Design and Simulation Analyses of a Five-Wheeled Stair-Climbing Mechanism Based on TRIZ Theory

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Abstract. Based on TRIZ theory, a five-wheeled stair-climbing mechanism is designed. Its function and structure of the system are analyzed, and the contradiction analyses are made on the problem existing in the design process. The ideal final result is found by combining 40 inventive principles. Then, the five-wheeled stair-climbing mechanism is simulated and analyzed to verify the rationality and stability of its structure. The mechanism is small in size and simple in structure. It is suitable for general stairs and has a good practical value.

Keywords: Five-wheeled stair-climbing mechanism · TRIZ theory · Simulation analysis · Innovative design

1 Introduction

At present, there are many kinds of stair-climbing mechanisms and stair-climbing robots in the market, which can be mainly divided into two types: crawler and tripod [1]. The center of gravity of tripod jumps greatly, which will produce impact on the moving objects. So it is not suitable for carrying sophisticated equipments. The crawler has small fluctuation of center of gravity, smooth movement but large weight, and its movement is not flexible enough. It causes tremendous pressure on the edge of stairs when climbing, which has certain damage to the stairs.

In view of the optimization of the stair-climbing mechanisms, many domestic scholars have carried out researches on it. Because of the particularity of the motion environment, the stair-climbing mechanisms should not only have a simple and compact structure, but also have extremely high stability, which makes the design particularly difficult. SI has designed a five-wheeled rotating stair-climbing cart, which can save strength by reducing the rotation angle of the wheels' center when going upstairs [2]. But its power can only come from people, unable achieve automatic stair-climbing. Wei, Yang, et al., research a kind of eight-wheeled stair-climbing robot, which verifies the rationality of its structure, but it is more suitable for the field with complex terrain [3]. Liu and Ma establish a kinematic model of a five-wheel articulated lunar robot traveling on rough terrain, laying a foundation for the motion control of the robots in three-dimensional terrain [4].

In recent years, the popularity and continuous improvement of the theory of solving inventive problems provides a powerful auxiliary tool for the solution of design

problems. In view of the above problems, this paper applies TRIZ tools to analyze the existing contradictions, solving the problems in the design process, and obtaining the optimal solution.

2 Analyses Based on TRIZ Theory

TRIZ (The Theory of Inventive Problem Solving) is a set of systematized and practical theories, methods and systems for solving inventive problems, which was established in 1946 by a group of scholars led by Altshuller, an inventor of the former Soviet Union [5]. The TRIZ theory is efficient. It uses systematic methods and tools to solve problems that are often unsolvable or difficult to solve, especially for designers to break the traditional inertia and get inspiration [6]. In this paper, the TRIZ theory are used to analyze the contradictions in the design process, and a five-wheeled stair-climbing mechanism is designed.

2.1 Basic Structure Design and System Completeness Analysis

The purpose of this design is using the principle of mechanical transmission to make the mechanism climb up stairs. Through the analyses of the current situation of the stair-climbing mechanisms, it can be seen that the small stair-climbing mechanisms mostly have two rows which are added three or five wheels in a flat plane. Its movement is unstable and unsafe. The six-wheeled and eight-wheeled stair-climbing mechanisms are stable but complex in control and structure. Too few wheels will reduce the stability accordingly, and too many wheels will make the control complicated and consume materials. Therefore, the stair-climbing mechanism of this design uses five wheels to make the structure as simple as possible under the premise of high stability. Instead of following the previous five-wheeled structure, a new five-wheeled stair-climbing mechanism with space movement is innovated. The distribution of the five wheels is shown in Fig. 1. The two front wheels are driven by motors, which provide the power source for the whole moving forward. The two rear wheels are connected by a rod. This is only a general idea, the power source of the auxiliary wheel and how to move, as well as its specific transmission mode need to be solved by using TRIZ tools.
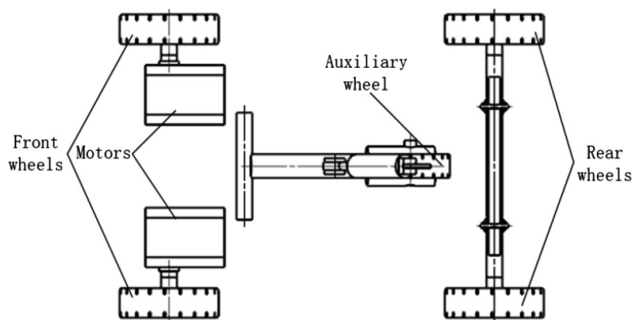

Fig. 1. The basic structure of five-wheeled mechanism

In order to achieve the function of the system, the complete structure of technical system usually includes at least four parts: power device, transmission device, actuator and control device, without which part of the system can not be established [7]. Table 1 shows the system completeness analysis of the five-wheeled stair-climbing mechanism.

Table 1. System completeness analysis

Energy source	Electricity
Power device	Motors
Transmission device	Rods
Actuator	Front wheels, auxiliary wheel, rear wheels
Product	Five-wheeled stair-climbing mechanism
Control device	PLC circuit control system
External control	Operator

2.2   Functional Analysis and Working Principle

Product is the carrier of function, and function is the core and essence of product. Analyzing product function is an important and practical activity [8]. The function of the stair-climbing mechanism is to replace the manual climbing action and save labor. The stair-climbing mechanism designed in this paper intends to let two front wheels climb up the stairs firstly and then two rear wheels climb up the steps, so as to achieve the goal of climbing up the steps as a whole. Therefore, the mechanism should have the function of pulling up the wheels. If the lifting part is set on the front wheels, it is unrealistic and will add redundant devices, which violates the principle of simple structure. Therefore, this design adds the front rod to the connecting rod of the auxiliary wheel, and the front wheels are lifted by stretching the front rod. After the front wheels are lifted, the mechanism loses the power source to move forward, so an additional motor is added to the auxiliary wheel. The lifting of the rear wheels are also accomplished by the rear rods. In this process, in order to ensure its stability, the auxiliary wheel forms a stable triangular structure with the front wheels and the rear wheels respectively, so the auxiliary wheel is an important transitional part for the front and rear wheels to climb up the steps. The designed transmission structure is shown in Fig. 2. The force direction of front and rear rods are marked respectively, and their other ends are attached to the fixed frame.
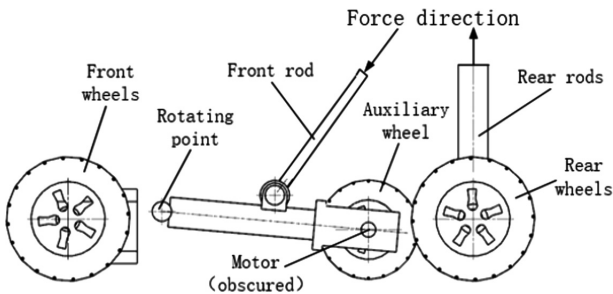

Fig. 2. Schematic diagram of the transmission structure

2.3 Technical Contradictions

A contradiction happens when an improvement of one of the system parameters will then lead to deterioration of other parameters [9]. The contradiction matrix is used to analyze the problems in the design process.

(1) In order to reach the purpose of pulling up the front wheels and rear wheels, the front rod and rear rods are required to be able to stretch. Since the force direction and analyses are determined, so flexible connectors such as springs cannot be used. Only the rods with certain stiffness can be used. The rods should be long enough to lift the front and rear wheels higher and the range of application is bigger. If the lengths of the front and rear rods are increased, the greater work done during the movement, which will cause energy loss. So there is a technical contradiction. The technical parameters of the system were abstracted into the 39 general parameters of TRIZ, and the technical contradiction is as follows.
Improving parameter: No. 3 the length of a moving object.
Deteriorating parameter: No. 22 energy loss.
Looking up the Altshuller contradiction matrix table, it can be found that available invention principles are 7, 2, 35, 39.
Through comparison and analyses, the contradiction is solved by the invention principle No. 7, that is nesting method. The front and rear rods are replaced by hydraulic cylinders and rods. When climbing a step, the hydraulic rods connected to the auxiliary wheel and the rear wheels are automatically stretched in turn, so that the whole device climbs up the steps, and then recovers in turn after climbing the steps. It converts the hydraulic energy of the hydraulic cylinder into mechanical energy and realizes the stair-climbing action. The hydraulic rods are stretched out when working and retracted when not working, which not only reduces the lengths of the rods, but also reduces the energy loss.
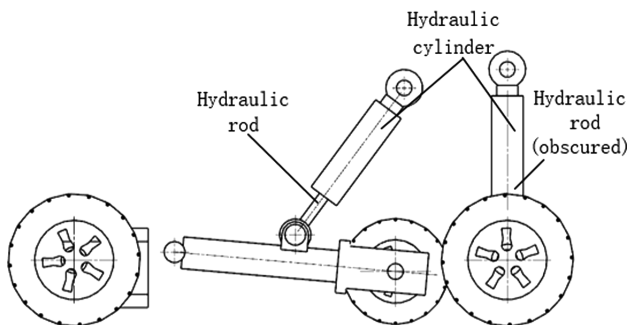Figure 3 shows the application of nesting method.

Fig. 3. The schematic diagram of improved structure

(2) Because of the limitation of stair steps width, it is required that the base area of the five-wheeled stair-climbing mechanism should not be too large, otherwise it

cannot be parked on the steps. However, the five-wheeled stair-climbing mechanism has a certain weight. If the area is reduced, the volume of the mechanism will decrease accordingly, which will lead to poor stability. So there is a technical contradiction. The technical contradiction is as follows.

Improving parameter: No. 13 stability.

Deteriorating parameter: No. 5 the area of a moving object.

Looking up the Altshuller contradiction matrix table, it can be found that available invention principles are 11, 2, 13, 39.

Through comparison and analyses, the contradiction is solved by the invention principle No. 11, that is preset defense method. After the head of the mechanism is lifted up, it is inclined and easy to turn over. The hydraulic cylinder connected to the rear wheel is controlled by the PLC circuit system. After the front wheels climb up the step, the hydraulic rod is immediately stretched out to lift the tail, so that the head and tail of the mechanism are on the same horizontal plane to prevent the mechanism from turning and ensure its stability.

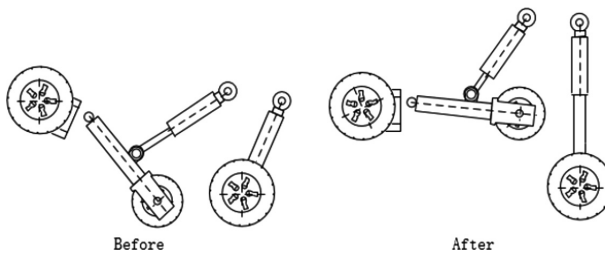Figure 4 shows the application of preset defense method.

Fig. 4. The preventing process

2.4   Ideal Final Result Analysis

Ideal final result: the mechanism can automatically and smoothly go up and down the stairs, without any fluctuation, without any damage to the stairs. Small in size and light in weight.

Ideal result: The mechanism can go up and down stairs as smoothly and automatically as possible without great vibration and damage to stairs. The volume is within the range that general staircases can accommodate.

The obstacles to the ideal result mainly include the width of stair steps, the weight of materials, and the collision between wheels and stairs.

Conditions for the absence of such obstacles: the volume of the device is not larger than the limit of the general staircases, and its movement is smooth.

Resources available to create these conditions: PLC control systems, motors, hydraulic systems, wheel shafting components, hydraulic cylinders, hydraulic rods.

According to the ideal result analysis, the scheme is as follows: the mechanism is designed with small volume, simple and compact structure, saving materials and reducing weight. By installing infrared sensor to accurately sense the distance between

the mechanism and the stairs. The head of the device is raised before the collision occurs, and there is no collision with the stairs in the process of movement, so that the device can work smoothly and the stairs can not be damaged. The length of the device is 280 mm, and the lifting height of hydraulic rod is 180 mm. It can climb steps with width more than 280 mm and height less than 180 mm. It's suitable for stairs in most places.

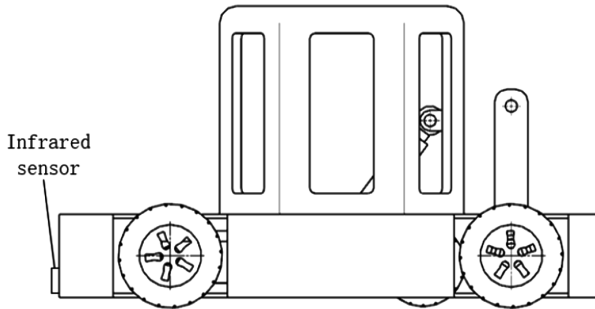The installation position of infrared distance sensor is shown in Fig. 5.

Fig. 5. Installation position of infrared sensor

3   Motion Simulation of the Five-Wheeled Stair-Climbing Mechanism

In the UG NX simulation software, the three-dimensional solid model is established, and the motion pair, drivers, motion function and contact condition are added in the motion simulation interface. The motion process of the five-wheeled stair-climbing mechanism is simulated to verify the rationality of its structure.

Before the motion simulation, the STEP function, which is an important part of controlling the stair-climbing motion, is introduced briefly. Because the stair-climbing movement is variable, there is a strict time sequence relationship between the movements. In order to control the movements accurately in time, the motion control function of UG NX - STEP function is needed [10]. The format is as follows:

$$STEP(x, x_0, h_0, x_1, h_1) \tag{1}$$

Where x is independent variable, x_0 is the initial value of the independent variable, x_1 is the terminal value of the independent variable, h_0 is the initial value of the function, h_1 is the terminal value of the function.

The meaning of STEP function is shown in formula (2).

$$step(time, t0, h0, t1, h1) = \begin{cases} h0 (time \leq t0) \\ h0 + \left(\frac{time - t0}{t1 - t0}\right)^2 .(h1 - h0)(t0 \leq time \leq t1) \\ h1 (time \geq t1) \end{cases} \tag{2}$$

The specific meaning expressed by STEP function needs to be determined according to the type of motion pairs. If it is a rotary pair, it can represent angle, angular velocity and angular acceleration. If it is a sliding pair, it can represent displacement, velocity and acceleration.

In this simulation environment, the steps width is 300 mm, the height is 100 mm. Three rotating pairs drives and two sliding pairs drives are defined in the 'Joints' interface, and the 3D contact friction coefficient of five wheels and the stair is 0.3. The specific motion pairs and contact conditions are shown in Fig. 6.
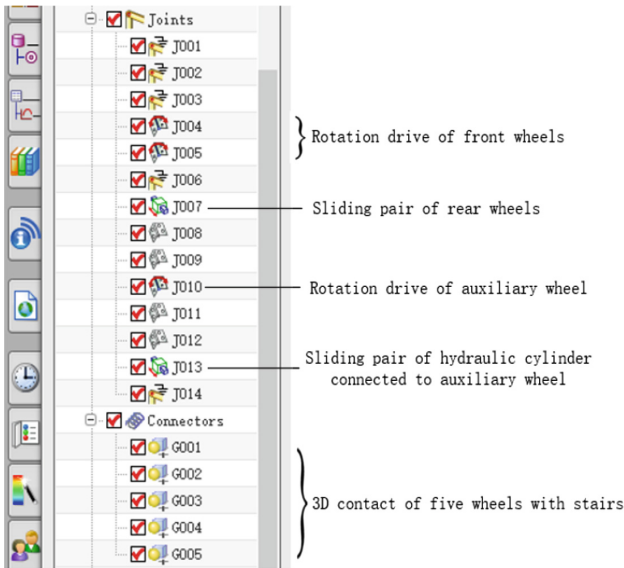

Fig. 6. The specific motion pairs and contact conditions

The simulation of the stair-climbing process is shown in Fig. 7. The five-wheeled stair-climbing mechanism goes straight as shown in (a). After the head of the mechanism is about to touch the vertical surface of the stairs, the hydraulic cylinder connected to the auxiliary wheel is pressurized, and the hydraulic rod is stretched out to lift the head of the mechanism as shown in (b). The whole device is driven by the motor connected to the auxiliary wheel to continue straight ahead. When the front wheels reach the level of the stairs as shown in Figure (c), the hydraulic cylinders connected to the rear wheels are pressurized, and the hydraulic rods are immediately stretching to lift the tail of the mechanism until the whole device is horizontal as shown in (d). Then the device continues to move forward powered by the motors connected to the front wheels. At this time, the auxiliary wheel starts to retract to just touch the horizontal plane of the step as shown in (e), forming a triangular structure with two front wheels to maintain the device stable. When the rear wheels are about to touch the vertical surface of the stairs, the hydraulic rods connected to the rear wheels are retracted as shown in (f). At the moment, the entire stair-climbing process is completed, and the device

returns to the initial state. Repeat this process, and the reciprocating stair-climbing motion is achieved. The device goes downstairs following the opposite route of going upstairs. The movement feasibility and structure rationality of the five-wheeled stair-climbing mechanism can be obtained through the simulation.
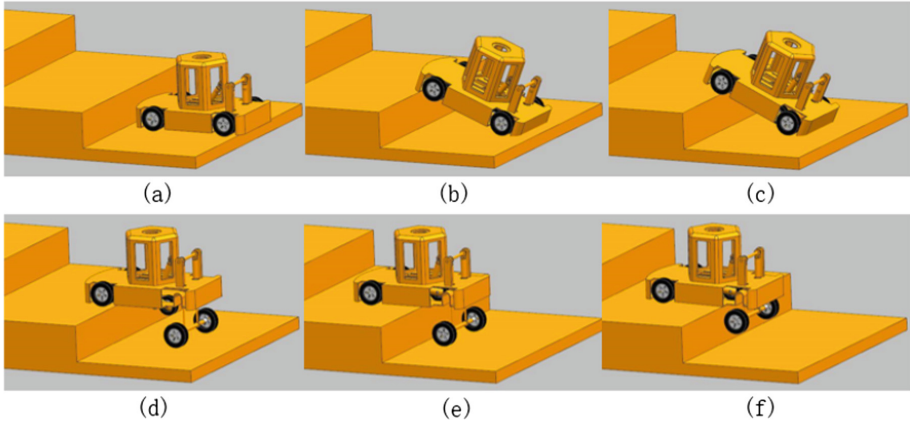

Fig. 7. Simulation of the stair-climbing process

Figure 8 shows the displacement of the barycenter of the five-wheeled stair-climbing mechanism in the Y-axis direction during the stair-climbing process. From the figure, we can see that the displacement curve of the barycenter in the vertical direction basically coincides with the shape of staircases. Although there are fluctuations, there is no large displacement mutation, and overall, it is still rising steadily.
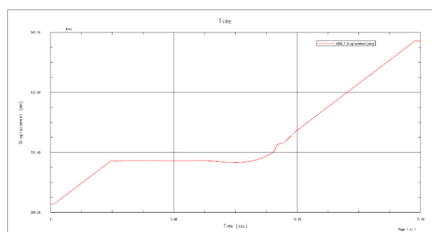

Fig. 8. The displacement curve of the barycenter in Y-axis

Figures 9 and 10 are respectively the torque curves of the motors connected to the front wheels and the auxiliary wheel in the stair-climbing process. The peak value of the motor connected to the front wheel is caused by driving the whole device forward before and after climbing the stairs, and the torque value is 0.14 N·m–2.12 N·m, with a few exceeding 2.12 N·m; The peak value of the motor connected to the auxiliary wheel is caused by the excessive load when lifting the head of the mechanism, and the torque

value is 0.89 N·m–3.88 N·m, with a few exceeding 3.88 N·m. The two peaks do not appear at the same time, which indicates that the wheels work alternately to support the loads in the stair-climbing process. It implies the structure of the five-wheeled stair-climbing mechanism. The torque value is within the allowable range, which proves that the motion is relative stable.
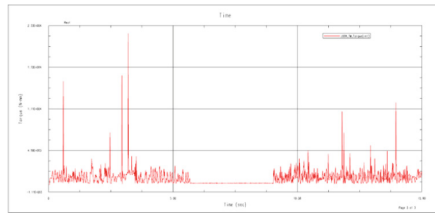

Fig. 9. Torque curve of the motor connected to front wheel
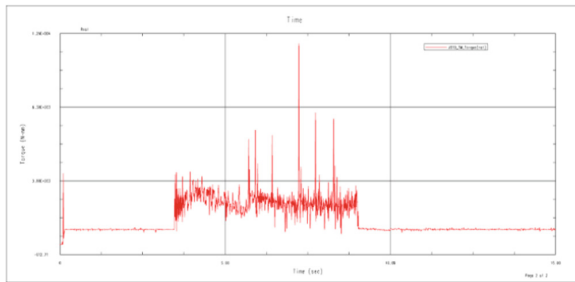

Fig. 10. Torque curve of motor connected to auxiliary wheel

Figure 11 shows the acceleration of the device in X-axis during the stair-climbing process. From the figure, it can be seen that the overall acceleration tends to be stable, but there is a big sudden change when the device is about to touch the steps. The acceleration reflects the inertia force of the device and the impact of the device on the steps. Obviously, the impulse of the device in the X direction has little effect to the steps, which can completely satisfy the purpose of not damaging the steps.
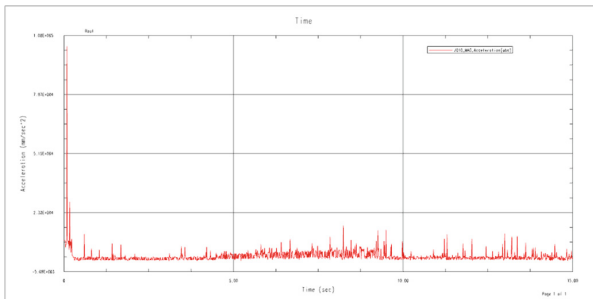

Fig. 11. Acceleration curve of the device in X-axis

4   Conclusions

(1)   A five-wheeled stair-climbing mechanism is designed by using TRIZ theory and relevant inventive tools. The contradictions in the design process are analyzed and the final ideal result is found. Through the ingenious structural design of the five wheels and the coordinated control of the movement time, the steady stair-climbing movement can be realized, and the mechanism can freely go up and down steps. It is convenient, safe and reliable.

(2)   The virtual prototype is used to simulate the stair-climbing process of the mechanism. The result shows that the moving trajectory of the centre of mass is similar to the shape of the stair steps. The five-wheeled structure designed is reasonable, which provides a reference for the practical application and in-depth study of the stair-climbing device.

(3)   The specific control parameters of the five-wheeled stair-climbing mechanism can be determined by the main performance indicators of the site. The best structural parameters needs further theoretical and experimental research.

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