MINISTRY OF EDUCATION AND TRAINING
MINISTRY OF AGRICULTURE AND ENVIRONMENT
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STUDY ON DYNAMICS AND CONTROL OF INDUSTRIAL FACTORY FIRE-FIGHTING ROBOTS

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Code: 9.52.01.03

SUMMARY OF DOCTORAL THESIS IN ENGINEERING

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The thesis was defended before the professional thesis evaluation council meeting at: Forestry University - Xuan Mai, Chuong My, Hanoi

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LIST OF ARTICLES AND SCIENTIFIC WORKS PUBLISHED

1. Hoang Son, **Nguyen Xuan Nguyen** , Nguyen Pham Thuc Anh, Nguyen Thi Huyen (2023). *Research on dynamics of industrial factory fire fighting robot during stair climbing* . Journal of Forestry Science and Technology, No. 2(2023), ISSN: 189-3828

2. Son Hoang, Anh Nguyen Pham Thuc, **Nguyen Xuan Nguyen** (2023). *Designing and Control Track-Belt Robot for Firefighting Task* . 2023 7th International Conference on Robotics and Automation Sciences , Electronic ISBN: 979-8-3503-1356-7, DOI: 10.1109/ICRAS57898.2023.10221617

3. Hoang Son, Vu Khac Bay, Nguyen Pham Thuc Anh, **Nguyen Xuan Nguyen** , Hoang Ha, Nguyen Thai Van (2024). *Research on the overturning phenomenon of firefighting and rescue crawler robots when climbing up and down* stairs. International Journal of Intelligent Robotics and Applications, ISSN (Print): 2366-5971, DOI:org/10.1007/s41315-024-00394-3 .

INTRODUCTION

1. Problem statement

Vietnam is a developing country, the urbanization rate is increasing rapidly, many residential areas, high-rise buildings are being built, many factories, enterprises, production workshops are being built, many types of flammable materials are being used to build these projects. That means the risk of fire, especially large fires, fires causing serious damage is also increasing.

In developed countries such as Japan, Europe, America, and China, robots have been used in firefighting, thereby providing high firefighting efficiency and safety for firefighters.

In Vietnam, the use of robots for fire fighting is very limited. Robots imported to Vietnam are large robots that can only move on the road and cannot move on stairs to serve the fire fighting of factories and high-rise industrial buildings.

In order to have a scientific basis for the design, manufacture and completion of industrial firefighting robots, when moving on the stairs as quickly and stably as possible without tipping over, it is necessary to have a full and comprehensive study on the dynamics and control of the firefighting robot when moving to approach the fire on the stairs of an industrial factory. For the reasons analyzed above, the doctoral thesis chose the topic "Research on dynamics and control of industrial factory firefighting robots".

2. Purpose of the thesis research

Build a model, establish the dynamic equation of the fire-fighting robot when climbing up and down stairs. From the survey results, the established dynamic equation is used as the input basis to establish the control algorithm for the fire-fighting robot to move on the stairs at the fastest speed, stable and without tipping over.

3. New contributions of the thesis

1) The model has been built, the dynamic equation of the robot interacting with the stairs during the process of moving up and down the stairs has been established, the anti-overturn mechanism has been proposed through the counterweight position control algorithm, the dynamic equation system has been surveyed and determined:

- The optimal value of the robot climbing angle (tilt angle in front of the chain) is $\gamma = 45^o$;
- The influence of the values (stair slope angle β , robot climbing angle γ, robot maximum speed Vmax and counterweight acceleration a_Q) on the robot's ability to overturn;
- The corresponding pairs of values, for each value of the stair slope angle β and the robot climbing angle $\gamma$with the maximum climbing velocity of the robot Vmax, require the corresponding acceleration value of the battery pack a_Q so that the robot does not tip over.

2) Propose a fuzzy PID control method to control the counterweight movement from the middle position (center of the robot's center of mass) to the two extreme positions (top, bottom) with the desired acceleration a_Q to prevent the robot from tipping over.

3) The model and experimental method of the theoretical calculation model of dynamics and control of the Robot moving on stairs have been built. The experimental results obtained with the correlation coefficient $r > 0{,}8$,with this result show that the theoretical calculation model has the necessary reliability, from which the theoretical calculation model proposed in the thesis is acceptable.

4. Scientific significance of the research results of the thesis

By theoretical research method, the thesis has built a model, established the dynamic equation for the crawler robot when climbing stairs (up, down) without considering the dynamics leading to overturning. This result is the scientific basis for calculating the electric motor drive system for the crawler to ensure the robot is able to overcome obstacles (climb stairs) to approach the fire;

The research results of the thesis provide a scientific basis for calculating, designing and perfecting the movement and control system of industrial fire fighting robots.

5. Practical significance of the thesis

The results of the thesis have been applied to the design calculation and experimental manufacture and completion of industrial fire fighting robots under the project code DTĐL.CN-98/21. In addition, the results of the thesis are also used as reference material in teaching, in the research of stair climbing robots, and robots overcoming foreign obstacles.

CHAPTER 1
OVERVIEW OF RESEARCH

1.1. Overview of the use and research of firefighting robots in the world

1.1.1. Use of firefighting robots in some countries in the world




1.1.2. Overview of research projects on firefighting robots in the world

There have been many research projects on firefighting robots in the world, including research on design and manufacturing, research on the dynamics of robotic arms opening stairs, research on the stability of robots when moving on steep slopes. From the research results of authors around the world, it is a scientific basis for graduate students to study during their research

1.2. Overview of the situation of using and researching firefighting robots in Vietnam

1.2.1. Using firefighting robots in Vietnam




1.2.2. Overview of research projects on robots in Vietnam

Vietnam has had a number of limited research projects on firefighting robots. There have been independent state-level projects on research on the design and manufacture of firefighting robots for industrial buildings. These projects only focus on research on design and manufacture, and do not include research on the dynamics and control of robots going up and down stairs.

1.3. Research objectives

To build a model and establish the dynamic equations of a firefighting robot when climbing up and down stairs, to survey the established dynamic equations, and to use the survey results as the basis for establishing an algorithm to control a firefighting robot when moving up and down stairs so that the robot can approach the fire as quickly as possible, stably, and without tipping over.

1.4. Research content of the thesis

1.4.1. Theoretical research

- Building a dynamic model of a stair-climbing robot without considering the phenomenon of overturning, from which to establish an electric motor drive control system for the robot's crawler;
- Building a model, establishing the dynamic equation when the robot collides with the stairs, proposing an anti-overturn method;
- Surveying the dynamic equation, from which to calculate the parameters to control the movement of the counterweight to prevent overturning.
- Building an algorithm to control the robot moving up and down the stairs

1.4.2. Experimental research

Verifying the theoretical calculation model, comparing the experimental research results with the theoretical calculation results, thereby evaluating the reliability of the theoretical calculation model, and drawing conclusions from the experimental research results.

1.5. Research object of the thesis

1.5.1. Characteristics and parameters of industrial building fires

- Fires often easily develop into large fires, causing serious damage to goods, property and the lives of workers working in industrial buildings.
- Fire temperature parameters: According to research results, the temperature of a solid fire is about 800-1100 degrees Celsius, liquid fire is 1000-1200 degrees Celsius and gas fire is 1000-1300 degrees Celsius depending on the area and scale of the fire;

1.5.2. Stairs in industrial factories

Industrial factory stairs are built according to the standard QCVN 06:2022/BXD on fire prevention and fighting for construction works, the shape of the stairs is square (not spiral), the size parameters such as landing (described in Figure 1.16), slope β≤45^0, width of stair tread ≥250 (mm).1.2.2. Tổng quan về các công trình nghiên cứu về robot tại Việt Nam

Vietnam has had some limited research projects on firefighting robots. There has been an independent state-level project on research, design and manufacturing of firefighting robots for industrial buildings. These projects only focus on research, design and manufacturing, and do not include research on dynamics and control of robots going up and down stairs.

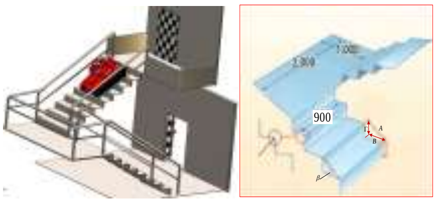


Figure 1.16: Industrial factory staircase specifications

1.5.3. Industrial building fire fighting robot

The research equipment is an industrial building fire fighting robot manufactured in the first version (version for research purposes, completed during the design and manufacture of the actual version) for the state-level project code: code DTĐL.CN-98/21

a) General structure of the industrial building fire fighting robot

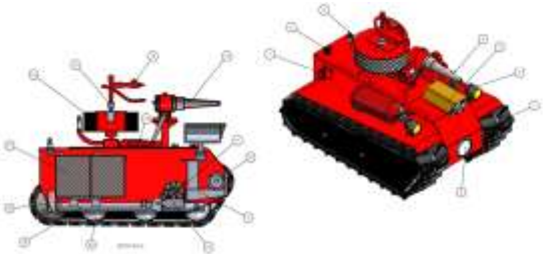


Figure 1.17: Structure of industrial factory fire fighting robot

1-Rubber track; 2,8-Yellow light (bone breaking, smoke breaking); 3-observation camera; 4-fire extinguisher or oxygen tank; push button system including 5-electric lock, 6-emergency stop button, 7-battery charging socket for battery; 9-frame; 10-star wheel (drive wheel for chain); 11-electric motor drives chain; 12-fire extinguishing liquid nozzle; 13-direction control system (angle) of nozzle; 14-flow control valve; 16-fire extinguishing coil joint to nozzle; 18-chain belt; 19-pulley-toothed belt system controls counterweight (moves battery cluster position).

b) Operating principle of fire fighting robot

Fire fighting robot moves through a crawler system, each side of the crawler is driven by an independent motor..

Figure 1.18: Structure of the part that changes the robot's center of gravity to prevent tipping over

(1) - Ball bearing slide creates a flat surface for mounting the battery; (2) - toothed belt; (3) drive shaft

1.6. Research methods of the thesis

1.6.1. Theoretical research method

Applying the theoretical mechanics research method to study the dynamics of the robot's stair climbing process.

1.6.2. Experimental research method

Applying methods of measuring non-electrical quantities by electricity to determine input parameters and determine output parameters.

Chapter 1 Conclusion

1. Robotic firefighting technology and equipment in Vietnam still have many limitations, and have not been widely applied outside the two major cities of Hanoi and Ho Chi Minh City. The use of firefighting robots provides high firefighting efficiency, safety for the lives and health of firefighters.

2. There are many research projects on firefighting robots in the world, which have been applied in practice to create firefighting robots for practical use.

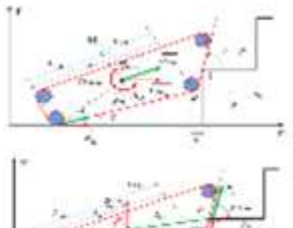
3. In Vietnam, there has been an independent state-level project to study the design and manufacture of experimental fire-fighting robots for industrial buildings, but the project only focuses on the design and manufacture content, without in-depth research on the dynamics and control of fire-fighting robots.

4. In order to have a theoretical basis for the design and calculation process, to perfect the ability to move up and down stairs, and to stabilize the robot without tipping over, it is necessary to study the dynamics and control of the process of climbing up and down stairs. The content: "Research on dynamics and control of fire-fighting robots for industrial factories" that the thesis chooses is necessary and topical.

CHAPTER 2
DYNAMICS AND CONTROL OF ROBOT MOVING UP AND DOWN STAIRS

2.1. Building the dynamic equation of the robot when climbing stairs

2.1.1. Dynamics at step 1 when climbing



Hệ phương trình động lực học robot tại bước 1 gồm:

$$\sum F_x = m\frac{d^2x}{dt^2} = ma_{CMx} = F_M\cos(\gamma+\varphi) + F_A - F_C$$
$$\sum F_y = m\frac{d^2y}{dt^2} = ma_{CMy} = F_M\sin(\gamma+\varphi) + N_A + N_C - m_c g \quad (2.1)$$

2.1.2. Robot dynamics at step 2 of the climbing process

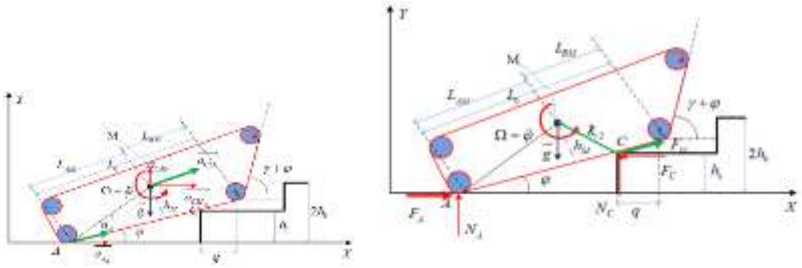


Figure 2. *2* : Dynamic analysis of step 2 of the stair climbing process

The robot dynamics equation in step 2 includes:

$$\sum F_x = m\frac{d^2x}{dt^2} = ma_{CMx} = F_M\, cos(\varphi) + F_A - F_C \qquad (2.7)$$

$$\sum F_y = m\frac{d^2y}{dt^2} = ma_{CMy} = F_M\, sin(\varphi) + N_A + N_C - m_c g$$

2.1.3. Robot dynamics at step 3 of the climbing process

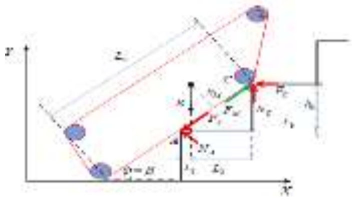


Figure 2.3 : Dynamic analysis of step 3 of the stair climbing process

The robot dynamics equation at step 3 is

$$\sum F_x = m\frac{d^2x}{dt^2} = ma_{CMx} = F_M\, cos\,\beta + F_A\, cos\,\beta - N_A\, sin\,\beta - F_C \qquad (2.10)$$

$$\sum F_y = m\frac{d^2y}{dt^2} = ma_{CMy} = F_M\, sin\,\beta + F_A\, sin\,\beta + N_A\, cos\,\beta - m_c g + N_C$$

2.1.4. Robot dynamics at step 4 of the climbing process

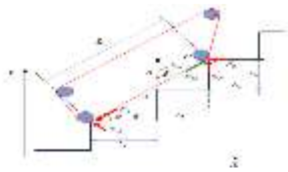


Figure 2.4: Dynamic analysis of step 4 of the stair climbing process

$$\sum F_x = m\frac{d^2x}{dt^2} = ma_{CMx} = F_M\, cos\,\beta + F_A\, cos\,\beta - N_A\, sin\,\beta - F_C \qquad (2.11)$$

$$\sum F_y = m\frac{d^2y}{dt^2} = ma_{CMy} = F_M\, sin\,\beta + F_A\, sin\,\beta + N_A\, cos\,\beta - m_c g + N_C$$

2.1.5. Robot dynamics at step 5 of the climbing process

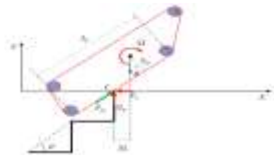


Figure 2.5: Dynamic analysis of step 5 of the stair climbing process

The robot dynamics equation system in step 5 includes:

$$\sum F_x = m\frac{d^2x}{dt^2} = ma_{CMx} = F_M\, cos\,\varphi - F_C \qquad (2.12)$$

$$\sum F_y = m\frac{d^2y}{dt^2} = ma_{CMy} = F_M\, sin\,\varphi + N_C - m_c g$$

2.2. Building the dynamic equation of the robot when climbing down the stairs

2.2.1. Robot dynamics at step 1 of the descent process

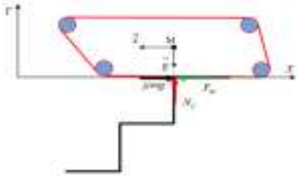


Figure 2.6: Dynamic analysis of step 1 of the stair climbing process

The robot dynamics equation at step 1 of the stair climbing process is:

$$\sum F_x = m\frac{d^2x}{dt^2} = F_M - \mu m_c g \tag{2.13}$$

2.2.2. Robot dynamics at step 2 of the descent process

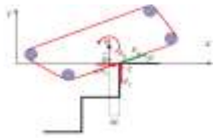


Figure 2.7 : Dynamic analysis of step 2 of the stair climbing process

The robot dynamics equation system at step 2 of the stair climbing process includes:

$$\sum F_x = m_c a_{CMx} = -F_M \cos\varphi + F_C = -F_M \cos\varphi + \mu m_c\, g \tag{2.14}$$

$$\Sigma C_c$$

$$\sum F_y = m_c a_{CMy} = -F_M sin$$

2.2.3. Robot dynamics at step 3 of the descent process

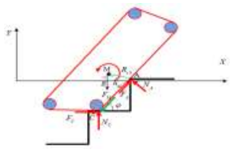


Figure 2.8: Dynamic analysis of step 3 of the stair climbing process

The robot dynamics equation system at step 3 of the stair climbing process includes:

$$\sum F_x = m_c a_{CMx} = F_C + F_A \cos\varphi - N_A \sin\varphi - F_M \cos\varphi \tag{2.15}$$

$$\Sigma_M \sin\varphi$$

$$\sum \quad F_y = m_c a_{CMy} = N_C + N_A \cos\varphi - F_A sin$$

2.2.4. Robot dynamics at step 4 of the descent process

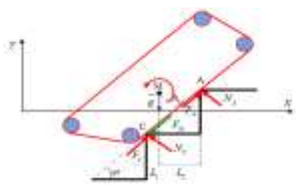


Figure 2.9 : Dynamic analysis of step 4 of the stair climbing process

$$\sum F_x = m_c a_{CMx} = (-F_M - F_A + F_C)\cos\beta - (N_A + N_C)\sin\beta \tag{2.16}$$

$$\sum(-F_M+N_A+N_C)\cos\beta(N_A+N_C)_c$$

$$\sum F_y = m_c a_{CMy} = sin$$

2.2.5. Robot dynamics at step 5 of the descent process

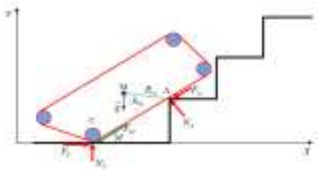


Figure 2.10 : Dynamic analysis of step 5 of the stair climbing process

The robot dynamics equation system at step 5 of the stair climbing process includes:

$$\sum F_x = m_c a_{CMx} = F_C - F_A\cos\varphi - N_C\sin\varphi - F_M\cos\varphi \tag{2.17}$$

$$\sum F_y = m_c a_{CMy} = N_C + N_A\cos\varphi - F_A\sin\varphi - F_M\sin\varphi$$

2.2.6. Robot dynamics at step 6 of the descent process

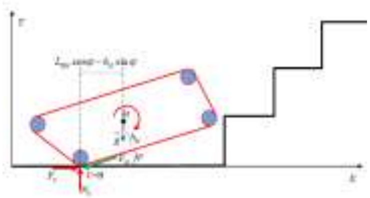


Figure 2.11 : Dynamic analysis of step 6 of the stair climbing process

The robot dynamics equation system at step 6 of the stair climbing process includes:

$$\sum F_x = m_c a_{CMx} = F_M\cos\varphi - F_C \tag{2.18}$$

$$\sum F_y = m_c a_{CMy} = F_M\sin\varphi + N_C - m_c g$$

2.3. Building a motion control system for robots

2.3.1. Calculation of drive motor for robot

The robot is equipped with 02 independent drive motors for 2 sprockets, installed through a gearbox and a star wheel (intermediate wheel connected to the transmission chain), described in Figure 2.12. The motor installed on the robot is a DC motor.

Figure 2.12 : Drive motor equipped for robot

2.3.2. Calculation of motor drive controller for robot

2.3.2.1. Motor control driver

Figure 2.13: Smart DC motor controller DRIVER PID SMART MOTOR DC

2.3.2.2. Building a motor control circuit

a) Central processing module

Figure 2.15: Arduino MEGA 2560 microcontroller

The interface circuit of the control system is developed as shown in Figure 2.16.

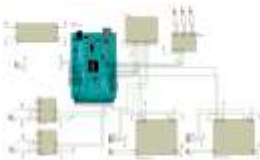


Figure 2.16: Interface circuit of the control system

2.3.2.3. Motor control algorithm

The algorithm is shown in Figure 2.17.

- Move

Figure 2.17: Algorithm diagram of fire fighting robot movement

- Motor control 1.

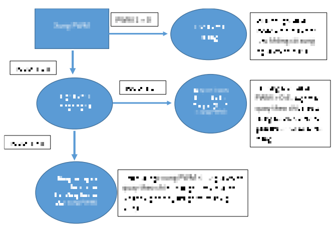


Figure 2.18: Motor control algorithm diagram 1

- Motor control 2.

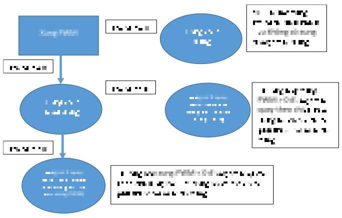


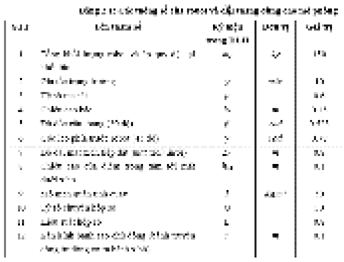
Figure 2.19: Motor control algorithm diagram 2

2.4. Simulation and evaluation of results through the stair climbing process of the Fire Fighting Robot

Because there is no sliding or rotation, the robot's motion has three components at each stage: a translational motion along the X axis, a motion along the Y axis, and a rotational motion along the Z axis. These three components are closely related to each other and to the robot's center of gravity.

2.4.1. Parameters and assumptions in simulation

To conduct the simulation process and evaluate the response results of the equipped BLDC motor, the thesis uses the parameters described in Table 2.1:



2.4.2. Simulation results

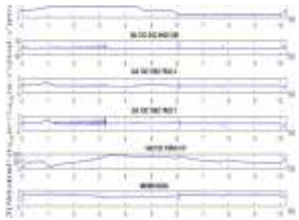


Figure 2.20 : Simulation results of the stair climbing process

(*Climb up - walk on the flat - climb down*)

a) Climbing process

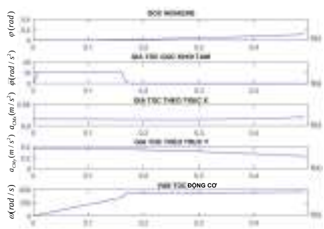


Figure 2.21 : Simulation results of step 1 of the climbing process

- Step 1 climb up.

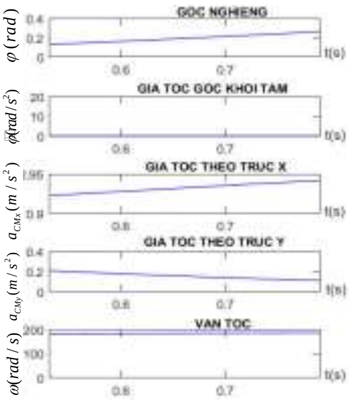


Figure 2.22: Simulation results of step 2 of the climbing process

- Step 2 climb up.

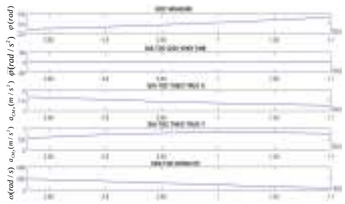


Figure 2.23: Simulation results of step 3 of the climbing process

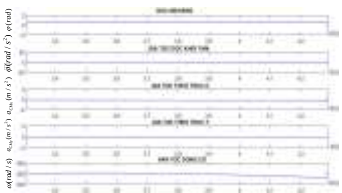


Figure 2.24: Simulation results of step 4 of the climbing process

- Step 3 and step 4.

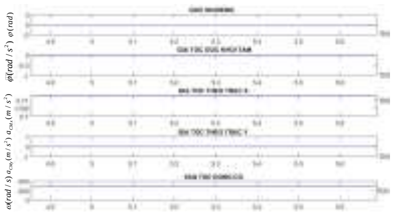


Figure 2.25: Simulation results of step 5 of the climbing process

- Step 5, the climbing process takes place when the robot's center of mass passes the last stair step (the landing's nose), then under the effect of gravity at the center of mass, the robot falls down to the landing when moving forward in step 5, then the tilt angleφ will transform down from $\varphi = \beta = 0.523(rad)$to $\varphi = 0$, the equivalent of the chain surface is horizontal on the landing. Then step 5 is finished, and the robot moves on the horizontal plane. The climb process is finished, as shown in Figure 2.26.

b) The process of climbing down

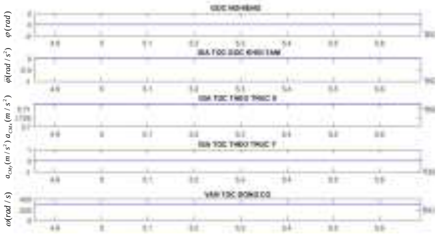


Figure 2.26: Simulation results of step 1 of the descent process

- Similar to the climbing process, the state of the climbing process from step 2 to step 6 (the robot's crawler is in contact with the horizontal ground plane) is described in turn in the figures from figure 2.27 to figure 2.30.

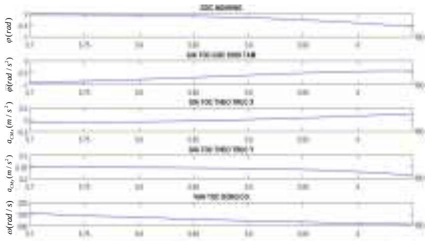


Figure 2.27: Simulation results of step 2 of the descent process

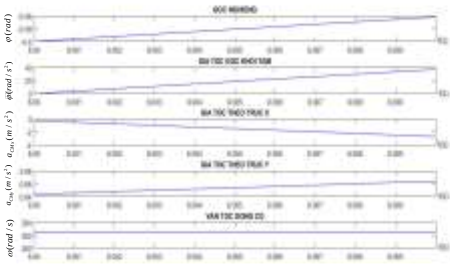


Figure 2.28: Simulation results of step 3 of the descent process

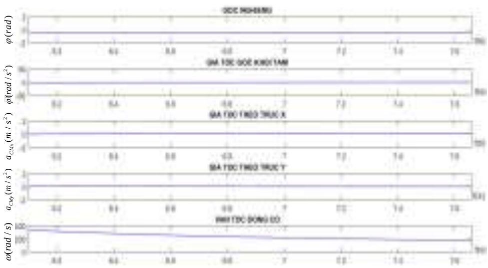


Figure 2.29: Simulation results of step 4 of the descent process

Figure 2.30: Simulation results of step 5 of the descent process

Chapter 2 Conclusion:

From the results obtained in chapter 2, the thesis draws the following conclusions:

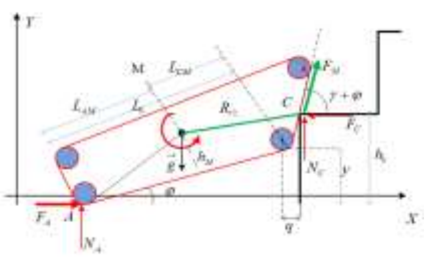
1. Built a model and established dynamic equations for the robot during the process of climbing stairs without considering the collision phenomenon leading to overturning;

2. Built a motion controller for a robot with a drive system for two crawlers using a BLDC motor with a speed control method (acceleration, deceleration) along with a motion control driver for the BLDC motor to drive;

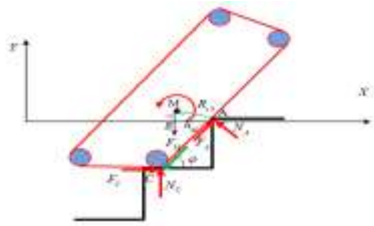
3. Simulated the movement of the robot going up and down the stairs, the simulation results of the dynamic equation system, demonstrated the control ability of the robot motion controller with the BLDC motor with the selected power, and at the same time demonstrated the accuracy of the built dynamic equation system.

CHAPTER 3
DYNAMICS OF TIP-OVER PHENOMENON AND SOLUTIONS CONTROL TO AGAINST TIP-OVER PHENOMENON WHEN ROBOT CLIMBING STAIR

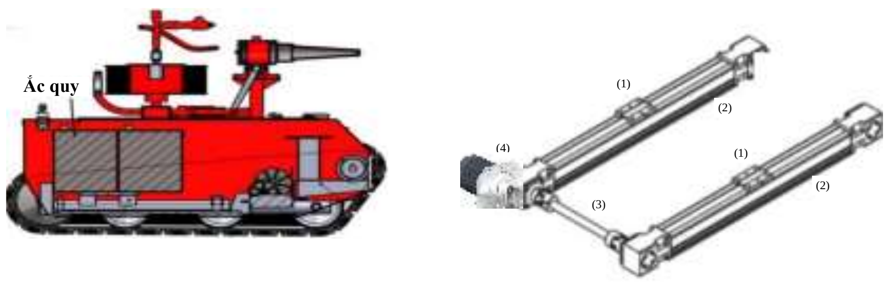
As analyzed in the section on the dynamics of a stair-climbing robot, the robot's tipping phenomenon is likely to occur at the beginning of the stair-climbing phase and the beginning of the stair-climbing phase. If the angle$\beta \geq 90^0$ then the robot will capsize.



a) rotation around C when the robot climbs the stairs



b) The phenomenon of rotation around C when the robot climbs down the stairs



c *) Proposal to use battery position to change robot center of gravity position*

Figure 3.1: Structure of the robot center of gravity change part

3.1. Constructing a dynamic equation considering the dynamic process leading to the robot's overturning phenomenon

3.1.1. Dynamic processes leading to overturning when climbing stairs

a) Consider the collision process at the first level

- The collision process at the first level is depicted in Figure 3.2 (A).

The collision impulse is obtained as:

$$\vec{N} = \frac{\sum \overrightarrow{S_k^e}}{\tau_0} = -\frac{m_c(1+k)}{\tau_0}.\vec{V} = \left(-\frac{m_c(1+k)}{\tau_0}V, 0\right) \tag{3.5}$$

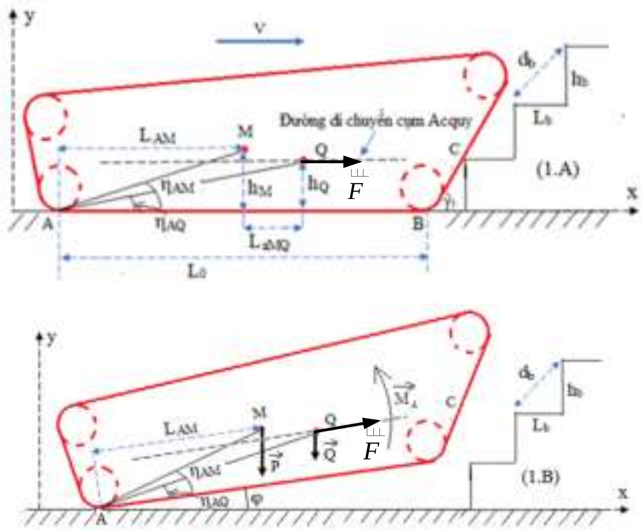


Figure 3.3 : Description of the collision between the car and the stairs at the first step

The dynamic equations of the system including two generalized coordinate systems 1 and generalized coordinate systems 2 are written as follows:

$$\begin{cases} J_A\ddot{\varphi} = -m_R.g.d_{AM}.cos(\eta_{AM} + \varphi) \\ -m_Q.g.\sqrt{(L_{AM} + x_Q)^2 + h_Q^2}.cos(\eta_{AQ} + \varphi) + M_A \\ m_Q\ddot{x} = F - m_Q g\sin\varphi + m_Q\dot{\varphi}^2.\sqrt{(L_{AM} + x_Q)^2 + h_Q^2} \end{cases} \tag{3.19}$$

b) Consider the collision process at the second level and above.

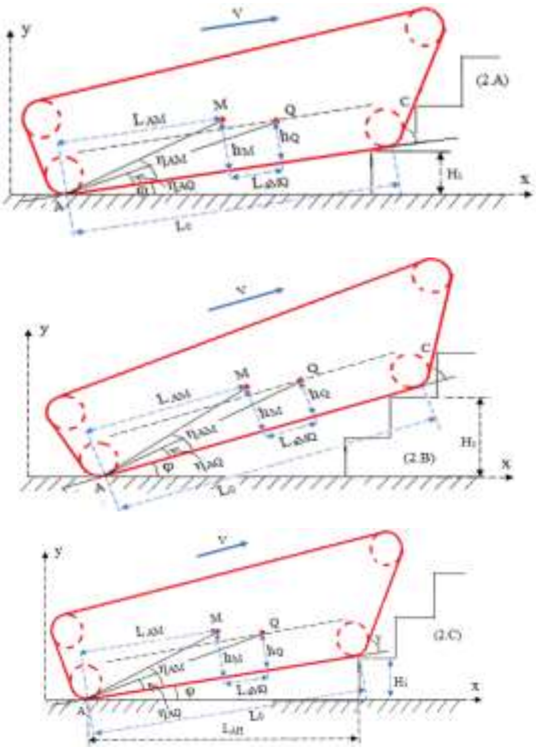


Figure 3.4 : Description of the collision between the vehicle and the stairs at the second step and above

The differential equation representing the variation of angle φ after time τ_0 will be:

$$J_A\ddot{\varphi} = -m_R g.d_{AM}.cos(\eta_{AM} + \varphi) \quad (3.36)$$

$$-m_Q g.\sqrt{(L_{AM} + x_Q)^2 + h_Q^2}.cos(\eta_{AQ} + \varphi)$$

3.1.2. Dynamic processes leading to overturning when climbing down stairs

a) The first stage when climbing down

- Consider the generalized coordinate system 1 .

The dynamic equation of the robot cluster will be:

$$J_{X_0}\ddot{\varphi} = g.cos\,\varphi\{(x_0 + V).(m_R + m_Q) - L_{OM}m_R - L_{OQ}(t).m_Q\} \quad (3.43)$$

b) Second stage when climbing down

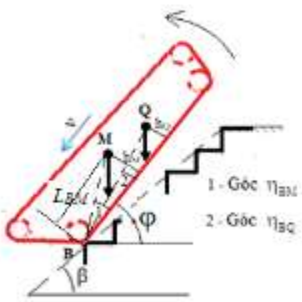


Figure 3.6: Description of the Robot vehicle in phase 2 when climbing down the stairs

Differential equation representing the rotational motion of the robot cluster:

$$J_B\ddot{\varphi} = -g.m_R.d_{BM}\,cos(\eta_{BM} + \varphi) - g.m_Q.d_{BQ}\,cos(\eta_{BQ} + \varphi) \quad (3.47)$$

3.2. Building a fuzzy PID controller to control the motion of a battery system to prevent tipping for a stair climbing robot

a) Controller selection analysis

- Has quick response to give early control results;
- Ensure the necessary accuracy;
- Has a structure that ensures simplicity so that it can be easily applied to programming on microcontrollers and industrial PLCs equipped in firefighting robots.

b) Control requirements

- When going up and hitting the first step (step 1)

$$\begin{cases} M_A = \begin{cases} M_A = \frac{m_c(1+k).h_b}{\tau_0} V khi t_1 \leq t < t_1 + \tau_0 \\ M_A = 0 khi t \geq t_1 + \tau_0 \end{cases} \\ F = m_Q\ddot{x}_Q - m_Q g\,sin\,\varphi + m_Q\dot{\varphi}^2.\sqrt{(L_{BM} + x_Q)^2 + h_Q^2} \end{cases} \quad (3.54)$$

- When going up and hitting the 2nd step or higher

$$\begin{cases} M_A = \begin{cases} M_A = \frac{(1+k)}{\tau_0}[(L_{AH} + L_b - V.T_c)b - ah] khi t_2 \leq t \leq t_2 + \tau_0 \\ M_A = 0 khi t > t_2 + \tau_0 \end{cases} \\ F = m_Q\ddot{x}_Q - m_Q g\,sin\,\varphi + m_Q\dot{\varphi}^2.\sqrt{(L_{BM} + x_Q)^2 + h_Q^2} \end{cases} \quad (3.55)$$

- When going down

$$\begin{cases} M_A = 0 \\ F = m_Q\ddot{x}_Q - m_Q g\sin\varphi + m_Q\dot{\varphi}^2.\sqrt{(L_{BM} + x_Q)^2 + h_Q^2} \end{cases} \tag{3.56}$$

When there is an impact of impulse, the moment is generated by the impulse $M_A \neq 0$, when there is no impact of impulse,$M_A = 0$

3.2.1. Formulate the force F control problem

Case 1 : If$M_A = 0$

- When the car goes up the stairs, the force F is designed to move the counterweight along the direction of the car's movement from its current position to the end point of the travel at the front of the car.

- When the car goes down the stairs, the force F is designed in the opposite direction to the direction of the car's movement, causing the counterweight to move towards the rear of the car.

Case 2: If $M_A \neq 0$, the force F needs to be reversed to reduce the impact of $M_A$the angle of inclination, avoiding the vehicle from tipping over.

- When the tilt angle = 0: force F remains unchanged;
- When the tilt angle is small: force F remains constant or increases slightly;
- When the tilt angle is moderate: force F increases slightly or moderately;
- When the tilt angle is large: force F increases moderately or greatly;
- When the tilt angle is very large leading to the risk of overturning: the force F increases greatly or very greatly.

The structure of the fuzzy PID controller is as follows (Figure 3.7):

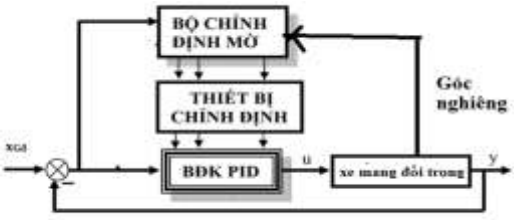


Figure 3.7: Fuzzy PID controller structure

Mathematical model of fuzzy PID

$$F(t) = K_p e(t) + K_t\int_0^t e(t)\,dt + K_d\frac{de(t)}{dt} \tag{3.57}$$

PID tuning law

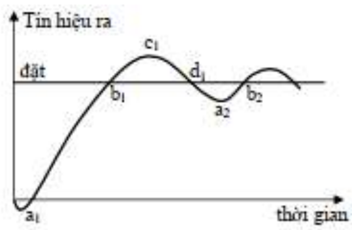


Figure 3.8: Fuzzy PID controller output signal

3.2.2. Building a fuzzy PID controller

1) Input/output variables:

- There are 2 input signals including: center of gravity position error, vehicle tilt angle;

- There are 3 output signals: KP, KD, KI

2) Define language variables:

- Counterweight position error: {large negative, small negative, zero, small positive, large positive}

ET={N3, N2, N1,ZE,P1,P2,P3}

- Tilt angle: {no tilt, small tilt, medium tilt, large tilt, very large tilt}

IG={L1,L2,L3,L4,L5}

Outputs:

- Proportion coefficient KP: { zero, small, medium, large, very large }= {Z, S, M, L, U}
- Differential coefficient KD: { zero, small, medium, large, very large } = { Z, S, M, L, U }
- Integral coefficient K_I: {zero, small, medium, large, very large}= {Z, S, M, L, U}

3) Determine fuzzy sets for input/output variables

- Determine the value domain of the ET variables

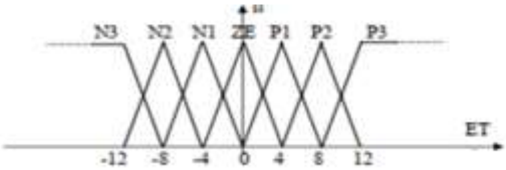


Figure 3.9: Value domain of ET

- Determine the value range of the tilt angle

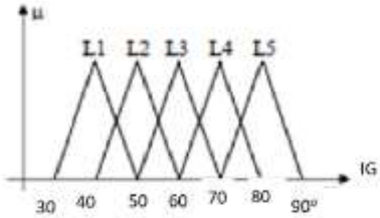


Figure 3.10: Range of values of tilt angle

4) Building the composition law and composition device

5) Defuzzification and optimization

The thesis selects the composition rule according to the Min-Max rule, and defuzzifies by the center of gravity method. The controller results are shown in the survey section below.

3.3. Investigation of the dynamics of the model leading to the possibility of robot overturning

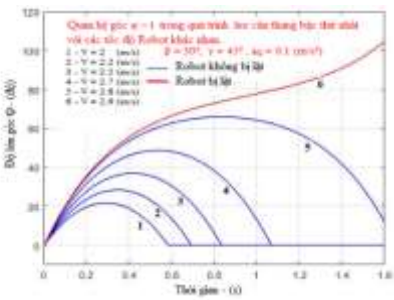


Figure 3.10: Survey results of robot tilt angle φ during climbing stairs to the first step at different speeds

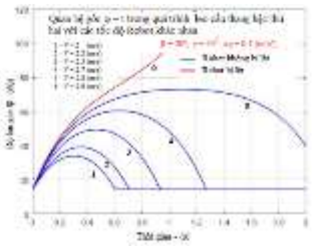


Figure 3.11: Survey results of robot tilt angle φ during climbing stairs to the second step at different speeds

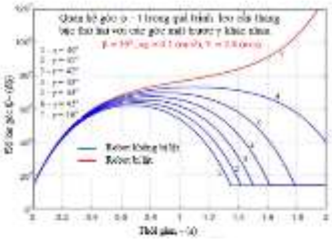


Figure 3.12: Survey results of robot tilt angle *φ* during climbing the second step of the stairs with climbing angles *γ*(*front angle of robot*) different

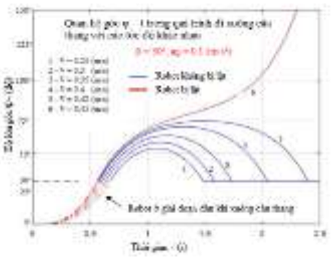
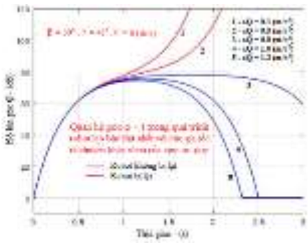


Figure 3.13: Survey results of robot tilt angle *φ* during climbing down stairs at different speeds



different moving accelerations a $_{\text{Q of the pressure}}$

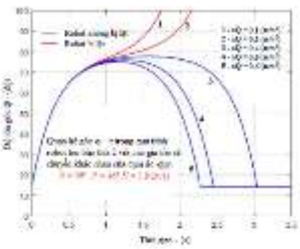


Figure 3.15: Survey results of robot tilt angle *φ during the process of climbing stairs to the second step with* different moving accelerations a $_{\text{Q of the pressure}}$

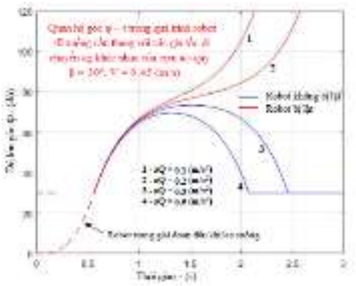


Figure 3.16: Survey results of robot tilt angle *φ during climbing down stairs with* different accelerations a $_{Q}$ of the pressure

Chapter 3 Conclusion

From the results presented in chapter 3 above, the thesis draws the following conclusions:

1. The model has been built and the dynamic equation has been established to consider the robot's overturning phenomenon;

2. Establish the relationship between the tilt angle φ as a function of the counterweight acceleration a $_{Q}$. This result facilitates the establishment of a fuzzy PID control algorithm to generate force F to move the counterweight from the initial position to the end of the stroke with acceleration$a_Q = \ddot{x}_Q$ to prevent tipping;

3. Based on the dynamic equation and counterweight controller, the thesis conducts a survey of the overturning phenomenon (applying Matlab software in calculation and simulation), from which the pair of values V and $a_Q = \ddot{x}_Q$corresponding to the angle values of the stairs with different inclination angles *(from 30 to 45 degrees, corresponding to the inclination angle of the stairs used in construction works in Vietnam today according to the standard QCVN 06:2022/BXD) is drawn.*

4. The thesis has determined the velocity value of the robot when climbing up and down the stairs corresponding to the slope of the stairs and the acceleration of the counterweight's center of gravity change a_{Q}. The research results in this chapter are reference materials for the research and manufacture of crawler firefighting robots climbing stairs. From these results, researchers can optimize the size of the firefighting robot while still ensuring the ability of the robot not to overturn when moving towards the fire at the maximum speed V_{max} , when using the center of gravity control method to prevent overturning.

CHAPTER 4
EXPERIMENTAL VERIFICATION OF THEORETICAL MODEL

4.1. Objectives and experimental tasks to verify the theoretical model

4.1.1. Objectives of experimental research

Determine the flip angle *φ* of the robot when climbing up and down stairs (the robot's tilt angle) with different velocities and different accelerations a_{Q}.

4.1.2. Experimental research tasks

- Determine the ability to climb stairs with the equipped drive system based on the dynamic model of the robot's stair climbing process (chapter 2);
- Determine the robot's flip angle when moving with collision leading to flipping phenomenon
- Re-verify the anti-rollover ability with center of mass motion control under different acceleration cases.

4.1.3. Experimental research subjects

The experimental research object is the state-level project " ***Research on technology, design and experimental manufacture of fire-fighting robots for industrial works*** ", code DTĐL.CN-98/21. The experimental location is at Vietnam Specialized Equipment Joint Stock Company.

4.2. Select control change parameters and evaluation parameters

4.2.1. Select control change parameters

- Stair slope changes from 30 degrees to 35 degrees
- Speed of the robot moving up the stairs
- Acceleration of change of center of gravity of counterweight

4.2.2. Select evaluation parameters

The objective of the study is that the robot approaches the fire as quickly as possible without tipping over, so the evaluation parameter is the robot's tipping angle. To evaluate the robot's ability to tip over, the thesis relies on the robot's tilt angle (angle φ). Therefore, the thesis chooses the experimental output evaluation parameter as the tipping angle φ

4.3. Methods for determining research quantities and measuring equipment

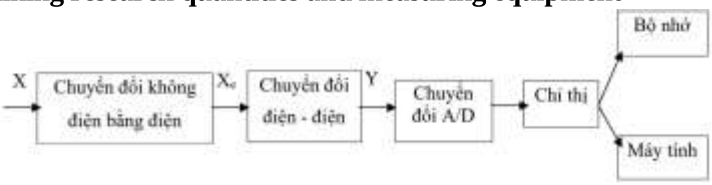


Figure 4.1: Block diagram of the experimental equipment

4.3.1. Method of adjusting the slope of stairs and method of determining the angle of inclination of stairs

To be able to experiment with robots climbing stairs with different angles, the thesis has manufactured a test staircase, which can change the slope of the stairs through joints (Figure 4.2).

Figure 4.2: Experimental staircase with joints manufactured to change the angle of inclination

Figure 4.3: Electronic protractor used to measure stair slope

4.3.2. Method of determining velocity and acceleration of movement

4.3.3. Method for determining the tilt angle of the robot

c) Cảm biến gắn trêm nắp xe robot tại điểm có mặt phẳng nằm ngang

Figure 4.5: Structure and method of mounting tilt angle sensor on robot

4.3.4. Amplifier and A/D converter

Figure 4.6: DMC Plus device

4.4. Organization of the experiment

4.4.1. Experimental organization

a) Installation of experimental equipment :

b) Parameters changed during the experiment

- The slope of the staircase β changes in different cases ($\beta = 30^o$ -45^o *According to QCVN 06:2022/BXD standard on fire prevention and fighting for construction works*) through adjusting the joints of the experimentally manufactured stairs, and in two stairs of two different schools.

- The robot speed changes in different cases by setting the input value from the remote control lever (*this speed is limited to* $V_{max} \le 2.8$ *(m/s) due to the responsiveness of the drive motor*).

c) Measure the output parameters of the experiment

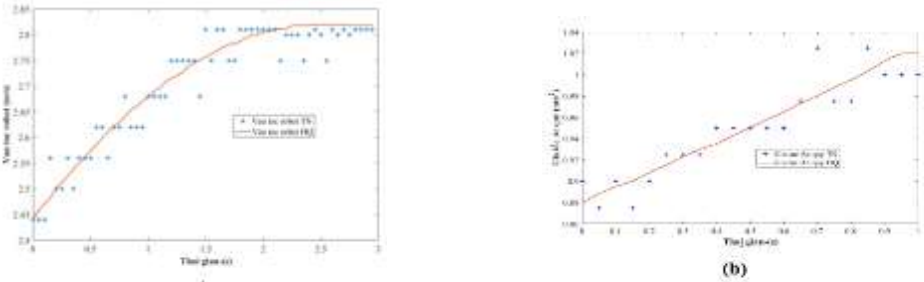
Robot tilt angle φ , robot climbing velocity V , a_Q , moving acceleration of battery pack (counterweight) are measured and recorded numerically in EXCEL environment.

d) Conduct the experiment

Hình 4.7: Tổ chức thí nghiệm

Hình 4.8: Tổ chức thí nghiệm và đo kết quả với cầu thang chế tạo có khả năng thay đổi độ dốc

4.4.2. Experimental results



(a) (b)

Figure 4.10: Robot velocity and battery cluster acceleration during the experiment of the robot climbing stairs over time

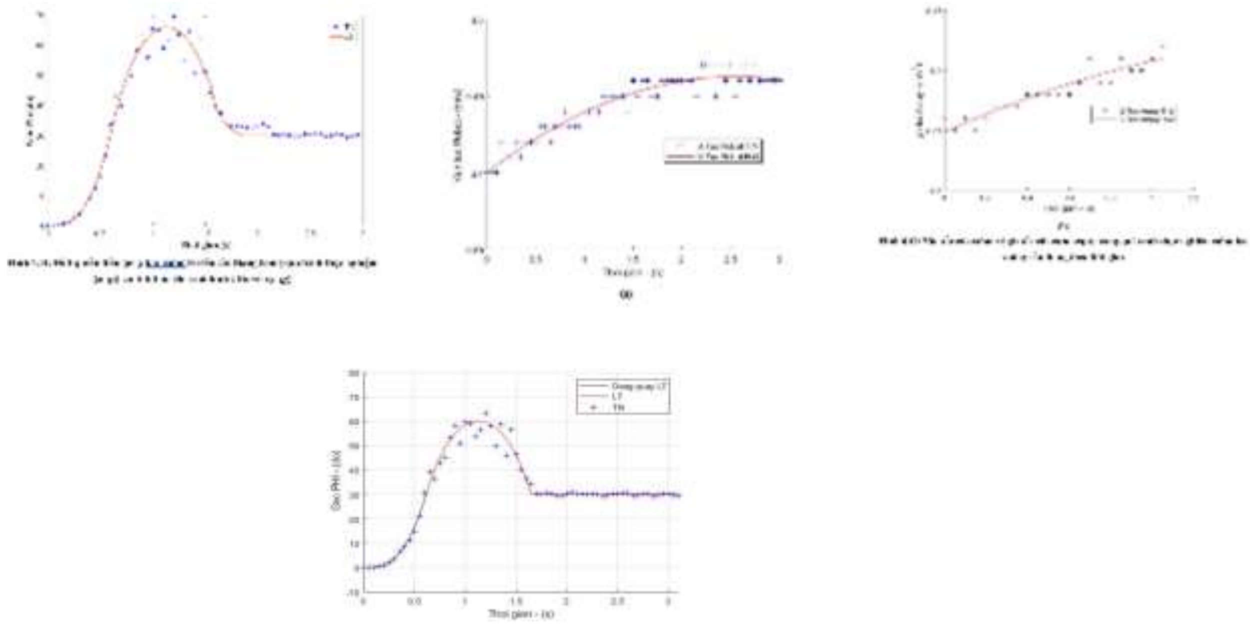


Figure 4.13: Graph showing the angle φ when the robot goes down the stairs during the experiment (φ_{TN}) and calculated according to the theoretical model (φ_{LT})

Chapter 4 Conclusion

From the results of experimental research, the thesis draws the following conclusions:

1. The thesis has established an experimental research method to determine the dynamics of the robot when colliding with stairs during movement (climbing stairs) leading to the robot's ability to flip, selected measuring equipment, measuring sensors, and experimental data processing methods.

φ is determined , corresponding to different velocities, stair inclinations and accelerations that change the coordinates of the center of gravity of the counterweight.

3. The thesis compared the experimental results with the survey results according to the theoretical calculation model. The comparison results showed that the series of these values all had a correlation coefficient > 0.8, which proves that the theoretical calculation model is acceptable.

CONCLUSION AND RECOMMENDATIONS

1. Conclusion

Based on theoretical and experimental studies on dynamics and control of industrial factory fire fighting robots, the thesis draws the following conclusions:

1. Using research methods in dynamic theory, a model has been built and a dynamic equation has been established for a stair-climbing robot without considering the dynamics of collision with the stairs. From this result, a drive control system for the motor has been proposed to ensure the robot's ability to move on flat roads and climb stairs (overcoming obstacles).

2. The model has been built, the dynamic equation of the robot interacting with the stairs during the process of moving up and down the stairs has been established, the anti-overturn mechanism has been proposed through the counterweight position control algorithm, the dynamic equation system has been surveyed to determine:

- The optimal value of the robot climbing angle (tilt angle in front of the chain) is $\gamma = 45^o$;
- The influence of the values (stair slope angle β , robot climbing angle γ, robot maximum speed $V_{\max}$ and counterweight acceleration a_Q) on the robot's ability to overturn;
- The corresponding pairs of values, for each value of the stair slope angle β and the robot climbing angle $\gamma$with the maximum climbing velocity of the robot $V_{\max}$, require the corresponding acceleration value of the battery pack a_Q so that the robot does not tip over.

3. Establish the relationship between the tilt angle φ as a function of the counterweight acceleration a_Q . This result facilitates the establishment of a counterweight control algorithm to prevent the robot from tipping over when colliding with stairs.

4. The thesis has built a table to determine the speed limit value of the fire fighting robot when moving up and down stairs during fire fighting operations (Table 3.3). This result is the basis for determining the safe use mode for fire fighting robots in industrial buildings.

5. The experimental results verifying the theoretical calculation model show that the correlation coefficient *r* between the series of tilt angle values φ leading to the overturning phenomenon of the theoretical calculation model and the experimental results both satisfy $r > 0.8$, which proves that the theoretical calculation model is consistent with reality and has the necessary reliability. Through experimental and theoretical research, the maximum speed of when going down the stairs $V_{\max} = 0.45$ (m/s) and when going up $V_{max} = 2.8$ (m/s) corresponding to the slope of the stairs $\beta = 30^0$ and the acceleration of the battery cluster (counterweight) change respectively is $a_Q = 0.4$ (m/s ^{2}) and $a_Q = 1$ (m/s ^{2})

2. Recommendations

Due to limited research time, to complete the topic, it is necessary to continue researching some contents outside the scope of the thesis as follows:

1. Study on the dynamic model of an industrial fire-fighting robot when climbing stairs while dragging a fire hose reel.

2. Study on the dynamic model of a fire-fighting robot when it climbs stairs, turns around, and pulls a fire hose reel.