



Robot model transporting people climbing stairs

Mô hình robot vận chuyển người leo cầu thang

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Abstract

The paper presents the results of an experimental analysis of the robot's movement process when transporting people up the stairs of a building. The robot's dynamic equation is set with the center of gravity coordinates that are automatically adjusted stably to all terrains, taking into account the ability to resist rollover. Experiment with a standard staircase with a slope of 3.5° shows that the robot's automatic balancing mechanism and adaptive mechanism respond well during movement. When going up the stairs, the robot does not tip over, the oscillation at the end of the stairs decreases, and the reliability of the properly established dynamic equations of the human transport robot structure is validated. The results of this research can be applied in the design and manufacture of specialized robots for transporting people with disabilities.

Keywords: robotic balancing; robotic dynamics; robot model; adaptive.

Tóm tắt

Bài báo trình bày kết quả phân tích thực nghiệm quá trình chuyển động của robot khi vận chuyển người lên cầu thang trong một tòa nhà. Phương trình động lực học của robot được thiết lập với tọa độ trọng tâm được tự động điều chỉnh ổn định theo mọi địa hình, có tính đến khả năng chống lật. Thực nghiệm với cầu thang tiêu chuẩn có độ dốc của cầu thang là 3,5° cho thấy cơ chế cân bằng tự động và cơ chế thích ứng của robot phản ứng tốt trong quá trình di chuyển. Khi lên cầu thang, robot không bị lật, dao động ở cuối cầu thang giảm và độ tin cậy của các phương trình động lực học được thiết lập hợp lý của cấu trúc robot vận chuyển người đã được xác nhận. Kết quả của nghiên cứu này có thể được ứng dụng trong thiết kế và chế tạo robot chuyên dụng để vận chuyển người khuyết tật.

Từ khóa: cân bằng robot; động lực học robot; mô hình robot; thích ứng.

1. Introduction

The mobility of people with lower limb polio is difficult as high-rise buildings are growing, including in rural areas. Robots capable of transporting people are devices that help them

overcome difficulties, but so far the research on robots with this function is still limited, not meeting the needs of people with disabilities. The biggest limitation is the problem of robots transporting people having to overcome the

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steep slope of the stairs of buildings without overturning. TaeWon Seo's research team, as well as Weijun Tao and colleagues, have built a robotic structure capable of climbing stairs. Although the robot's ability to move on stairs has been proven, its ability to transport people is still limited [1, 2]. The phenomenon of robots overturning during movement on stairs due to the inability to adapt to changes in the operating environment, the robot structure is quite complicated, and safety is not guaranteed. Regarding robots that transport people who are capable of moving on flat surfaces and moving on stairs with a structure consisting of wheels combined with crawlers, L. Xueshan Gao and Sulguti Sai Phani Kumar Reddy have spent a lot of time researching. They developed dynamic equations and experimentally tested this combined system [3, 4]. The anti-tipping due to the deviation of the robot's center of gravity during stair movement has also been reviewed and calculated by Weijun Tao, Yi Ou, and Hutian Feng through the analysis of the dynamics of robot control [5]. Even the problem of improving a robot with an auxiliary support mechanism to reduce tipping through synchronizing the drive system and adjusting the center of gravity according to the calculation of the robot's mechanical system has been initially researched by Weijun Tao, although the robot still needs rear support to ensure safety and is limited by the size of the ladder [6]. In his master's thesis, Homayoun Rastan built a structure and established a robot dynamics model capable of moving up the stairs in the forward direction and down the stairs in the opposite direction using a crawler [7]. However, this is just a pure robot, not to mention the robot's transportation application, so the issue of safety for users has been overlooked. The process of moving up the stairs in the direction of the user's gaze was analyzed by LI Jing-yi's research team using the center of gravity projection method

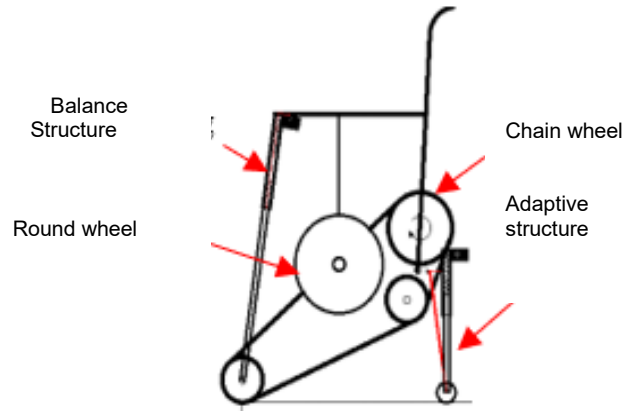
[8]. The kinematic model performed for the operation mode transition and automatic posture adjustment according to the terrain was carried out by the research teams of Bibhu Sharma and André A. Jorge. In particular, on the basis of the kinematic equations and dynamics of the robot, the authors have built a closed-loop control system to control deviations and maintain stability in the movement of the robot [9, 10]. Tian-Ci Jiang, Sheng-Hao Yin, and Eiichiro Tanaka analyzed the operation of robots on stairs, verifying their mobility and restriction of flipping through a logical control system between parts based on a kinematic, dynamic model built in [11]. A control principle for the stability of the robot was presented in [12].

It can be seen that in the above-mentioned studies, the kinematic model and dynamics of the robot system were used to test the robot's ability to move on stairs; the process of building the control algorithm was also based on the dynamics equations, and the limitations in the research process were also concluded. That shows that people transport robots are not really reliable for the use of transporting people on stairs. The research mentioned in this paper will come up with a robotic structure that transports people capable of automatically adjusting the robot's center of gravity and adapting to the operating environment. The robot kinematic equation is built on the basis of factors affecting the operation of the robot, such as the robot structure, the operating position, the contact point on the stairs, the user mass, the robot center of gravity balancing mechanism, and especially the adaptation mechanism at the end of the staircase.

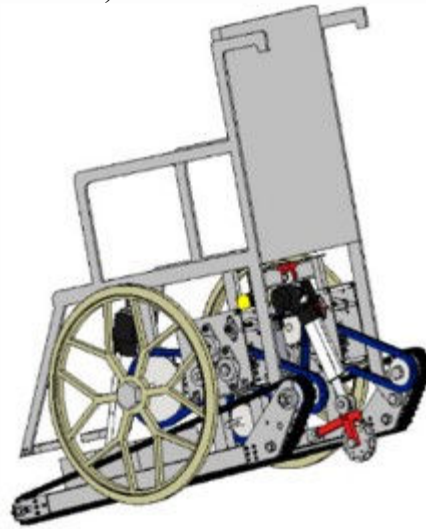
2. Model of a human transport robot

2.1. Model structure

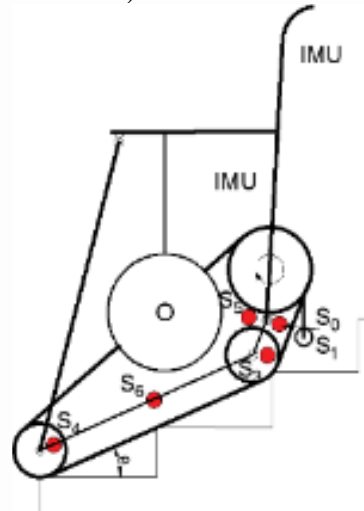
The general structure of the robot transporting people on the stairs of the building is set up as Figure 1.



a) General structure



b) 3D Model



c) Sensors

Figure 1. Human transport robot structure

The robot works with two separate modes: moving on a flat surface with a round wheel and moving on stairs with a crawler. The balancing mechanism automatically controls the balance

for the robot user, and the adaptive mechanism makes it possible for the robot to operate on all terrains without suddenly flipping backwards. When operating, the robot always comes into

contact with a minimum of 2 steps, so the flipping factor due to contact point limitation is not present. Microelectromechanical sensor systems and distance sensors are used to determine the robot's position and operating status.

In normal mode, the robot moves with 2 round wheels combined with the support of extra wheels on the plane. When going up and down stairs, the robot always moves with crawlers in the direction of the user's top-down view. When starting to go up the stairs, the robot activates the balancing mechanism through the sensors s_0, s_1 . Sensors s_3, s_4, s_5, s_6 , locating the robot as it moves, help control the mechanism to adapt to changes in the staircase. The IMU sensor will measure the tilt angle θ (0) as the robot moves up the stairs, and the anti-tipping balance mechanism will be adjusted according to the change in the robot's tilt angle. On the robot there is also a sensor s_2 to determine the motion state of the sprocket.

2.2. Motion model of the human transport robot

The robot's up and down the stair movement is analyzed with a controlled center of gravity coordinate system that changes according to the angle of inclination (Figure 2). The center of gravity of the robot frame, G_R (l_{Rx}, l_{Ry}) and G_n (l_{nx}, l_{ny}) is the coordinate of the center of gravity of the balance mechanism for the robot (chair). The coordinate system when the robot moves on a plane (Figure 2a) is set as follows:

$$\begin{cases} l_{Rx} = L \cos \beta \\ l_{Ry} = L \sin \beta \end{cases}; \begin{cases} l_{nx} = a_2 - b \cos \alpha_0 \\ l_{ny} = c + b \sin \alpha_0 \end{cases} \quad (1)$$

Where: l_{Rx} (mm), l_{Ry} (mm), l_{nx} (mm), and l_{ny} (mm) are the centers of gravity of the robot frame along the x-axis and y-axis, respectively; L (mm) is the distance between the coordinate system and the center of gravity; a_2 (mm) is the passive wheel distance and the seat rotation shaft position according to the x-axis; c (mm) is the distance from the seat swivel shaft to the sprocket face; α_0 ($^\circ$) is the angle of rotation of the chair; β ($^\circ$) is the angle of gravity of the robot frame relative to the chain; b (mm) is the distance from the center of gravity of the seat to the spindle.

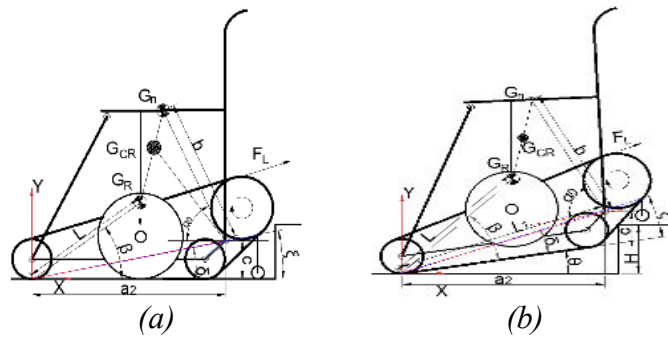


Figure 2. Diagram of the coordinate system of the stage when the robot begins to move up the stairs

When the robot starts moving on the steps with an angle of inclination θ (Figure 2b), the coordinate system is changed according to the inclination of the robot as follows:

$$\begin{cases} l_{Rx} = L \cos(\beta + \theta) \\ l_{Ry} = L \sin(\beta + \theta) \end{cases}; \begin{cases} l_{nx} = a_2 \cos \theta - b \cos \alpha_0 \\ l_{ny} = c + a_2 \sin \theta + b \sin \alpha_0 \end{cases} \quad (2)$$

The center of gravity of the robot, G_{CR} (l_{cx}, l_{cy}) is controlled to limit the robot from tipping over. The position of the robot's center of gravity is determined on the basis of the robot's center of gravity position, G_R , and the robot's center of gravity, G_n , which varies with the angle of inclination θ .

$$\begin{cases} l_{cx} = \frac{m_n l_{nx} + m_R l_{Rx}}{m_e} \\ l_{cy} = \frac{m_n l_{ny} + m_R l_{Ry}}{m_e} \end{cases} \Rightarrow \begin{cases} \dot{l}_{cx} = \frac{m_n \dot{l}_{nx} + m_R \dot{l}_{Rx}}{m_e} \\ \dot{l}_{cy} = \frac{m_n \dot{l}_{ny} + m_R \dot{l}_{Ry}}{m_e} \end{cases} \quad (3)$$

In which $m_n(\text{kg})$, and $m_R(\text{kg})$ are the mass of people and the mass of the robot; $m_e(\text{kg})=m_r+m_n$ is the total volume of robots. The robot's

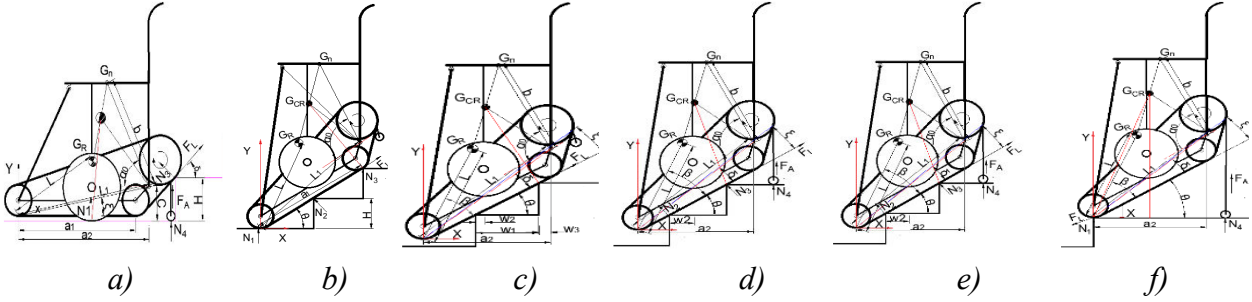


Figure 3. Stages of the robot moving up the stairs

$$\begin{aligned} \sum F_x &= F_L \cos \delta - N_3 \sin \delta + \frac{\eta m_e g l_p}{l_p + l_w + \eta l_{cy}} = m_e \ddot{l}_{cx} \\ \sum F_y &= -m_e g + N_1 + N_4 + N_3 (\cos \delta + \eta \sin \delta) = 0 \quad (4) \\ \sum M_R &= N_1 l_w - N_4 l_p - \frac{\eta m_e g l_p}{l_p + l_w - \eta l_{cy}} l_{cy} = 0 \end{aligned}$$

In which l_p (mm) is the distance of the robot's center of gravity to the support wheel position; l_w (mm) is the distance of the robot round wheel on the ground; η is the coefficient of friction; $N_1(\text{N})$, N_3 (N), N_4 (N) are the jet forces at the stairwells; $F_L(\text{N})$ is the traction of the sprocket; $\delta(^{\circ})$ is the angle of the sprocket; g (m/s^2) is the acceleration of the gravitational field. The robot performs the re-adaptation mechanism and moves completely by means of a crawler; the equation of dynamics of the state of movement to the first step of the staircase is represented as the system of equations (5):

$$\begin{aligned} \sum F_x &= (F_L + \eta N_3) \cos(\delta + \theta) - \eta N_1 \sin(\delta + \theta) = m_e \ddot{l}_{cx} \\ \sum F_y &= (F_L + \eta N_3) \sin(\delta + \theta) - m_e g + N_1 (1 + \eta \cos(\delta + \theta)) = m_e \ddot{l}_{cy} \\ \sum M_R &= -m g \left(\frac{C_c}{\tan(\alpha_3 - \theta)} + l_3 \right) + N_1 (\eta H - a_3) = (m_e R_c + I_s) \ddot{\theta} \end{aligned} \quad (5)$$

$$R_c = \sqrt{(l_{cy} - H)^2 + \left(\frac{C_c}{\tan(\alpha_3 - \theta)} + l_3 \right)^2}$$

movement process and factors affecting the robot's operating status when climbing stairs are shown as Figure 3.

When the robot operates on a flat surface (Figure 3a), the sensors perform the stair climbing mode transition. The kinematic equation [13] in this mode is as follows:

In which $R_c(\text{mm})$ is the distance from the robot's center of gravity to the first step; $C_c(\text{mm})$ is the distance from the center of gravity to the seat rotation axis along the axis Y; l_3 (mm) is the distance from the stairs to the center of the chair rotation axis, a_3 (mm) is the distance from the passive wheel to the stairs; H (mm) is the height of the ladder; $\theta(^{\circ})$ is the angle of inclination measured from the IMU; $\alpha_3(^{\circ})$ is the angle of the robot's center of gravity; I_s (kg.m^2) is the moment of inertia. The robot's flip moment begins to affect the operation process as the robot gradually moves up the stairs. The dynamic equation of the system in this stage is affected by two jets, N_1 , N_3 ; and the focus of change is built as follows:

$$\begin{aligned} \sum F_x &= (F_L + \eta(N_1 + N_3)) \cos \theta - N_3 \sin \theta = m_e \ddot{l}_{cx} \\ \sum F_y &= (F_L + \eta N_3) \sin \theta + N_1 + N_3 \cos \theta = m_e (\ddot{l}_{cy} + g) \\ \sum M_R &= N_1 (\eta H - a_1 \cos \theta - l_4) = I_s \ddot{\theta} + m_e (R_{c1}^2 \ddot{\theta} - g(a_2 - l_{cx} - l_4)) \end{aligned} \quad (6)$$

$$\begin{aligned} R_{c1} &= \sqrt{(a_2 - l_{cx} - l_4)^2 + (l_{cy} - H)^2} ; \\ l_4 &= (a_1 \sin \theta - H) / \tan \theta \end{aligned}$$

The robot length can be exposed to three steps at the same time. At this stage, the risk of tipping is less, but the possibility of tipping due to the

robot's center of gravity being unbalanced compared to the stair slope is greater. The equation of equilibrium dynamics at the stage where the robot moves with the staircase slope (Figure 3b) is as follows:

$$\begin{aligned} \sum F_x &= (F_L + \eta(N_1 + N_2)) \cos \theta - N_2 \sin \theta - \eta N_3 = m_e \ddot{l}_{cx} \\ \sum F_y &= (F_L + \eta N_2) \sin \theta + N_1 + N_2 \cos \theta + N_3 = m_e (\ddot{l}_{cy} + g) \\ \sum M_R &= -F_L \cos \theta (2H - a_1 \sin \theta) + (2N_3 + N_2)(\eta H + a_1 \cos \theta) \\ &\quad - N_2 w_1 = I_s \ddot{\theta} + m_e [g(a_1 \cos \theta - l_{cx}) + R_{c2}^2 \ddot{\theta}] \\ R_{c2} &= \sqrt{(a_1 \cos(\theta))^2 - l_{cx}^2} \end{aligned} \quad (7)$$

In which R_{c2} (mm) is the center of gravity distance to the first step in the direction of robot movement; w_1 (mm) is the width of the ladder; a_1 (mm) is the passive distance between the two wheels; a_3 (mm) is the distance from the robot's head crawler to the stair step; a_2 (mm) is the distance between the passive wheel and the rotating axis of the projection seat on the OX.

The robot begins to switch adaptation mode, reducing oscillation when the sensor detects the robot's position on the last step of the stairs (Figure 3c). When it reaches the last step of the robot starting to leave the stairs (Figure 3c), this is the stage when the risk of tipping is highest, and then the dynamic equation that controls the balance of the robot is as follows:

$$\begin{aligned} \sum F_x &= (F_L - \eta(N_3 - N_2)) \cos \theta - N_2 \sin \theta = m_e \ddot{l}_{cx} \\ \sum F_y &= F_L \sin \theta + (N_2 + N_3)(\eta \sin \theta + \cos \theta) = m_e (\ddot{l}_{cy} + g) \\ \sum M_R &= F_L (w_1 \sin \theta - H \cos \theta) - m_e g w_2 + N_3 (\eta H + w_1) = 0 \end{aligned} \quad (8)$$

In which w_2 (mm) is the distance from the first step to the center of gravity projection in the direction of movement; w_1 (mm) is the ladder width. The adaptation mechanism works thanks to sensors that locate the robot already on the stair platform (Figure 3d). The phase kinematic equation with adaptive structural participation is implemented as system (9):

$$\begin{aligned} \sum F_x &= [F_L - \eta(N_3 + N_4 - N_2)] \cos \theta - (N_2 + N_3 - F_A) \sin \theta \\ &= m_e (\ddot{l}_{cx} \cos \theta + \ddot{l}_{cy} \sin \theta) \\ \sum F_y &= (F_L + \eta N_4) \sin \theta + (N_2 + N_3)(\cos \theta + \eta \sin \theta) + F_A \\ &= m_e [\ddot{l}_{cx} \sin \theta + (\ddot{l}_{cy} + g) \cos \theta] \\ \sum M_R &= F_L (w_1 \sin \theta - H \cos \theta) + N_3 (\eta H + w_1) + \\ &\quad F_A \left[\frac{H_1}{\tan \theta} + w_1 \right] \\ &= I_s \ddot{\theta} + m_e (R_{c3}^2 \ddot{\theta} + g w_2) \end{aligned} \quad (8)$$

$$R_{c3} = \sqrt{\left(l_{cy} - \left(a_1 \cos \theta - \frac{H_1}{\tan \theta} \right) \tan \theta \right)^2 + \left(a_1 \cos \theta - l_{cx} - \frac{H_1}{\tan \theta} \right)^2}$$

$$F_A = F_g + F_a + F_f \quad (9)$$

In which H_1 (mm) is the distance from the stair platform to the original position of the support wheel; R_{c3} (mm) is the distance from the center of the robot to the last step of the stairs; F_A (N) is the lifting force of the adaptive mechanism; F_g (N) is the gravitational force; F_a (N) force is produced by acceleration; F_f (N) is the frictional force. The stage where the robot moves to the position as shown in Figure 3e has the center of gravity located on the stair platform position, so at this stage the robot rolls over in the direction of motion; the dynamic equation in this process is presented as equation (10).

$$\begin{aligned} \sum F_x &= (F_L + \eta(N_3 + N_4)) \cos \theta + (-N_3 - F_A) \sin \theta = m_e (\ddot{l}_{cx} \cos \theta + \ddot{l}_{cy} \sin \theta) \\ \sum F_y &= (F_L + \eta(N_3 - N_4)) \sin \theta + (N_3 - m_e g) \cos \theta + F_A = m_e (\ddot{l}_{cy} \cos \theta - \ddot{l}_{cx} \sin \theta) \\ \sum M_R &= [F_L (a_1 \cos \theta - l_{cx}) + N_3 w_2] \sin \theta + F_A \frac{H_1}{\tan \theta} \\ &\quad - m_e g [(H_1 - a_1) \cos \theta + l_{cx}] = (I_s + m_e R_{c4}^2) \ddot{\theta} \end{aligned} \quad (10)$$

$$R_{c4} = \sqrt{(a_1 \cos \theta - l_{cx})^2 + (l_{cy} - l_{cx} \tan \theta)^2}$$

In the above equation system, R_{c4} (mm) is the distance from the center of gravity to the platform, ending the staircase ascent phase when the robotic tilt angle is determined to zero. When the robot is about to move down the stairs, the mechanism adapts to the robot lifting operation in accordance with the slope θ . At the beginning of the stairway descent phase (Figure 3f) the step

detection sensor and the robotic position sensor provide the robot status control information. The

equation of dynamics of this stage is presented as follows:

$$\begin{aligned}\sum F_x &= (-F_L + \eta(N_3 + N_4)) \cos \theta = m_e [\ddot{l}_{cx} \cos \theta + (\ddot{l}_{cy} + g) \sin \theta] \\ \sum F_y &= [-F_L + \eta(N_3 + N_4)] \sin \theta + N_3 + F_A = m_e [(\ddot{l}_{cy} + g) \cos \theta - \ddot{l}_{cx} \sin \theta] \\ \sum M_R &= -F_A \tan \theta + \eta N_3 \sin \theta - F_L \sin(\theta) = I_s \ddot{\theta} + m_e [R_{c6}^2 \ddot{\theta} - g l_{cx}]\end{aligned}\quad (11)$$

$$R_{c6} = \sqrt{l_{cx}^2 + l_{cy}^2}$$

The dynamic equation of the robot when moving down the stairs is the same as the process of moving up the stairs; however, the impact force is F_L in the opposite direction.

3. Experiment

3.1. Initial conditions

The experiment was conducted with a human transport robot designed and built with a driving source as shown in Figure 1 and Figure 4,

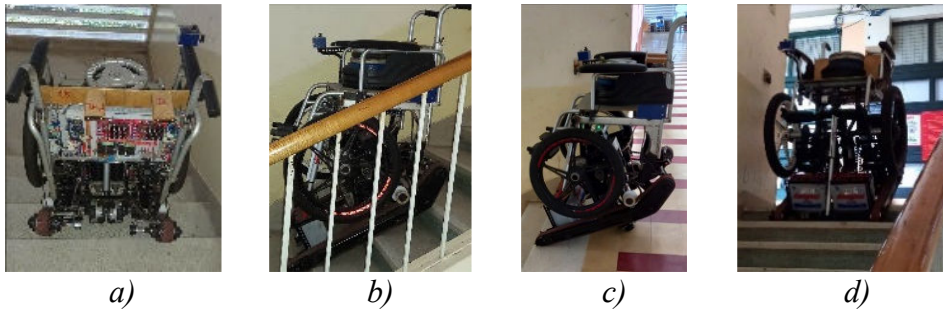


Figure 4. Robot experiments up and down stairs

4. Results and discussion

The results of the robot's center of gravity acceleration along the x-axis and y-axis are shown in Figure 5. The moment of the robot

structures and sensors as shown in section 2.1, the built mathematical models: (4), (5), (6), (7), (8), (9), (10), (11), and (12), objects weighing 100 kg to replace human weight, stairs with a standard slope of 35° ; central control circuits and component control circuits connected to sensors, actuators, and computers.

3.2. Illustration images

The experiment was repeated several times, and the signal acquisition results were randomly taken from one of the above iterations, Figure 4.

operating with the staircase slope is shown in Figure 6; in Figure 7 is the result of the robot balancing mechanism response.

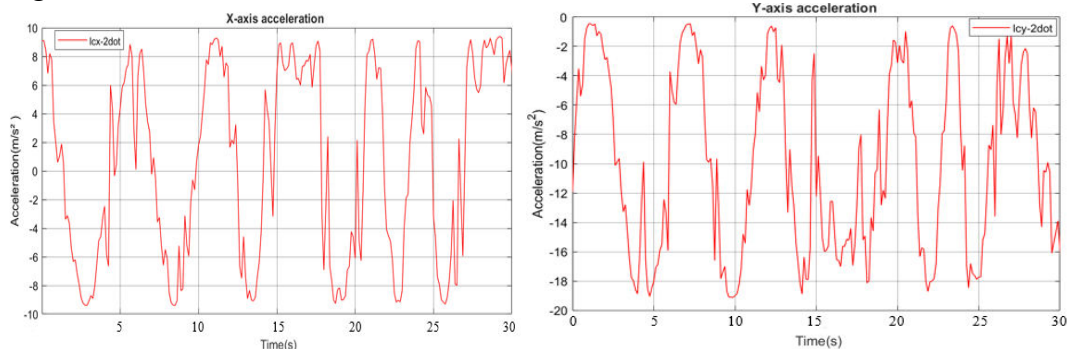


Figure 5. Acceleration of the robot's center of gravity along the x-axis and y-axis

The results show that the robot begins to balance and move up the stairs with a signal from the IMU sensor; the robot's center of gravity control mechanism lowers the robot's center of gravity to perform the mode of moving up the stairs in the first seconds, the robot's center of gravity will be continuously adjusted during the movement. When the robot moves to the 15th second, it will switch modes to adapt to the staircase slope; the robot's center of gravity

is in balance with the response of the adaptation mechanism as shown in Figure 7. At the end of the robotic staircase, the moment of movement will be reduced; the response of the adaptive mechanism can reduce oscillations while the robot descends completely to the stairwell. As the robot moves down the stairs with automatic adaptation from the stair step determination sensor, Figure 8, Figure 9.

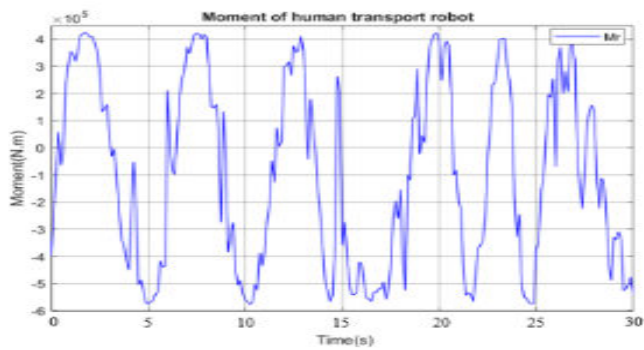


Figure 6. Moment of the robot transporting people

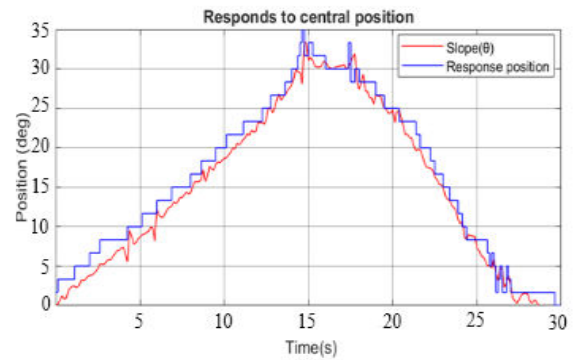


Figure 7. Meet the seat position according to the slope of the stairs

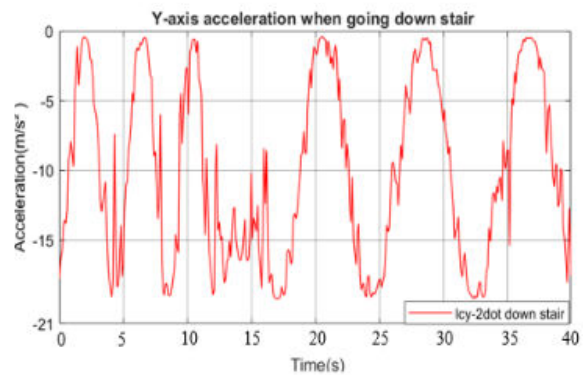
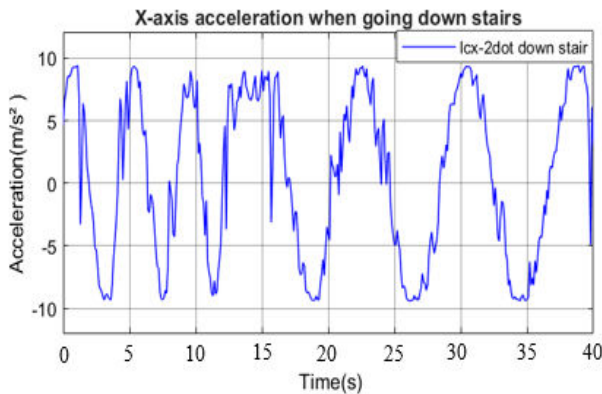


Figure 8. Acceleration of the robot's center of gravity along the x-axis and y-axis when descending stairs

The slope θ when the robot performs lifting and moving down is shown as the red line Figure 1. In the first 10 seconds, the robot completes the lifting and starts moving down in 16 seconds. In

this process, the center of gravity balancing mechanism also performs a slope balancing process like the blue line in Figure 10.

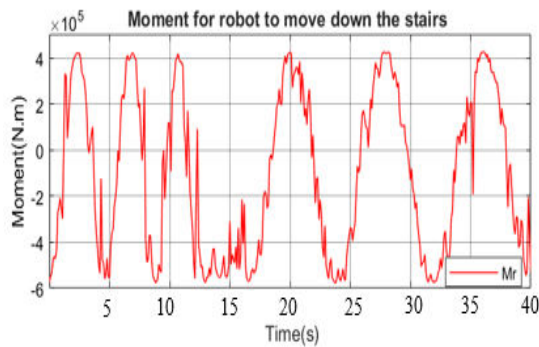


Figure 9. The moment of the robot when moving down the bridge

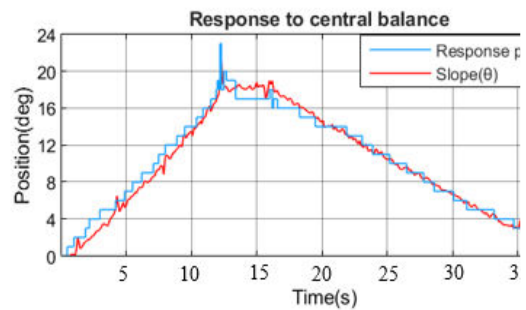


Figure 10. Response of the robot's center of gravity when descending stairs

5. Conclusion

The robot kinematic equation is built on the basis of factors affecting the operation of the robot, such as the robot structure, the operating position, the contact point on the stairs, the user mass, the robot's center of gravity balancing mechanism, and especially the influence of the adaptive mechanism at the end of the staircase. The experiment was conducted with a human transport robot designed and built. Objects weighing 100 kg replace the mass of people; stairs have a standard slope of 3.5° . The experiment was repeated several times; the signal acquisition results were randomly taken from one of the repetitions, and the results did not change much. To sum up, the robot can move up and down stairs; the robot balancing process through a dynamic equation is built to ensure that the robot does not tip over; and the center of gravity of the robot can ensure safe operation when the robot moves with a standard slope. The construction of intelligent controllers and optimal research on the basis of the built equations should continue to be considered.

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