to the reference position in a finite time. The steady-state error approaches zero, no overshoot, and the steady-state error is eliminated. The response results and response errors are shown in figure 5. The control signal of the SMC-PID controller is shown in figure 6.

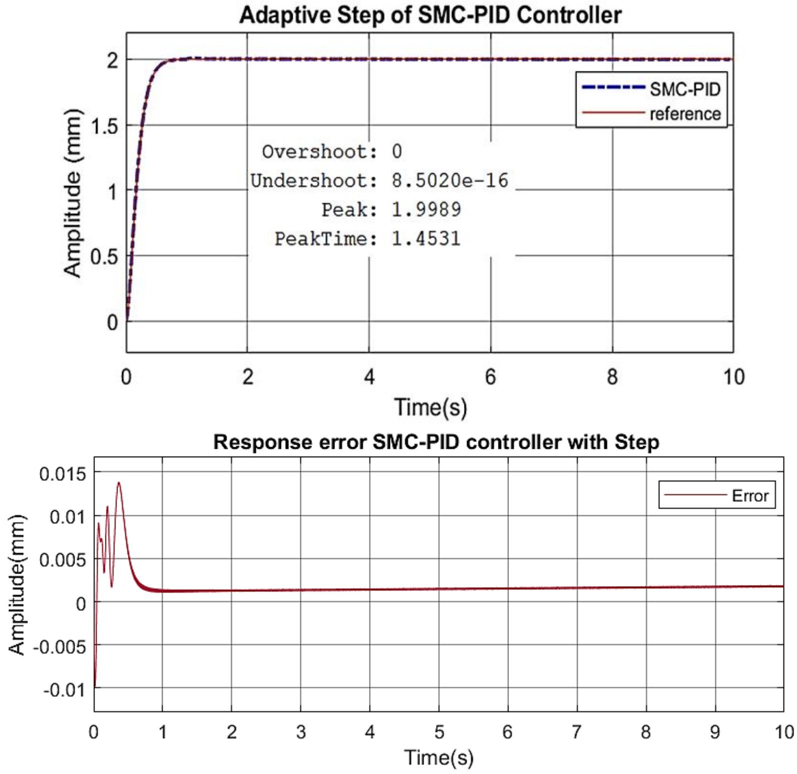

Figure 5. *Response and error of SMC-PID controller.*

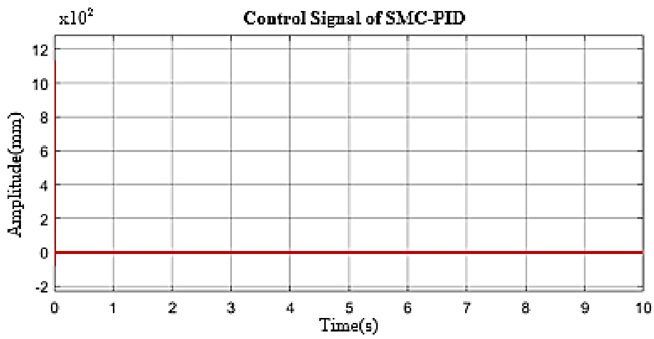

Figure 6. *The control signal of SMC-PID controller for human transport robot.*

The response of square pulse, sine pulse, and response error of the anti-roll control algorithm for the human transport robot are shown in figures 7 and 8. The response of the square pulse and sine pulse shows that the position of the user's center of gravity still converges to the desired position. The steady-state error approaches zero, although there is still oscillation during the control process, but the result is insignificant. The oscillation in the square pulse error is less than 0.12 mm, and the error with the sine reference signal is not greater than 0.007 mm, which shows the stability of the control algorithm with different signal types.

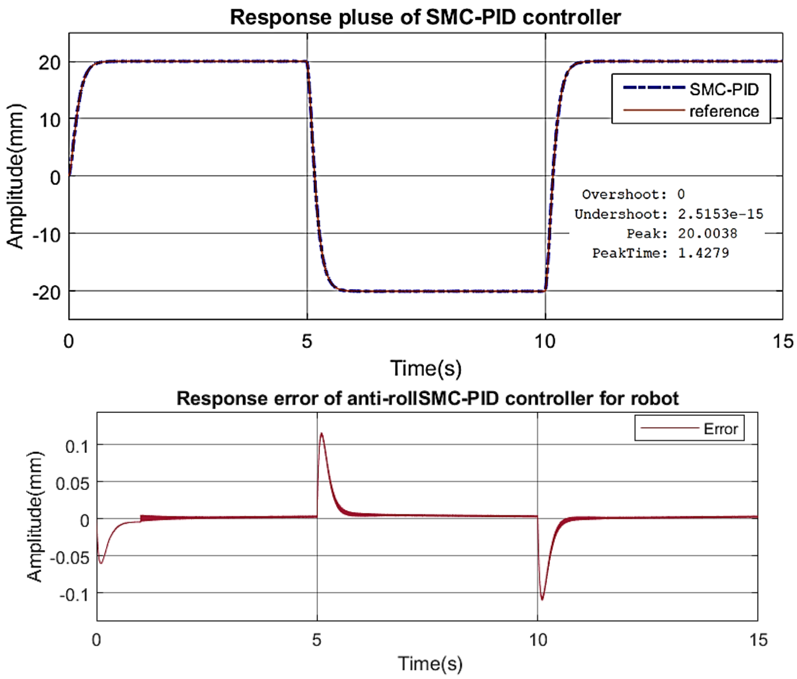

Figure 7. *Response and error of anti-overturn PID sliding controller for a robot with the pulse signal.*

The simulation results of the SMC-PID algorithm of the anti-roll system for the human transport robot when moving up the stairs with random noise signals are presented in figure 9, which also gives quite good results. The response of the controller still follows the desired signal. The response error is quite good, not larger than 0.07 mm. Through figure 9, we can further confirm the effectiveness of the proposed controller for the control process of the anti-roll mechanism for the human transport robot.

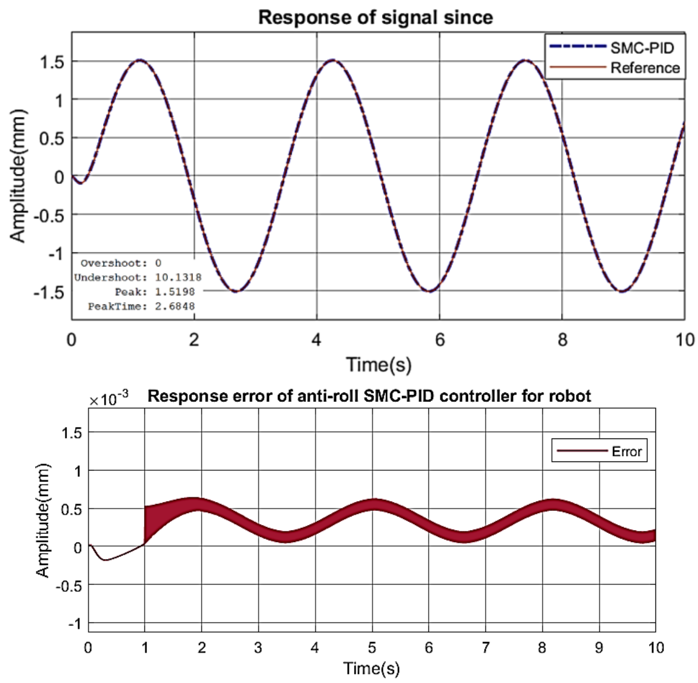

Figure 8. *Response of the anti-roll SMC-PID controller for the robot to a sine signal.*

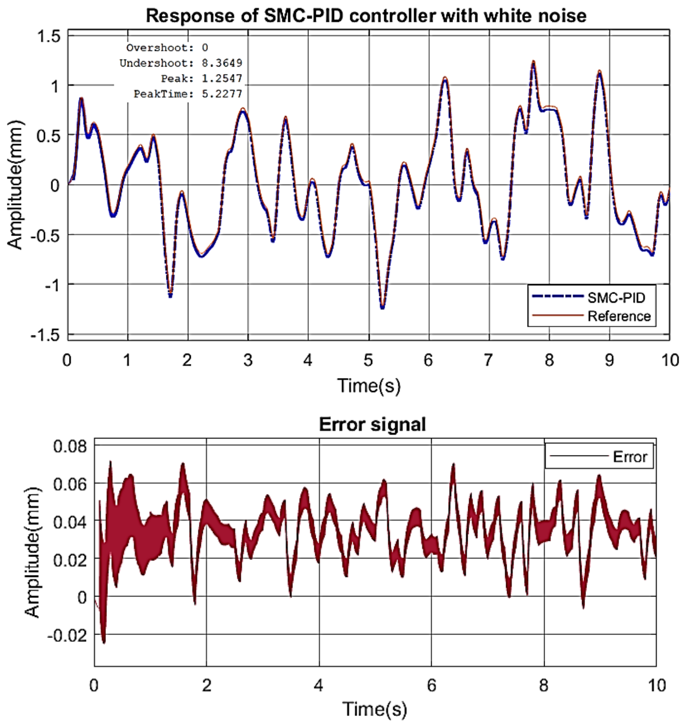

Figure 9. *Response to noise and error of SMC-PID controller.*

The comparison results of the response of the SMC-PID controller with the basic PID, SMC controller used for anti-rollover control of the human transport robot are presented in figure 10. The simulation results show that the response of the SMC-PID controller is better than that of the PID, and SMC controller. The response time and chattering phenomenon of the sliding controller are improved.

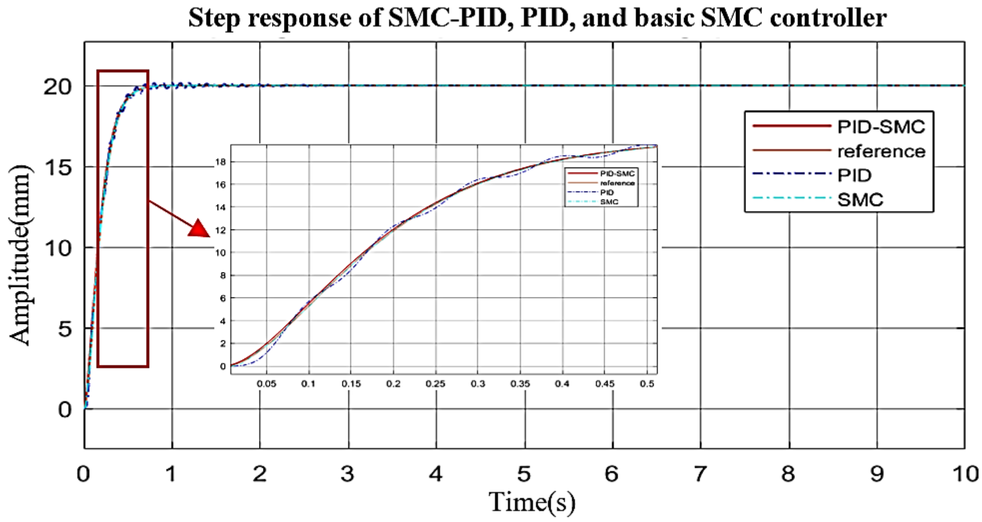

Figure 10. *Step response of SMC-PID; SMC; PID controllers.*

5. CONCLUSIONS

In this paper, the authors have applied the PID sliding control algorithm to build an anti-roll control algorithm for a robot that transports people up and down stairs. The anti-roll control mechanism for the robot that transports people is built based on the operation of a linear actuator, and an electric cylinder. The response of the built control method ensures that the user's center of gravity position follows the desired position, while the deviations during the control process are relatively small. The simulation results with MATLAB/Simulink show the effectiveness and suitability of applying the SMC-PID controller to the control process of the center of gravity position of the robot that transports people. The position response of the system compared to the set value has met the requirements, but there are still some fluctuations in the control. For better control results, the research team will continue to build controllers that adapt to changes in load and sudden changes in the environment. This is the basis for the group to manufacture specialized robots to transport people.

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TÓM TẮT

Ứng dụng thuật toán điều khiển trượt PID điều khiển chống lật cho robot vận chuyển người

Bài báo trình bày thuật toán điều khiển trượt PID được ứng dụng trong điều khiển chống lật cho robot vận chuyển người lên, xuống cầu thang. Robot vận chuyển người di chuyển trên các địa hình phức tạp cần được phân tích và điều khiển chống lật trong quá trình di chuyển nhằm đảm bảo quá trình hoạt động của robot được hiệu quả và mang đến sự an toàn cho người dùng. Quá trình điều khiển chống lật khi robot di chuyển được thực hiện thông qua điều khiển vị trí cơ cấu vận chuyển người bằng cơ cấu chấp hành tuyến tính là xi lanh điện. Thuật toán điều khiển trượt với mặt trượt PID được áp dụng điều khiển đáp ứng của xi lanh điện tuyến tính theo sự thay đổi độ dốc của cầu thang đảm bảo quá trình chống lật cho robot thông qua dịch chuyển trọng tâm người dùng. Kết quả mô phỏng của ứng dụng bộ điều khiển trượt vào điều khiển chống lật cho robot được thực hiện trên phần mềm Matlab/Simulink. Vị trí của cơ cấu chống lật thay đổi tuyến tính theo độ dốc cầu thang, qua đó cho thấy tính hiệu quả của bộ điều khiển trong quá trình điều khiển chống lật cho robot. Qua mô phỏng cho thấy tính hiệu quả của thuật toán đề xuất, điều này giúp cho quá trình thiết kế và chế tạo robot vận chuyển người trở nên hiệu quả hơn.

Từ khoá: Robot vận chuyển người; Điều khiển trượt PID; Điều khiển chống lật.