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Control Solusions for Stair Climbing Robot Mechanism

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Abstract. The paper presents an adaptive control method for robots transporting people up and down stairs. The research focuses on controlling the adaptive mechanism of a crawler-driven electric wheelchair robot that can adapt to the operating environment that is the intersection of the end point of the stairs and the plane to the next floor. The response of the system will affect how much free fall the robot will fall when moving through this environment. The control process is carried out through two stages of the structure, the first stage when the robot has just crossed all the steps and is about to move up the stairwell, the second stage when the robot prepares to move down the stairs from the stair sill. Research and build a robot control solution using distance sensors combined with PI-FUZZY adaptive control algorithm. The results of simulation and experiments show the effectiveness of the measurement solution to determine the location as well as the operating status of the robot. The built adaptive control algorithm has increased the system's responsiveness to changes in the staircase environment. The robot moves through the stairs without sudden fluctuations. The research creates a premise for the design and manufacture of robots to transport people up and down stairs to become more specialized and safer.

Keywords. Adaptive control, control PI, climbing stair robot, distance sensor

1. Introduction

Crawler electric wheelchair robots are robots capable of transporting people up and down stairs with different steps, but the phenomenon of fluctuations during movement is quite large when the robot moves up the stairs, which creates an unsafe feeling for users. The phenomenon of free fall often occurs when the robot moves from the last stair position to move on the plane to the next floor, both of which make accidents often occur during the robot's human transport. The reason may be that the robot lacks mechanisms to adapt to the operating environment or may be due to the ineffective response of these adaptive mechanisms. Currently, studies on the design and control of this adaptive structure in an automated way have not been studied much, and the majority of studies have carried out control through observation of the robot's movement position. In the study [1] a vibration reduction mechanism was used thanks to a cylinder that controls the mechanism adapted to the staircase, the system acts as a trap and is controlled manually through the user's adjustment. Study [2] uses 2 support mechanisms in front and rear to go up and down stairs. These two mechanisms have many disadvantages when the stairs are of different sizes, and at the same time it is easy to tip over when the mechanism is not suitable for the stairs, the control system has not yet applied adaptive control to the system. In the study [3] the authors used the

[1] staircase adaptation mechanism when moving up and down, which is controlled automatically through sensors and calculations in mathematics. However, the research was carried out with a fixed staircase size, the automatic adaptation mode has not yet been implemented, the operation process of the adaptation mechanism is carried out when the robot stops and waits for the adaptation mechanism to work. In the study [4], the lifting and lowering mechanism of the system is also used when moving up and down the stairs. The system is researched and controlled manually, is still in the process of simulation, and has not yet been implemented in practice. There are also a number of studies of cranial structures, adaptive mechanisms that work through the manipulation of state angles between different steps presented in the study [5], [6], [7]. The tension control of the drive belt helps the robot to adapt to the stairs carried out in the study [8]. Most of the studies

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have also carried out the control of this mechanism through the observation of robot operators, so the response of the adaptive system and the safety of users are not high. Robots transporting people up and down stairs require high safety during movement, the implementation of automatic adaptation helps the robot minimize fluctuations, and the rollover of the robot is also limited. The robot's movement makes the user's vision of the star limited, so the introduction of automated control solutions and algorithms helps to overcome this, and the system's responsiveness is also enhanced. In this study, we will propose an automatic solution to reduce vibration for the process of going up and down the end of the stairs through the application of a control algorithm that adapts to the linear actuator. Control signals are built in case the robot moves up the stair platform and prepares to move down the stairs. The robot moves on different staircase terrains, so the signal from the sensor has a large deviation because the construction of a measurement solution by multi-sensor combination is carried out and the filtering of the sensor signal is also applied in the study. The dynamic equations of the robot's staircase adaptation mechanism are presented. The control process of the adaptive mechanism based on the control law is built to ensure that the response of the system can operate stably, adapting to different ladder sizes. The paper is organized with the following structure: Section 2 presents the operating status of the robot and the equation for controlling the executive mechanism. Section 3 details the adaptive controller. Modeling and simulation of the adaptive mechanism control algorithm is presented in section 4. Finally, the conclusions and proposed directions of the paper are shown in section 5.

2. Methodology

2.1. Stages of operation of the adaptive structure

The human transport robot is designed with the system structure as shown in Figure 1. The adaptive system during moving up and down the stairs is designed with a linear actuator combined with Omni wheels to help the robot bear part of the robot's force. The adaptation system is based on the distance from the support wheel to the stair platform to control the actuator to adapt to the robot's movement.

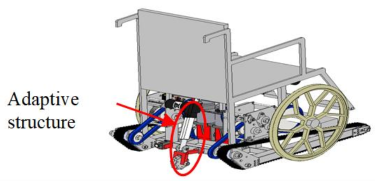

Figure 1. Stair climbing robot model.

The adaptive mechanism control of the robot transporting people up and down the stairs operates when moving up the stair platform and the stage of preparing to go down the stairs is considered with 4 stages: the stage of preparing to go up the stairs (2a), the stage of being on the stairs (2b, c), the grounding stage (2e), the stair descent preparation stage (2f). Ultrasonic sensors, infrared sensors are used to determine the robot's position and distance when moving through stairs. The installed sensor location and the operating states of the adaptive mechanism are shown as Figure 2

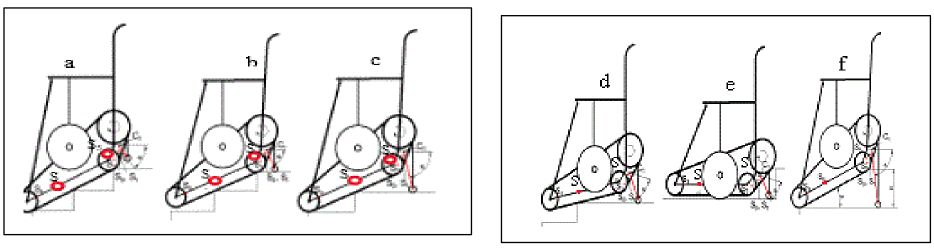

Figure 2. Diagram of the stages of operation of the adaptive structure.

The automatic operation process of the adaptation mechanism is carried out by two ultrasonic sensors S_0 and S_1, the distance of the support wheel is measured by the S_3 ultrasonic sensor and the travel of the support wheel is measured by the C_1 optical encoder, the S_4 and S_5 sensors are used to detect the presence of steps and the end of the stairs when going down and up the stairs. All the adaptation depends on the response time of the linear actuator as the electric cylinder is fitted as Figure 2. Starting the robot support cycle, the S_5 sensor will detect all the steps, at this time the S_3 ultrasonic sensor will measure the distance from the support wheel to the stair platform, the controlled actuator moves down according to this distance.

When the position of the support wheel is equal to the measured distance, the electric cylinder stops. The S_6 sensor determines the robot's stable position on the stair platform, then signals the cylinder to move to the moving position on the plane. The mechanism adapts when moving down stairs according to the measurement value from the S_4 sensor. Similar to the process of going up the stairs, the S_6 sensor determines the robot's position while going down the stairs, the electric cylinder retracts the wheel to carry out the process of going down the stairs.

2.2. Kinematic Equations of the Executive Structure

The electric cylinder is the actuator of the adaptive part on the human transport robot it has a basic structure including DC motor, gear set, screw nut, push lever. The quantities that affect the position control process of the support wheel mounted on the adaptive mechanism acting on the cylinder include the moment of bearing the load m TL (Nm), the friction moment Tf (Nm), the screw moment Tsrew (Nm), the engine moment TM (Nm), these quantities are shown as Figure 3. The control motor for the electric cylinder is a DC motor, FL(N) is the force generated by the electric cylinder that performs the support of the robot when moving.

$$F_L = F_g + F_a + F_f \quad (1)$$

Where Fg (N) is the gravitational force, F_a (N) is the acceleration repulsive force, F_f (N) is the frictional force.

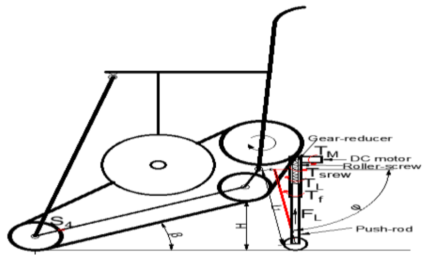

Figure 3. Structure and force moments of electric cylinder.

The equation for an electric motor that drives an electric cylinder is presented as follows:

$$V(t) = L_m \frac{di}{dt} + R_m i + K_b \omega$$
$$\Rightarrow \frac{di}{dt} = \frac{1}{L_m}\left[V(t) - R_m i - K_b \frac{d\theta}{dt}\right]$$

(2)

Where L_m (H) - armature inductance, R_m (Ω) - armature resistance, K_b (V/rad/s) - armature dynamic power factor, ω (rad/s) - rotation speed of the motor, θ (Arc) - rotation angle of the motor shaft, i (A) - current, V (V) - armature voltage.

$$J_m \frac{d^2\theta(t)}{dt^2} = K_t i(t) - b\frac{d\theta(t)}{dt}$$

(3)

In which J_m (kg*m^2) - Moment of inertia of the rotor, b (Nms) - Damping coefficient, K_t (Nm/A) - Moment coefficient.

Moment:

$J\dot{\omega} = T_M - T_f - T_L$ (4); $T_f = f_b \frac{d\theta}{dt}$ (5) $T_L = \frac{F_L P}{2\pi\eta n}$ (6);

$$J\frac{d^2\theta}{dt} = Ki(t) - f_b\frac{d\theta}{dt} - \frac{F_L P}{2\pi\eta n} \quad (7)$$

Where J (kg*m^2) is the moment of inertia of the screw (J = Jm + JL.n), f_b is the coefficient of viscous friction of the drivetrain, P (mm) is the step of the screw, η is the system performance, n is the ratio of transmission, J is the moment of inertia of the drivetrain.

The ΔL displacement of the electric cylinder is controlled through the distance signal received from the S_3 ultrasonic sensor, and the stroke of the cylinder is measured by the encoder mounted with the spindle of the electric cylinder fixing rod, so we can establish the relationship between the cylinder stroke length and the measured value of the

$$\varphi = \frac{n_1}{n_0}360 \qquad (8)$$

Replace the formula (6) with the expression(5):

$$J\frac{d^2\theta}{dt} = Ki(t) - f_b\frac{d\theta}{dt} - \frac{F_L}{\eta\theta}\Delta L \qquad (9)$$

In which L_1 is the length of the vertical cylinder fixing rod of the robot, L_0 is the initial length of the Equation (9) can be represented as a state equation as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \frac{1}{J}[Ki(t) - f_b x_2(t) - \frac{F_L}{\eta x_1(t)}\Delta L] \end{cases}$$

(10)

2.3. Building an Adaptive Control Algorithm

A fuzzy controller is an intelligent controller, based on the "If-Then" laws, with the advantage that it does not require a mathematical model of the control object, so it can be effectively applied to complex systems and even to nonlinear systems [9], [10]. The PI-Fuzzy control algorithm is used in linear actuator control to ensure that the response of the system is fast with zero steady-state error [11]. The adaptive mechanism controller of the input of the built-in dimming controller is the distance measured from the sensor that determines the

encoder as follows:

$$\Delta L = L_1 - L_0 = L_1\sin(\varphi) - L_0 = \frac{\theta P}{2\pi n}$$

electric cylinder, ɸ is the rotation angle of the cylinder fixing rod, n1 is the number of pulses received from the Encoder and n_0 is the number of pulses read from the encoder in 1 rotation of the cylinder fixing rod spindle.

Set $x_1 = \theta(t)$, $x_2 = \dot{\theta}(t)$ and the system output is $y(t) = \theta(t) = x_1$

height of the support wheel position to the platform plane. The output of the controller will be the speed of the electric cylinder to ensure the position of the support wheel meets the system. When moving, the factors of cylinder placement point deviation, rotational friction and other impacts are ignored. Based on the hardware structure installed on the robot, the dim PI-controller is built with two inputs, E ∈ [-255, 225] and DE ∈ [-255, 255]. The output is DU ∈ [-255, 255]. In this study, three language variables are used for the input blurring process, Low, Medium, and High, respectively, for the near, medium, and farthest distance of the perpendicular line from the support wheel to the horizontal plane. The output used with the five language variables of Very-Slow, Slow, Medium, Fast and Very-fast is equivalent to the five speeds of an electric cylinder. The input-output variable interfunctions are shown in Figure 4.

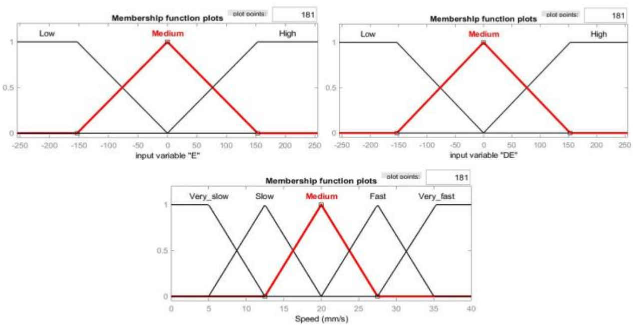

Figure 4. Function of the input-output variable of the PI-Fuzzy controller.

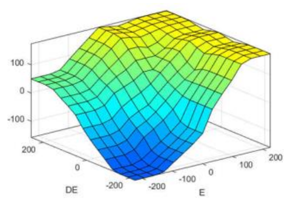

Figure 5. The face that puts the representation of the relationship in and out.

For fuzzy controller design, it is important to establish interdependent functions and control laws because they are established based on the experience of the expert. Based on experience and experimentation, with two input quantities with 3 language variables and five output variables, the control law of the system has been formulated as follows : (Table 1)

Table 1. PI-Fuzzy Control Rules for Electric cylinders.

DE / E	Low	Medium	High
Low	Very-slow	Slow	Fast
Medium	Slow	Medium	Fast
High	Medium	Fast	Very-fast

3. Result and Discussion

The experiment was conducted on matlab Simulink software with a system built based on the model of a human transport robot system. The proximity sensors will be read directly and through a low-pass filter to process a portion of the sensor's noise signal. The control process is carried out with glass rings. The control model consists of a distance calculation block, two PI-Fuzzy controllers that control the adaptation process when going up and down stairs and when running on a flat surface, an input signal block used to carry out the step detection signal, and finally an electric cylinder actuator. The model is constructed as shown in Figure 6.

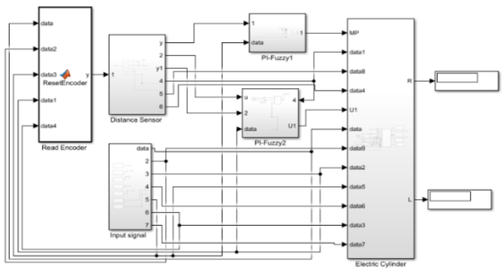

Figure 6: Simulink Matlab simulation diagram.

The experiment was carried out with stairs with a slope of about 350, the experiment was conducted with two stages of the robot: when moving up the stair platform and moving down the stairs. The control system diagram is shown in Figure 6, with the stage when moving up the ladder the robot performs the adaptation by moving the electric cylinder down and ends the travel journey when the support wheel distance is equal to the measured distance from the sensor. At this time, the robot moves to the stage of lowering the stair platform and moving on a flat surface. The experimental results presented in Figure 7 show that as the distance of the measured sensor increases, the response of the cylinder still follows, and the cylinder travel distance will be stable when the support gear has landed. When returning to move on the stair sill, the response to the position of the electric cylinder still ensures that the support wheel distance is always in contact with the plane and stable when the robot fully approaches the stair sill.

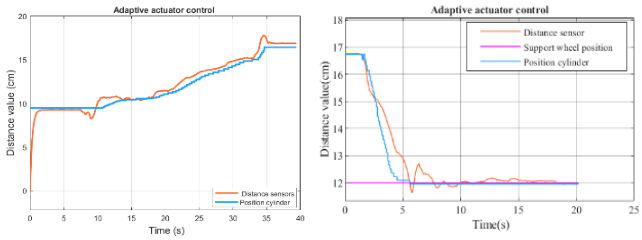

Figure 7. Experimental results of controlling the adaptive mechanism position with the PI-Fuzzy controller.

When moving down the stairs, the robot depends on the height and width of the stairs to perform the movement. The results of the process of moving down the stairs are presented in Figure 8, it can be seen that the response of the robot follows the measured value, the error and the ridiculous jump of the system still ensure good system control. The system's response when the robot enters plane travel mode (Figure 9) with the crawler 70 mm above the ground indicates that the controller still responds as desired. However, it can be seen that the response time of the system is still limited.

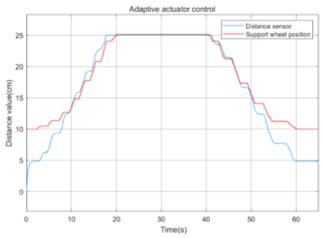

Figure 8. Experimental results when moving down the stairs.

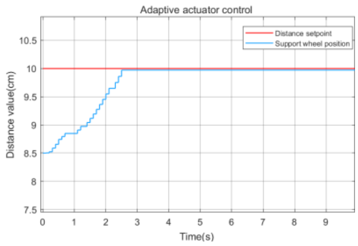

Figure 9. Experimental results when the vehicle switches to travel mode on a flat surface.

Through the experimental results on Matlab simulink, the model of the robot system that works directly on the stairs with a slope of 350, with a step height of 150 mm, and a step width of 300 mm is presented as shown in Figure 10. These results show that the automatic control solution for the adaptive mechanism works effectively, the robot does not oscillate when moving through the last step of the stairs nor when moving down the stairs. The measurement solution and control algorithm are suitable for the operation of robots that transport people across stairs by crawlers.

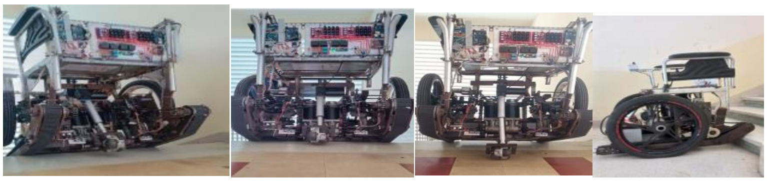

Figure 10. Experiment with robots adapting to stairs.

4. Conclusion

This paper presents an automatic control solution that adapts to the stairs of a human transport robot, by using an ultrasonic sensor and an external infrared sensor combined with an optical encoder to perform linear actuator control for the adaptive mechanism. The results showed that the robot was able to respond to the activity of moving on the last step of the stairs without oscillation. The effect of using the PI-Fuzzy algorithm to control the system adapts to the robot's movement. The response of the controller can be adapted to the different operating environments of the robot. However, this control process is still limited in terms of system optimization, but this problem can be overcome in the future with smarter algorithms, using filtering algorithms to filter signals better.

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