

Research on wheel-tracked climbing and transportation trolley based on mechanical design, control technology and sensor technology

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Abstract. With the development of the logistics industry, there is an increasing demand for cargo transportation in complex environments. For the difficult to access places such as stairs, the traditional handling method has the problems of low efficiency and high cost. In this paper, a wheeled stair climbing handling trolley is designed, which adopts a shear fork structure design to realize the free switching between flat ground and stairs, and is equipped with a variety of devices such as a retractable push rod, a pressure sensing booster device and an ergonomically adjustable pusher to realize the functions of cargo lifting and on-demand booster. By combining mechanical design, control technology and sensor technology, the trolley effectively solves the problem of cargo transportation in complex environments, featuring diverse functions, strong environmental adaptability, convenient operation, space saving, high safety and good economic benefits, and has a broad application prospect in the logistics and freight forwarding, medical care and other industries.

Keywords: Wheeled design, Scissor and fork construction, Stair transportation, Cargo lifting, Pressure sensing assistance.

1. Introduction

With the rapid development of social economy, the logistics industry plays an increasingly important role in the national economy. However, the transportation of goods in complex environments, such as stairs, ramps, etc., still faces problems such as low efficiency, high cost and poor safety. The traditional way of handling mainly relies on manpower, which not only consumes a lot of manpower and material resources, but also is inefficient and the safety is difficult to ensure.

In order to solve this problem, this paper designs a wheeled climbing and handling trolley. However, the following problems are common with other existing solutions: most devices cannot run quickly on flat ground and cannot save time running on flat ground; commercially available devices do not have adjustable push rods and are not ergonomic; the cost of commercially available drive units is higher than that of controllable assist devices; most models do not have a self-locking device to improve safety; and they have a single function and cannot lift goods.

The trolley adopts a shear fork structure design, which can realize the free switching between flat ground and stairs, and is equipped with various devices such as retractable push rod, pressure sensing booster device and ergonomic adjustable push rod to realize the functions of cargo lifting and on-demand booster. By combining mechanical design, control technology and sensor technology, the trolley can effectively solve the problem of cargo transportation in complex environments and bring revolutionary changes to the logistics industry [1].

The aim of this study is to explore the structural design, control strategy and sensor application of wheeled climbing and handling trolley, and to analyze and evaluate its performance. Through the study of the cart's multifunctionality, high environmental adaptability, ease of operation, space saving, safety and economic benefits, it provides an efficient and safe solution for the transportation of goods in the logistics industry and promotes the development of the logistics industry in the direction of automation and intelligence [2].

2. Overall design

In this study, a wheel-tracked stair climbing and handling trolley is designed to solve the logistics handling problem in complex environments, especially to provide efficient solutions in difficult-to-access places such as staircases. The trolley is designed with a shear-fork structure, with double tracks on the bottom inner frame and one roller at each of the four top corners of the outer frame profile, which can realize the free switching between level ground and stairs. The interior of the trolley is equipped with a retractable push rod, pressure sensing booster and ergonomic adjustable push rod and other devices to realize the functions of cargo lifting and on-demand booster to meet the use of old high-rise buildings, nursing homes, hospitals, office buildings and other scenes that require the handling of goods in complex environments. The design idea of the work is shown in Figure 1.

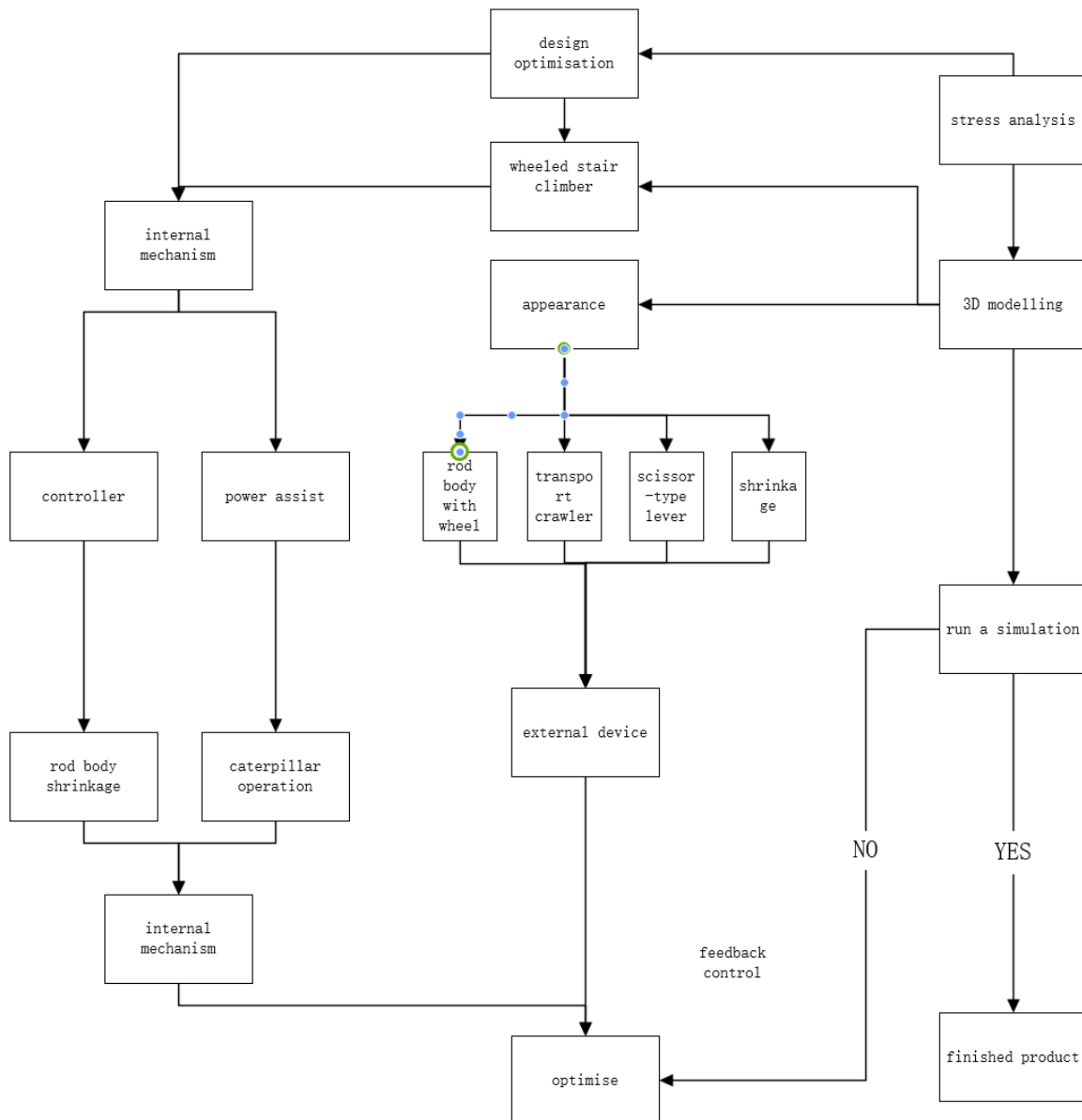


Figure 1. Design idea of the work

Realization Steps:

- (1) The dismantling of the problem led to the identification of the main operating components: the shearer frame, the pusher, the crawler and its booster.
- (2) Draw a design using CAD to confirm the basic structure of the work.
- (3) Using Solid Works software to complete the initial modeling design and derive the three-dimensional architecture; and

(4) by the force analysis and software ANSYS using simulation, derived from the basic device size and assembly position;

(5) Adopting big data analysis method and adjusting the parameters of the track and its booster and the contraction device for the scissor-type bracket according to the market research information and the simulation parameters after the simulation to derive the contraction node and rotation point of the pushrod;

(6) Refinement of the initial modeling; and

(7) Selection of materials for the device under conditions of simulation of maintenance costs, market research and material calculations.

(8) The parts are adjusted for assembly motion and color rendered using Key Shot software.

3. Design analysis and theoretical verification

3.1. Theoretical analysis

3.1.1. Drive motor status

In the power system of the trolley, the motor is the most central part, which determines the safety and reliability of the device use to some extent [3]. The power of the trolley when climbing stairs is:

$$P = \frac{mgv \sin \varphi}{\eta} \quad (1)$$

Where m represents the mass of the car body plus people (kg), v represents the speed of the trolley climbing stairs (m/s), g represents the acceleration of gravity (m/s^2), ρ represents the maximum inclination angle of the stairs, η represents the efficiency of the motor

According to the design requirements, the maximum climbing angle of the trolley φ is 60° , the maximum climbing speed v is $0.5m/s$. The weight of the trolley is designed to be about $50kg$, and the maximum load is designed to be $100kg$, the efficiency of the motor is taken as 0.8 , and the power of the trolley is 0.8 . The power is taken as 0.8 when it climbs the stairs:

$$P = \frac{mgv \sin \varphi}{\eta} = \frac{50 \times 10 \times 0.5 \times \frac{\sqrt{3}}{2}}{0.8} = 270(W) \quad (2)$$

3.1.2. Force analysis in the climbing condition

In order to facilitate the force analysis in the trolley coordinate system, the real force at the contact point between the trolley and the stair tread and the vertical side of the staircase in the world coordinate system is expressed by the equivalent force. F for the purpose of force analysis in the trolley coordinate system, the real forces at the contact points of the trolley with the stair treads and the vertical side of the staircase in the world coordinate system are expressed as equivalent forces. F'_{y1} is the equivalent traction force and the equivalent support force in the trolley coordinate system, F'_{f1} and F'_{y1} are the real traction force and the real support force in the world coordinate system, u is the static friction factor of the crawler with the staircase, and α is the angle between the crawler and the stair treads.

A sufficiently necessary condition for non-slip is satisfied when the track contacts the edge line of the stair step:

$$-u \leq \frac{F'_{f1}}{F'_{y1}} \leq u \quad (3)$$

Sufficiently necessary to securely hook the stair tread when the track teeth contact the stair tread

$$-u \leq \frac{F'_{f1}}{F'_{y1}} = \frac{F_{f1} \cos \alpha - F_{y1} \sin \alpha}{F_{f1} \sin \alpha + F_{y1} \cos \alpha} \leq u \quad (4)$$

In The event that $\mu < \cot \alpha$

$$\frac{\sin \alpha - u \cos \alpha}{\cos \alpha + u \sin \alpha} \leq \frac{F_{f1}}{F_{y1}} \leq \frac{\sin \alpha + u \cos \alpha}{\cos \alpha - u \sin \alpha} \quad (5)$$

Setting $d = \frac{F_{f1}}{F_{y1}}$, from equation (4), we get

$$d_{\max} = \begin{cases} \frac{\sin \alpha + u \cos \alpha}{\cos \alpha - u \sin \alpha} & u < \cot \alpha \\ +\infty & u \geq \cot \alpha \end{cases} \quad (6)$$

3.1.3. Stability analysis in the loaded state

In the process of loading, the center of gravity of the trolley changes, the dynamic analysis of stability analysis of the trolley in the state of loading, the friction between the track and the concrete steps $\mu = 0.7$. Take the common handling object refrigerator as an example, the weight of the refrigerator M2 is selected as 120kg, and the weight of the trolley M1 is 20kg, the height of the trolley track h1 is 10cm, and the height of the refrigerator h2 is 2m.

The center of gravity of the trolley in the loaded state is analyzed to obtain:

$$\text{Barycentric coordinates} = \frac{\sum (\text{Mass of a body} \times \text{Barycentric coordinates})}{\sum \text{Mass of a body}} \quad (7)$$

Substitute the relevant data to calculate: the center of gravity of the cart in the loaded state h_1 for 0.95m.

The angle of inclination of the staircase is θ_1 , the angle between BC and AC is θ_2 , the angle between AC and the plumb line where the front end of the staircase is located is θ_3 , the height of the center of gravity of the vehicle is h_1 , and the horizontal distance from the center of gravity to the front edge of the staircase is X . In order to make the vehicle stable, then it should be ensured that the projected point of the center of gravity should not exceed the front edge of the staircase, i.e.:

$$X \geq 0.05 \quad (8)$$

For X there is:

$$\sin\left(\frac{\pi}{2} - \theta_1 - \theta_2\right) = \frac{X}{\sqrt{(h_1)^2 + (h_2)^2}} \quad (9)$$

When $h_3 = \frac{0.2}{\sin \theta_1}$:

$$h_2 = 0.5 - \frac{0.2}{\sin \theta_1} \quad (10)$$

$$X = X_{\min} = \sin\left(\frac{\pi}{2} - \theta_1 - \theta_2\right) \sqrt{h_1^2 + h_{2\min}^2} \quad (11)$$

For θ_2 :

$$\theta_2 = \arctan\left(\frac{h_1}{h_2}\right) \quad (12)$$

At this point:

$$X = \sin\left(\frac{\pi}{2} - \theta_1 - \arctan\left(\frac{h_1}{0.5 - \frac{0.2}{\sin \theta_1}}\right)\right) \sqrt{h_1^2 + \left(0.5 - \frac{0.2}{\sin \theta_1}\right)^2} \quad (13)$$

Substituting $h_1 = 0.95\text{m}$, the solution is.

$$\theta_1 = 60^\circ$$

3.2. Design of mechanical structures

3.2.1. Scissor structure design

The general frame of this work is made of stainless steel with scissor-fork structure, the bottom inner frame is made of double tracks, each of the four top corners of the outer frame profile is equipped with a roller, and the interior of the trolley is equipped with an electromagnetic relay device to control the scissor-fork frame to rise and fall. This mechanical structure device realizes the conversion between wheels and tracks, which increases the range of transportation efficiency and saves transportation costs [4].

State Representation:

When signaled, the trolley's large structural frame contracts. When it is in the off state, four wheels are on the ground and the tracks are overhead; when it is in the on state, the outer contour bar frame rises, four wheels are overhead and the tracks are on the ground. The design effect is shown in Figure 2.

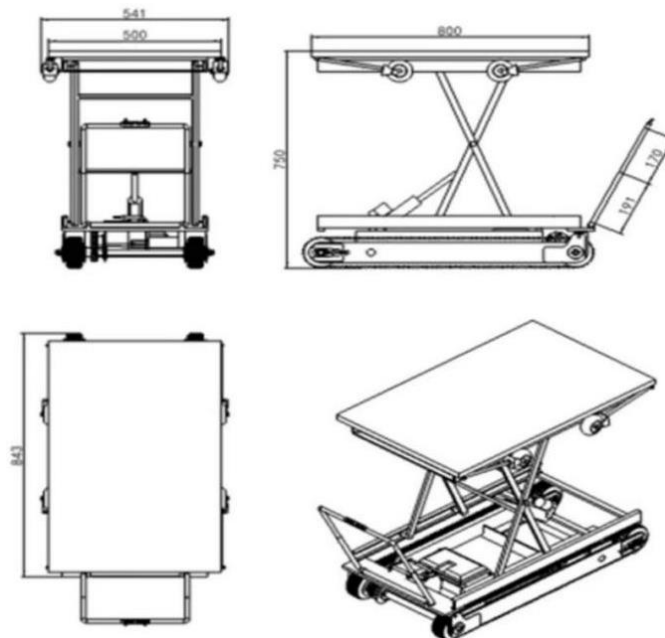


Figure 2. Schematic design effect

3.2.2. Crawler booster structure design

Combining the alloy material booster with the track and using Hall effect sensor to realize the control of the speed of the track by pressing the handle, which is convenient for the user to transport the goods and reduces the labor cost and labor cost. At the same time, the square rotation controller is added to control the direction of rotation of the booster motor [5].

3.2.3. Track movement and anti-skid design

The surface of the track is rough, the appearance is T-gear shape, rubber material, and the body is self-locking to prevent the trolley from slipping back, which provides a strong safety [6][7].

3.2.4. Actuator rotation contraction design

The push rod is made of aluminum alloy, a telescopic structure, controlled by DM542 telescopic, the shortest is 39cm, the highest can be extended to 52cm, its bottom half fixed on the cart load board, can be based on the bottom to rotate, the fixation is equipped with self-locking device [8]. The work is ergonomic and saves space occupation, the design idea is shown in Figure 3.

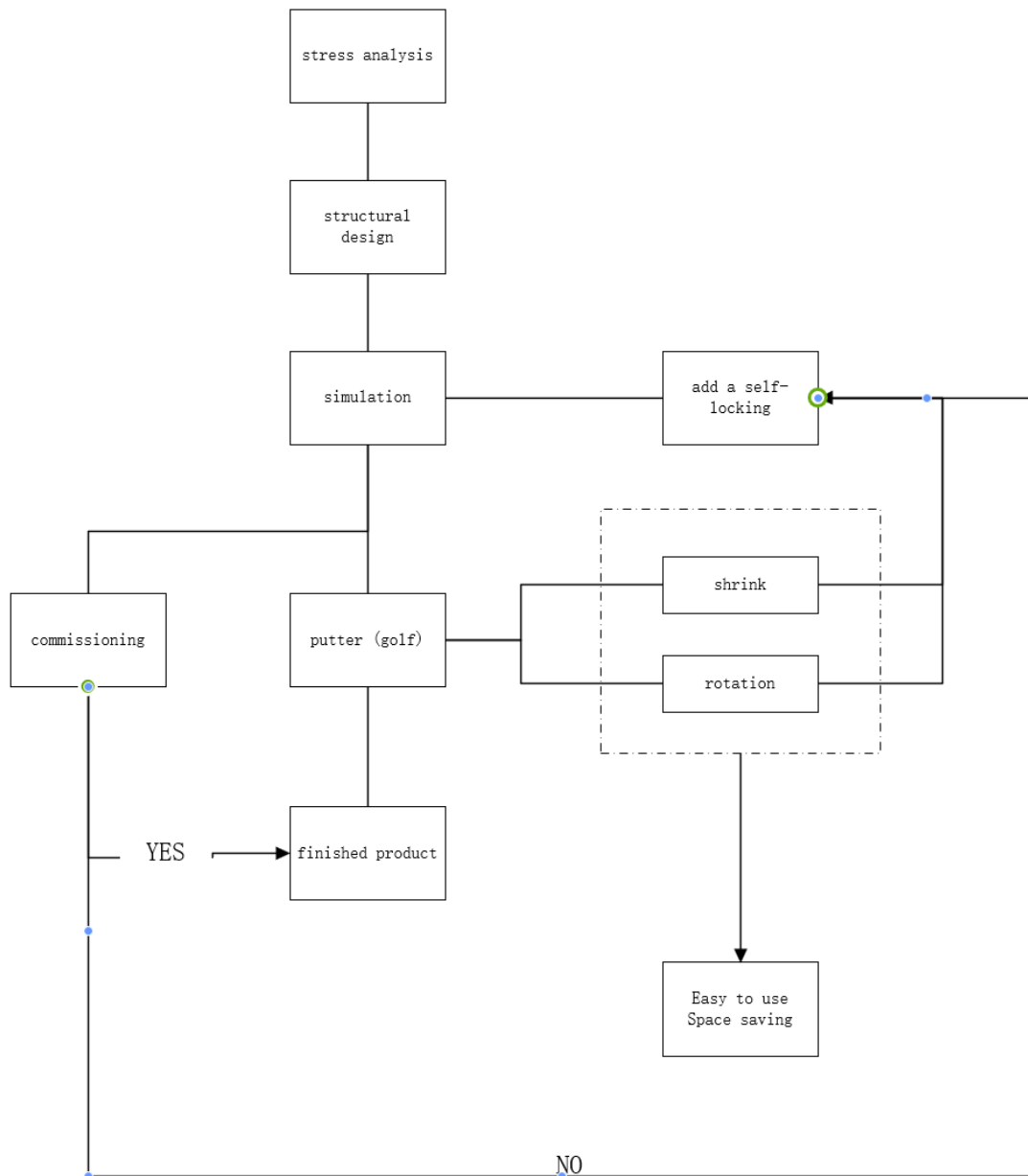


Figure 3. Schematic diagram of the actuator rotation contraction technique

4. Control circuit design

The operation of the mechanical structure described above also requires control. In order to realize the circuit device regulation to realize the functions of scissor frame rising and falling, push rod telescoping, crawler rotation and its steering control, this paper according to the size of the control function will be divided into the basic control and the three major control modules of the control

structure design. (Three major controls: crawler control, forklift control, and drawbar retraction control)

4.1. Foundation control

For the realization of the trolley function, this paper further divides the basic control module into power supply module, microcontroller module, power supply monitoring module, filter module, device control, and brushless motor drive.

4.1.1. Power supply module

(1) power switch

In order to increase the safety and to turn off the whole machine in time in case of electronic control failure through mechanical switches for easy management of the power supply, we add mechanical boat switches for easy and quick disconnection of the power supply [9].

(2) Power connector

Grid-type terminals are used for safe passage of motor drive current.

4.1.2. Microcontroller modules

Using a microcontroller (Model: STM32F103C8T6) to process each signal, and summarize and control the multiple ends to reduce the clutter of wires, facilitate the realization of the function, and flexibly control the corresponding link board. And another small chip as an auxiliary to make the system more stable. Display OLED (size: 0.96 inch) can be well displayed debugging. Microcontroller (Model: ESP-01S) communicates with the outside world through WIFI wireless network to realize wireless burning program.

4.1.3. Monitoring module

Through the monitoring module, the internal signals are externally displayed to achieve the purpose of real-time monitoring of the internal state. Therefore, we designed the monitoring module, respectively for the microcontroller and power supply monitoring, battery voltage monitoring two parts.

(1) Power supply and microcontroller status display

Because the internal circuit signals are not easy to detect, so we designed the LED status display circuit, through the LED color and light off, to understand the device microcontroller and power supply signals of the working state, to achieve the internal signals for the purpose of external display. When the microcontroller works normally, the LED green light; when the power supply is normal, the LED red light.

(2) Battery voltage monitoring

The battery voltage is used as a criterion to evaluate whether the power supply is normal or not, thus we design the battery voltage detection circuit by collecting the signal of battery voltage to reach the purpose of monitoring the state of battery voltage.

4.1.4. Filter Module

Capacitors are used for circuit filtering, the motor belongs to the inductive components, start or stop the power supply will have an impact on the power supply, which can easily lead to a drop in the power supply voltage, therefore, increase the large capacitance to filter out the low-frequency interference noise; increase the small capacitance to filter out the high-frequency interference noise.

4.1.5. Device control

Dividing the control unit into three parts: signal transmission, signal connection, and signal externalization

(1) signaling

Through the design of the circuit, the introduction of motor emergency stop, up and down button junction port, the realization of the external control buttons associated with the internal device, on this basis, and the two red dots shown in the diagram were connected to the microcontroller IO

interface to achieve a low-level trigger, in the realization of the premise of the control to save an IO port, to achieve the purpose of the internal send. Realized the external signal and internal correlation, and finally completed the signal sending instruction.

(2) signal connection

Darlington tube array is used to amplify the current, in order to realize the scissor frame retraction and lowering function, the purpose of signal connection is achieved by designing the relay circuit, which uses the direction of energization as a signal identification mark to decide the direction of push, pull and release [10].

(3) Signal Exposure

PushrodA, PushrodB connected to the scissor frame motor, electromagnetic relay normally closed to get the wire polarity reversed, that is, you can control the up and down through an IO. Through the electric pushrod switch to realize the midway off, limit the height. Pushrod expansion and contraction need to signal for regulation, so we designed the electric pushrod circuit, which includes the host control part and switch signal linkage part.

4.1.6. Brushless motor drives

The microcontroller IO interface controls the MOS tube driver chip, and the MOS tube driver chip controls the MOS tube to be used for motor phase change drive.

(1) MOS Tube Driver Chip Signal Connection

The IO port drive capability of the microcontroller is weak and not enough to turn on the MOS tube gate, the use of MOS tube driver chip can provide enough drive capability to improve the switching performance, and integrated protection to avoid damage to the MOS tube

(2) Three-phase bridge rectifier circuit

Brushless motor coil is connected by star, need to energize the motor U, V, W three-phase in a certain order, therefore, this circuit is designed for the "six-phase method", through the microcontroller advanced timer to drive the brushless motor rotation.

(3) Cooling Fan Circuit

MOS tubes tend to heat up when passing current, and overheating of MOS tubes can lead to breakdown, which leads to safety hazards, so two cooling fans are added for cooling.

4.2. Caterpillar, Scissor Frame, and Tie Rod Expansion Control Module Designs

4.2.1. Caterpillar control module design

- (1) Turning on the tracks with the push of a button
- (2) Forward and reverse track rotation by pushbutton

Motor Regulator: This regulator is responsible for adjusting the steering and speed of the motor based on input signals. Contains a microcontroller or similar control unit that receives commands and regulates the operation of the motor.

(3) On-demand speed regulation of the tracks by means of Hall effect sensors

Hall Sensors: Hall sensors are used to detect rotational speed and positional information from motors. They provide feedback on the status of the motor, such as the position and speed of the rotor, information that is essential for precise motor control.

◆ design proposal

The track control module of the cart consists of a Hall sensor, a motor steering rotation regulator, and a MOS driver chip.

MOS Driver Chips: MOS driver chips are part of the motor control circuitry that receives signals from the regulator and converts them into a current capable of driving the motor coils. These chips are typically designed to withstand high voltages and currents and can be switched quickly for precise motor control.

4.2.2. Scissor frame control module design

(4) Design Requirements

Pushbutton for Scissor frame Rise and fall.

The user sends a control signal by pressing the UP or DOWN button and the control unit sends a signal to the motor to start rotating. The direction of rotation of the motor determines whether the scissor frame rises or falls. For safety and control purposes, there are usually limit switches for rise and fall. When the scissor frame reaches its highest or lowest position, the limit switches cut off the power to the motor and stop the scissor frame from moving.

◆ design proposal

Scissor frame Controller: Electromagnetic relay

The control unit realizes the forward and reverse rotation of the motor through the electromagnetic relay to commutate the motor of the scissor frame, and the forward and reverse rotation of the motor makes the scissor frame rise or fall.

4.2.3. Tie rod expansion control design

(1) Design Requirements

Free retraction of the actuator by means of a pushbutton

Pushbuttons send signals to the control unit to raise or lower the scissor bar

◆ design proposal

Tie Rod Retractable Controller: DM542, Hall Sensor

DM542 is a high-performance stepper motor driver which is mainly responsible for receiving control signals and driving the stepper motor for telescopic operation. It can accurately control the stepping angle and rotational speed of the motor to realize the precise telescoping of the drawbar. The role of Hall sensors here is to monitor the telescoping position and status of the drawbar. They provide accurate feedback on the current position of the motor, ensuring precise control of the telescoping process.

5. Conclusion

The wheel-tracked climbing and handling trolley designed in this study successfully realizes the automation and high efficiency of cargo transportation in complex environments, bringing a revolutionary change to the logistics industry. Through experiments and theoretical derivations, it has been concluded that the trolley has the following advantages:

1) Multi-functionality(Fig .4): It can realize free switching between level ground and stairs, and has the functions of cargo lifting and on-demand booster to meet the transportation needs in different scenarios.

2) High environmental adaptability: Wide adaptability for transportation in a variety of complex environments such as stairs and ramps.

3) Convenient operation: The actuator is ergonomically designed for easy and convenient operation.

4) Space-saving: Adjustable actuator and self-locking mechanism saves space.

5) High safety: Self-locking and anti-slip device for safe operation.

6) Good economic benefits: It can reduce labor costs, improve transportation efficiency and save transportation costs.

The trolley has a broad application prospect in logistics and freight transportation, medical care and other industries, and is expected to promote the development of the logistics industry in the direction of automation and intelligence. In the future, the intelligent control and energy consumption optimization of the trolley can be further studied to improve its performance and practicality.

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