Design of A Wheel-Legged Stair Climbing Robot

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***Abstract*—This paper presents a wheel-legged robot capable of overcoming steps and climbing stairs with six linear actuators as legs. With its control algorithm, this design can conquer irregular stairs with high operation stability. We built our physical prototype and developed the climbing procedures for a single stair and multiple stairs. Experiment results showed the feasibility of our mechanical design and the effectiveness of its climbing algorithms. The leg-wheel platform design and climbing algorithms show the potential application in various areas include service robots, goods transportation, and wheelchairs.**

***Keywords*—stair-climbing, wheel-legged robot, robotics design**

I. INTRODUCTION

In the field of developing a mobile platform for service robots or goods transportation, the aspect of overcoming stairs remains largely unsolved. Many approaches proposed for stair-climbing solutions generally involve complex and custom mechanical designs. Although tracked, wheel-linkage and modified wheels design are existing solutions to overcome the stairs [1]-[4], they often result in complex structure or irregular shapes, and thus suffer from instabilities during climbing. Some designs utilize modified wheels to achieve stair climbing, and it is unclear how much payload they are capable of carrying. Besides, the flat surface operation remains an issue for these designs. Based on these drawbacks, these current solutions are difficult to integrate into real-world applications such as wheelchairs and general transportations. Some hybrid robots employ unique transformation mechanisms that allow stable operation on the ground, but they still rely on custom wheel design when climbing [5]. Another design approach is to combine the advantage of the legs and wheels as seen in some previous work, [6]-[9]. These designs require a well-designed control scheme and usually a fair amount of actuators. Furthermore, some are not designed specifically for accomplishing stair-climbing tasks and may be more appropriate on uneven terrain [7], [8].

This study presents an effective robot that exhibits strong single or multiple steps climbing capabilities. The climbing stability is superior to the many proposed mechanisms with generally less control complexity relative to many designs. The mechanical design utilizes a wheel-legged system with linear actuators as its legs. A comprehensive control algorithm enables our design to conquer single and multiple steps with different step lengths. With its simple mechanism and high stability, the design can be easily integrated into current vehicles. The control implemented integrated with the design is simple but powerful. Moreover, the robot also behaves like a conventional wheeled vehicle upon operating on flat surfaces. We hope this paper will advance the research of stair-climbing wheelchairs by simplifying current complicated climbing mechanisms.

II. METHODS

A. Design

Our proposed design features six linear actuators, which can be considered as "legs," that are capable of performing vertical elevation independently in a parallel pair. Six wheels are attached at the bottom of the legs. Four active wheels enable the horizontal translation of the vehicle while the other two wheels are passive and only involve supporting the climbing operation. Thus, the robot performs just like a regular vehicle when driving on a flat surface. Another two front passive wheels extending in front of the front leg are connected directly to the vehicle's main body. They are considered a part of the chassis and they support the weight of the vehicle during the climbing operation.

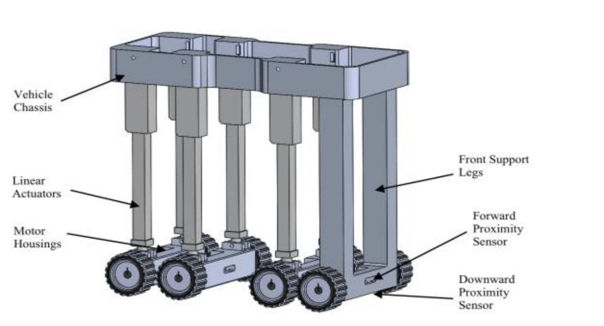

Fig. 1. Design of the stair-climbing robot

The design employs eight proximity sensors in total, mounted on the connecting structures of the wheels. Therefore, there will be two sensors for each parallel pair of the wheels as all three parallel pairs of the linear actuators operate independently. The number of proximity sensors is expected to be lower if the position feedbacks of the linear actuators are available as the controller can be programmed to store the heights of the steps. These proximity sensors measure the distance between the wheels and the steps. Four proximity sensors will be installed facing the front, mainly responsible for ascending climbing tasks. Meanwhile, the other four proximity sensors will be positioned facing toward the ground, primarily responsible for descending climbing operations.

Fig. 2. Prototype of the stair-climbing robot.

A prototype model of our robot design was built to confirm the mechanical feasibility and verify the climbing schemes. The overall dimensions of the model chassis are 250 mm in length, 140 mm in width, 232 mm in height including the contracted legs and wheels. The chassis houses the microcontroller, batteries, and motor controllers, and it is fabricated on a 3D printer. The selected linear actuators can extend 10 cm and their operations are only required during the climbing process. Since the selected linear actuators feature lead screw shaft drives with brushed motors, their self-locking characteristics suggest that there is no need to apply brakes to the linear actuators. Besides, they do not consume energy when they are locked in the desired length. Without loading, the operational speed of the linear actuators is 1.5 cm per second with 12 volts. The model prototype is equipped with four N20 motors with 75 revolutions per minute at 9 volts and eight 4.3 cm diameter wheels.

The maximum incline angle of stairs for our current prototype is limited by the ratio of the maximum extension length of the linear actuators in the back (d), the horizontal distance between the furthermost back wheels and furthermost front wheels (x). The maximum incline angle (Θ) can be computed by using the formula: $\Theta = \arctan(d/x)$. With current design parameters, Θ is about 28 degrees.

B. Positional Configuration of the Active Wheels

There are a total of six combinations of active wheel positions in the design. Two major strategies of installing the active wheels are investigated: two groups of active wheels to be distributed in the front and back respectively or all four active wheels to be placed in the front or back. However, the strategy of installing two groups of active wheels in the front and back respectively can cause stall conditions when the distance between the two groups of wheels is close to the distance between two steps as demonstrated in Fig. 3. The stall conditions occur when both the two active wheels are lifted above the ground, resulting in the inability of moving forward. Therefore, our prototype placed the two pairs of active wheels next to each other in the back of the robot to ensure that there is always at least one pair of active wheels touching the ground, avoiding the problem as mentioned above.

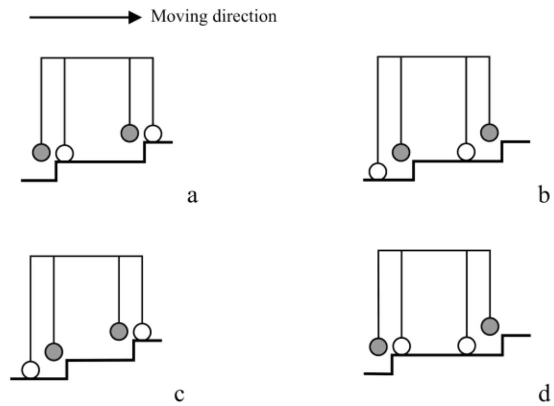

Fig. 3. Four wrong configurations of the active wheel for the design. The grey solid circle presents the active wheel while the white circle solid circle stands for the passive wheel.

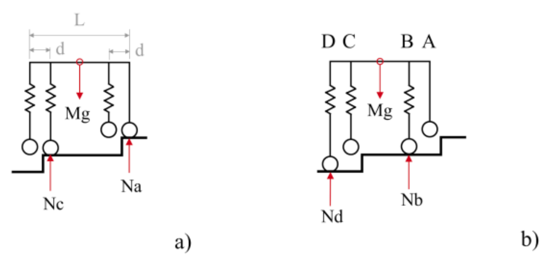

Fig. 4. Free-body diagram of the vehicle in the worst scenarios. The zig-zag line represents the linear actuators.

C. Loading Analysis

Based on the proposed design, the loadings of the platform are determined by the specification of the linear actuators. The worst-case scenario is shown in Fig. 4, leg C supports the most weight in (a) while leg B supports the most in (b). The assumption is that the center of gravity is at the center of the vehicle's main body. Thus, the minimal static supporting force required for the linear actuator can be expressed as:

$$2N_{min} = \frac{Mg}{2-2d/L} \tag{1}$$

where M is the total mass of the vehicle. Note that $2N_{min}$ is always greater than half of the vehicle's weight. The coefficient of 2 in front of $2N_{min}$ indicates that the legs are distributed at both sides of the vehicle. The maximum loading is limited by leg C or leg B. In our prototype, the N_{min} is limited by the linear actuators (maximum 20 N during operation), resulting in a max static load of 4.3 kg. Power and type of the linear actuator and the safety factor should be considered in further analysis when the full scale model is built.

D. Climbing Process

Climbing one single step is the simplest case that stair-climbing robots would encounter. In this case, the assumption is that the gap length of each step is far larger than the length of the vehicle. The most common scenario for this case is climbing the step of a sidewalk. As shown in Fig.5, the climbing operation is achieved by following steps.

1. Wheel C is initialized at the same height as wheel A.
2. The vehicle stops from cruising when it detects the step.
3. Legs D and B are lengthened sufficiently until A is at the top of the step. Leg C will not operate and passively elevate with the vehicle chassis itself. The vehicle then moves a distance of …… until wheel B touches the next step. The sensors will ensure that wheel A firmly touches the higher ground.
4. Leg B shortens until its wheel is at the same height as wheel A, which implies the wheel on leg B should be at the top of the step.
5. The vehicle moves until wheel D touches the step. This also means that wheel C firmly stations on the top of the step.
6. Finally, wheel D raises to the same height as all other wheels. The vehicle then continues to cruise.

There are six control sequences in total for a single step. As indicated in the climbing sequence, the operation of leg C is not required to complete the process.

If a group of stairs has a step length longer than the vehicle length, our mechanism will treat each step using the control sequence mentioned above.

A more complicated case would be the robot climbing the staircase. This is the common scenario that it will encounter in a public building without accessible facilities. The assumption is made that the gap length of each step is far smaller than the vehicle body length. The vehicle can first attempt to complete a single-step algorithm. When the front sensor detects the second step, interrupting the single-step algorithm, the vehicle would proceed to the multiple-stairs algorithm. As shown in Fig.6 while climbing the stairs, the vehicle is kept moving horizontally until any of the wheels almost touch the edge of the next step. As wheel A touches the next step, leg B, C, D will extend simultaneously until wheel A reaches the top of the step. This is the step where the chassis is lifted to the new level. Also, if wheel C touches the cliff, leg C would contract until wheel C positions at the top of the next step. If wheel B touches the next step, leg B contracts to the same length of leg A. Similarly, if wheel D touches the next step, leg D shortens to the same length of leg C. To ensure safety or prevent loss of support, only one procedure is allowed to be executed at the same time. Furthermore, contraction of leg B is only permitted when both proximity sensors on wheel A and B detect the step, and, similarly, contraction of leg D is only allowed when both proximity sensors on wheel C and D detect the step.

Two special cases are considered: if wheel B and D touch the step at the same time, the contraction of both leg B and D is allowed simultaneously; if wheel B and C are close to the step at the same instant, leg B and C can both shrink simultaneously. While ensuring safety, this method reduces the number of control sequences, and thus it increases the climbing speed.

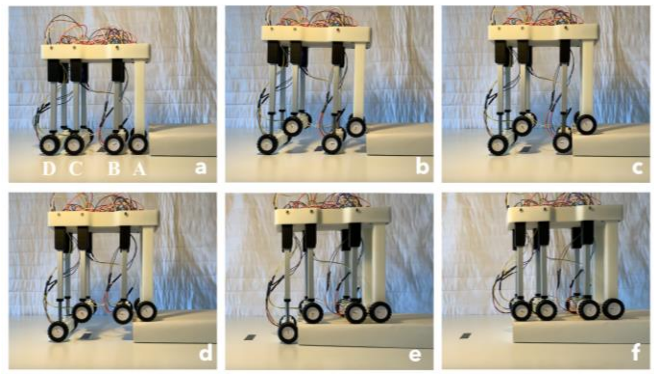

Fig. 5. Robot prototype performs single step operation.

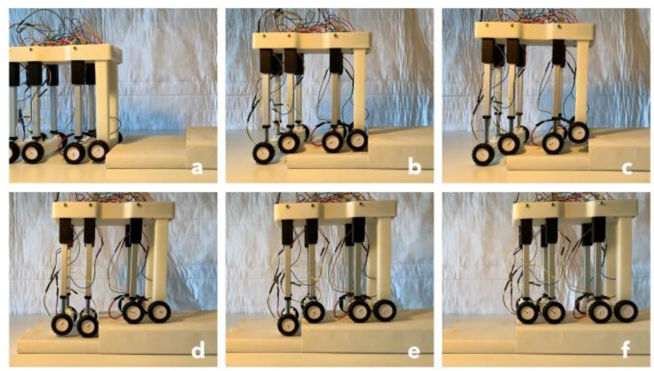

Fig. 6. Robot prototype performs multiple stairs operation

Even given that the stairs are not well constructed and the step heights are different, the control algorithm assumes no regularity of the stairs and can still work safely as the front and rear unit generally process the stair information independently. For descending motion, the vehicle direction will be reversed and the control sequence is exactly the opposite of the ascending motion.

III. Experimental Results

The prototype was tested with one single step and a set of two stairs. For the experiment of a single step, the step height is 4.2 cm, and the prototype is placed 10 cm away from the edge of the step to test the prototype speed on the flat surface. For the experiment of overcoming two stairs, the first step height is 2.5 cm and the second one is 3 cm, and the distance between the two steps is 16.5 cm. This experiment is designed to test the ability to operate on the step with different heights and lengths smaller than the vehicle length. The prototype completed all six repeated single-step trials, and the average time of completing the whole test is 25.7 (±3.1) seconds. The average time to complete the action without the flat surface operation in Fig. 5 is 24.3 (± 3.2) seconds. The prototype also completed six two-step tests seen in Fig. 6 with 51.2 (± 3.9) seconds. The results demonstrate that the vehicle can climb one or multiple steps with high stability while also exhibits highly stable flat surface operation. Also, the vehicle transitions from the flat surface operation state to the climbing state smoothly and vice versa.

TABLE I. COMPARISON OF VARIOUS STAIR-CLIMBING MECHANISMS

Mechanism	Actuators	Wheels	Active Linkages or Legs	Climbing Stability	Flat Surface Stability	Control Complexity
Zero Carrier [6]	4 driving motors and 8 linear actuators	8	8	High	High	Medium
RHex [10]	6 motors	N/A	6	Low	Low	High
RHyMo [2]	N/A	6	12	Medium	High	Low
Curved-Spoke Tri-wheel [11]	2 driving motors	3 (2 with modification)	N/A	Low	Low	Low
Loper [3]	4 driving motors	4 with modification	N/A	Low	Low	Low
Asguard [4]	4 driving motors	4 with modification	N/A	Low	Low	Low
Erect Wheel-legged [12]	4 motors	6	N/A	Low	High	High
Self-Configurable Tracked [1]	2 driving motors and 1 pitch motor	6	N/A	High	High	High
Claw-Wheel Transformable [5]	4 driving motors and 2 transformation motors	5 (with one ball caster)	N/A	Low	High	Medium
Our design	4 wheel motors and 6 linear actuators	8	6	High	High	Medium

IV. DISCUSSION

While demonstrating its strong ability in overcoming steps and irregular stairs, the design presented possesses a medium level of control complexity compared to other robots' control strategies. While erect RHex, wheel-legged, and self-configurable tracked designs utilize fewer actuators, they involve complex control schemes with sophisticated models. Some even require tuning of the controller to the geometry of the stairs to ensure the success of the climbing [10]. The tracked mechanism described assumes well-constructed stairs for their general procedure, and it requires extra mathematical models and calibrations for conquering irregular stairs [1]. Our climbing algorithm for the design does not require a rigorous and intensive dynamic model and assumes no regularity of the stairs. Moreover, our algorithm is proven to be simple but reliable, undergoing a fair amount of climbing tests without failure or adjustment.

The amount of the active legs or linkage is lower relative to other mechanisms, whilst the numbers of actuators are also lower than Zero Carrier. The reduction of quantities of actuators decreases the complexity of electronics design, reduces the number of control sequences during climbing, and offers slightly less control complexity than Zero Carrier's [6]. Other benefits include the reduction in energy consumption per step and lowering the cost of manufacturing.

The design presented achieves high operating stability on climbing and cruising on regular surfaces in comparison to other mechanisms (Table I). The vehicle body remains parallel to the ground while climbing or cruising. Although the tracked mechanism also demonstrates high stability in both climbing and operating on the ground, the loaded tracked vehicle will produce tremendous damage to the stair edges, especially the stairs with the nose. Compared to the tracked mechanism, our design does not require intensive frictional analysis and is unlikely to encounter slippage while climbing stairs. Furthermore, by implementing positional feedback of the future linear actuators in our design, the climbing process is expected to be even more stable with a closed-loop strategy. The high stability on both the ground and stairs highlights the potential and benefit of applying such mechanisms into goods transportation, wheelchair, and other service robots.

Although our design was not optimized for operating on stairs with incline angles larger than 28 degrees, slight modifications such as increasing the extension length of the linear actuators in the rear and decreasing the vehicle length can be easily applied to the design.

V. CONCLUSION

In this work, we present an effective robot design with strong stair climbing ability that can conquer various steps with simple control sequences. This robot design has high versatility and stability on both stairs and ground. Based on the design, we built a prototype model which completed the stair climbing as expected. We also discussed the advantages of our design compared to other stair climbing mechanisms including tracked, modified wheels, and linkage-wheel designs. We plan to improve our design by implementing closed-loop control on our linear actuators and optimizing the design parameters to increase the ability to operate on steeper stairs. In the future, we intend to continue developing our mechanical design and explore more robust control algorithms.

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