A New Driving Mechanism to Allow a Rescue Robot to Climb Stairs

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There have been numerous studies directed toward the development of driving mechanisms for off-road mobility and rescue robots. To achieve surveillance, reconnaissance, and rescue, it is necessary for robots to have a driving mechanism that can handle off-road environments. We propose a new type of single-track driving mechanism with a variable geometry for a rescue robot. This mechanism has a symmetric configuration so that the robot can advance in two directions and also remain operable when overturned. By transforming its geometry, the robot can reduce energy consumption in steering and rotating as well as maximize its ability to climb obstacles such as stairs. The robot is also designed to have a compact size and low center of gravity to facilitate driving when on a set of stairs. In this paper, we analyzed the design parameters of the robot for the four phases of climbing stairs and determined the specifications needed to enhance its adaptability.

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NOMENCLATURE

θ = attack angle
N = repulsive power
F = friction power
M_d = driving moment
M_o = rotation moment of system
μ = friction coefficient
c = distance between two wheels of arm
d = contact length with ground in mode 1
a = contact length with ground in mode 2
r = wheel radius

1. Introduction

Massive loss of life and property has been caused by building collapses due to fires, earthquakes, terrorism, and wars. Recently, there has been a substantial increase in these types of disasters. Robots in the place of humans can play a key role in rescue operations and scouting unknown terrain in dangerous areas such as buildings that have been damaged by fire or explosion. Therefore, it has become important to develop rescue robots that are efficient and effective in these types of situations.

Since 1976, there has been a wealth of studies on driving mechanisms that allow rescue robots to climb steep paths, including the Variable Configuration Tracked Vehicle (VCTV). VCTV-1 presented by Kohler[1] and VCTV-2 proposed by Maeda[2] were designed to maximize their adaptability to steep paths and to minimize their resistance to rotation by transforming the geometry of the four tracks. Iwamoto's VCTV-3[3] was the first single-tracked mechanism with planet wheels that could climb stairs. Martens[4] developed the robot Andros, which had a similar mechanism to that of VCTV-1 and controlled the tension of the tracks using idlers. Xevious, developed by Yoneda[5], used powder packs to increase the friction coefficient of its tracks. Hagen[6] used a double-track mechanism with dual-attack angles on the robot Pandora.

Rescue robots and driving mechanisms have been studied since the beginning of the 21st Century, including the Micro-VGTV by Inuktun Corp., Packbot by the iRobot Corp.[7] and DT-2 by KAIST MSD-LAB.[8]

2. Driving Mechanism

2.1 Design Concept

The main requirements and structure of the driving mechanism needed by a rescue robot are shown in Fig. 1. First, robots with track mechanisms are more stable and adaptable to various ground conditions than robots having wheels or legs. Track mechanisms are

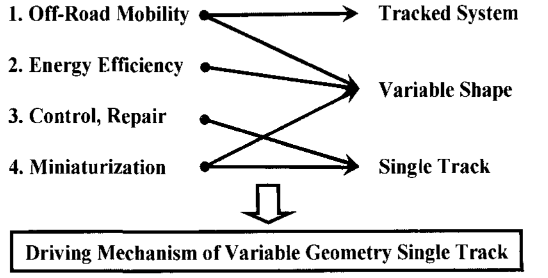


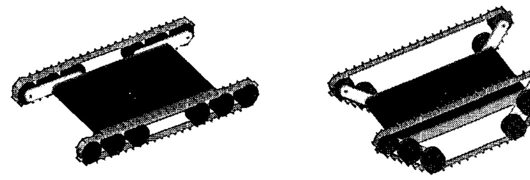
Fig. 1 Design requirements

more suited to allowing the robot to overcome unexpected obstacles, steep paths, and stairs. By transforming the geometrical structure of the tracks, the robot can reduce energy consumption in steering and rotating as well as maximize its ability to climb obstacles such as stairs. In particular, a single track system provides a way to minimize the robot size for passing through small spaces, to easily transport the robot, and to more effectively control the robot during urgent rescue circumstances. Therefore, a Variable Geometry Single-Tracked (VGST) driving mechanism is proposed in this paper.

2.2 Design Proposal

The driving mechanism must have unique characteristics compared to that of existing systems. Existing systems have trouble when they encounter unknown terrain and unexpected disturbances. The proposed system is able to turn quickly and move both forward and backward without distinction between the front and the rear of the robot. The system also reduces energy consumption by minimizing the contact length of the track with the ground during high-speed motion on flat terrain. On the other hand, the track maximizes contact length with the ground for adaptability to off-road environments and stairs. The robot also has a lower center of gravity for stability. Finally, the track is able to transform and generate different attack angles to overcome various obstacles such as stairs.

Figure 2 shows the proposed driving mechanism, which has a single track with a variable configuration. Mode 1 in Fig. 2(a) has a low center of gravity and long contact length with the ground so that the robot is capable of climbing stairs. Mode 2 has a variable attack angle and short contact length so that the robot can overcome obstacles and minimize energy consumption during steering. This mechanism can also transform into various shaped configurations, including a rectangle, trapezoid, and inverse-trapezoid, and can generate attack angles ranging from 0 to 90 degrees. During the transformation, the total track length does not change.



(a) mode 1 (b) mode 2

Fig. 2 Proposed design

The robot must be able to travel over a wide variety of surfaces. However, the design focus of the system was toward climbing stairs.

3. Specific Design

Figure 3 shows the four phases needed for the robot to climb stairs. First, the robot scales the first step utilizing an attack angle in mode 2. Second, it transforms into mode 1 on the first step in order to reach the second step. Third, it continues in mode 1 and scales the second step. Finally, it ascends the remaining steps along a normal slope which is typically 34 degrees. In this section, the performance indices and constraints on the system were analyzed.

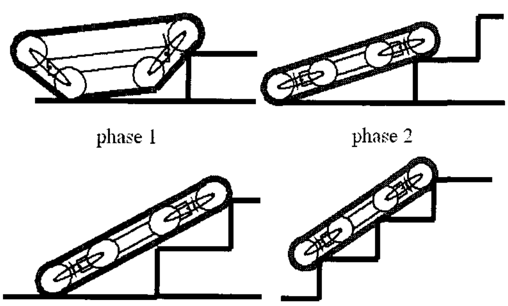
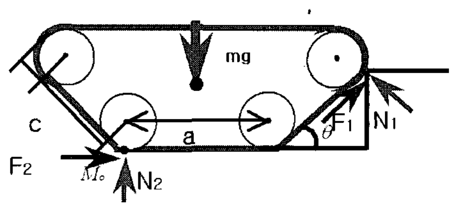


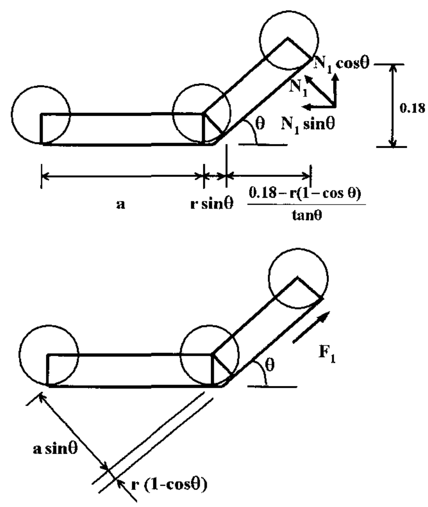
Fig. 3 Four phases for climbing stairs

3.1 Performance Index: Phase 1

Figure 4 shows a free-body diagram containing the forces acting on the robot during phase 1. The force balance equation is shown in (1) and the moment M_0 for the rear contact point is shown in (2). Here, it is assumed that the maximum height of the first step is 0.18 m, which is the size of a standard step. Since the robot has to rotate to climb the first step, the moment must have a positive value.



(a) Free-body diagram



(b) Detailed dimensions

Fig. 4 Free-body diagram of phase 1

$$\begin{aligned} &F_x : F_2 + F_1\cos\theta - N_1\sin\theta = 0 \\ &F_y : F_1\sin\theta + N_2 + N_1\cos\theta - mg = 0 \\ &\quad where\ \ F_1 = \mu N_1 \quad F_2 = \mu N_2 \end{aligned} \tag{1}$$

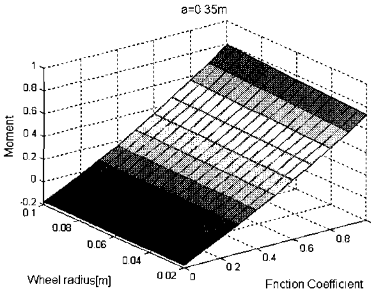
$$\begin{aligned} M_0 = &\left(a + r\sin\theta + \frac{0.18 - r + r\cos\theta}{\tan\theta} + 0.18\tan\theta\right)N_1\cos\theta \\ &+ (a\sin\theta + r - r\cos\theta)F_1 - \frac{amg}{2} \end{aligned} \tag{2}$$

By combining terms from (1) and (2), the performance index for the robot in phase 1 can be expressed as (3). By assuming an attack angle of 45 degrees, the performance index can be simplified as shown in (4).

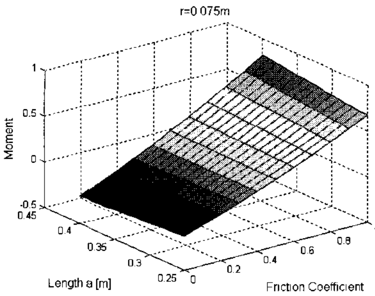
$$\begin{aligned} &M_0 \times \left(\frac{\mu^2+1}{mg}\right) \\ &= a\left(\frac{\mu}{\tan\theta} + \frac{\mu^2-1}{2}\right) + r\left(\mu + \frac{\mu(\cos\theta-1)}{\sin^2\theta} + \frac{\mu^2(1-\cos\theta)}{\sin\theta}\right) + \frac{0.18\mu}{\sin^2\theta} \end{aligned} \tag{3}$$

$$\left(\mu + \frac{\mu^2-1}{2}\right)a + 0.414\,(\mu^2+\mu)r + 0.36\,\mu > 0 \tag{4}$$

The moment required to scale the step is plotted as a function of the wheel radius r and the friction coefficient μ in Fig. 5(a), and as a function of the contact length a and the friction coefficient μ in Fig. 5(b). Figure 5 indicates that climbing the first step becomes easier with a decrease in contact length and an increase in wheel radius. The robot can scale the first step if the friction coefficient is greater than 0.3.



(a) Moment vs. wheel radius vs. friction coefficient



(b) Moment vs. length a vs. friction coefficient

Fig. 5 Performance index during phase 1

The moment required to scale the step is plotted as a function of the wheel radius r and the friction coefficient μ in Fig. 5(a), and as a function of the contact length a and the friction coefficient μ in Fig. 5(b). Figure 5 indicates that climbing the first step becomes easier with a decrease in contact length and an increase in wheel radius. The robot can scale the first step if the friction coefficient is greater than 0.3.

3.2 Performance Index: Phase 3

After climbing the first step, the robot transforms its configuration into mode 1 where it comes into contact with the wall of the second step. Figure 6 shows a free-body diagram containing the forces acting on the robot and the design parameters in phase 3. The force equilibrium equation and the moment M_0 for the rear contact point are shown in (5) and (6) in the same manner as that for phase 1.

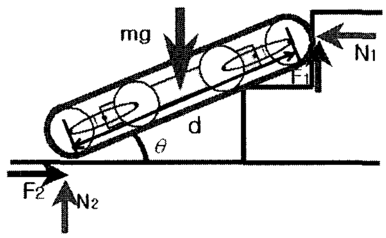
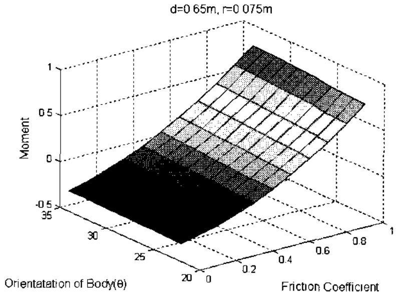


Fig. 6 Free-body diagram of phase 3

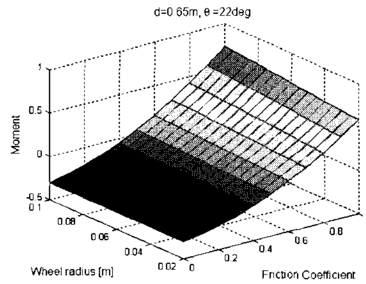
$$\begin{aligned} &F_x : F_2 - N_1 = 0 \\ &F_y : F_1 + N_2 - mg = 0 \\ &\quad where\;\; F_1 = \mu N_1,\; F_2 = \mu N_2 \end{aligned} \tag{5}$$

$$M_0 = (d\sin\theta + r)N_1 + (d\cos\theta + r)F_1 - (\frac{d}{2}\cos\theta)mg \tag{6}$$

The moment required by the system is expressed in Fig. 7(a) as a function of the body orientation angle θ and the friction coefficient μ. With the ascension to the second step, the body orientation angle θ changes from 22 to 34 degrees. Moving to the initial state of 22 degrees is the most difficult part of phase 3. From Fig. 7, the robot can ascend the second step if the friction coefficient is greater than 0.45, which is higher than that of phase 1.



(a) Moment vs. orientation angle vs. friction coefficient



(b) Moment vs. wheel radius vs. friction coefficient

Fig. 7 Performance index during phase 3

3.3 Performance Index: Phase 4

In phase 4, the robot, which has been transformed to mode 1, actually climbs the stairs. The robot has to contact the edges of at least three stairs in order to climb in a stable manner. The minimum length of the system is expressed in (7). Here, the steepest standard step, which is 34 degrees, is applied and the ground contact length d is selected as the minimum value for the system.

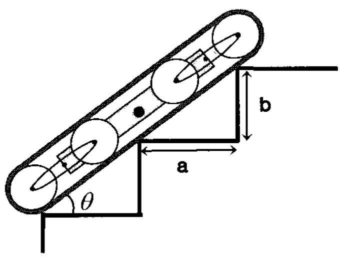


Fig. 8 Contact length during phase 4

$$\begin{aligned} &d \geq 2\sqrt{a^2 + b^2} \;\; \text{where a} = 0.27\text{m}, \text{b} = 0.18\text{m} \\ &d \geq 0.65m \end{aligned} \tag{7}$$

3.4 Design Parameters

In the previous sections, the performance indices were analyzed for each phase in order for the robot to climb the stairs. The main design parameters were the ground contact length (d), the length between the centers of the wheels (c), and the wheel radius (r).

Besides the performance indices, there are some constraints on the body size, clearance depth between the body and the ground, and minimum gap between the wheels. Also, the robot height in mode 1 has to be more than 18 cm. These constraining equations can be written as:

$$\begin{aligned} &2(r + c) \leq 0.68, \qquad 0.06 \leq r \leq 0.1 \\ &2r + 0.03 \leq c, \qquad -1.414r + 0.254 \leq c \end{aligned} \tag{8}$$

The contact length d was selected to be the minimum value required during phase 4. The values of r and c were then selected using the performance indices and the constraining equations in order to optimize the performance of the robot when climbing stairs.

4. Tests

4.1 Specifications

The system was manufactured according to the design values calculated in the previous section and is shown in Fig. 9. Table 1 shows the specifications of the robot, including the dimensions and design parameters of the system.

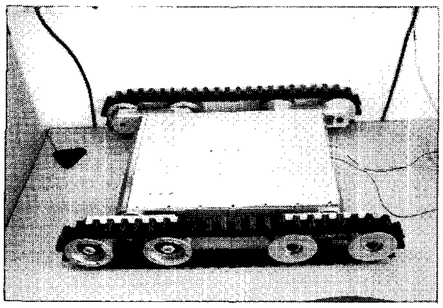


Fig. 9 Manufactured robotic system

Table 1 Specifications

	Specifications
Body Size	550 (L) × 400 (W) × 90 (H) [mm]
Total Size	800 (L) × 560 (W) × 150 (H) [mm]
Mass	34 kg
Motor for Driving	90W × 2 (43:1 gear ratio)
Motor for Transformation	150W (353:1 gear ratio)
Materials	Body: Al Track: Rubber

4.2 Experimental Results

Tests in which the robot geometry was transformed, the robot was turned, and the robot climbed stairs were executed to assess the performance of the manufactured system. The robot did not have a self-navigation ability and was controlled by an operator.

4.2.1 Transforming the Geometry

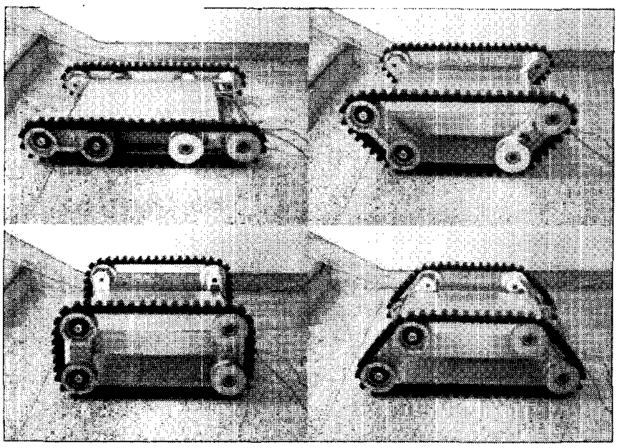


Fig. 10 Transforming the geometry

The front and rear arms were synchronized so that when the front arm was rotated, the rear arm was rotated symmetrically in the opposite direction. As shown in Fig. 10, the system could generate various geometrical configurations. Due to the mass of the system, at least 8.4 Nm was required to transform the system to a state where the angular velocity of the rotating arms was about 0.7 rad/s. The test demonstrated that it was possible to transform the mechanism into a configuration that matched the specific ground conditions.

4.2.2 Turning

In order to determine the performance of the robot during turning, tests were carried out in the two modes shown in Fig. 11. The contact length was 0.68 m in mode 1 and 0.28 m in mode 2. Theoretically, the moment required to turn the robot in mode 1 was 2.4 times larger than that in mode 2. This means the system turned about 1.5 times slower in mode 1 than in mode 2.

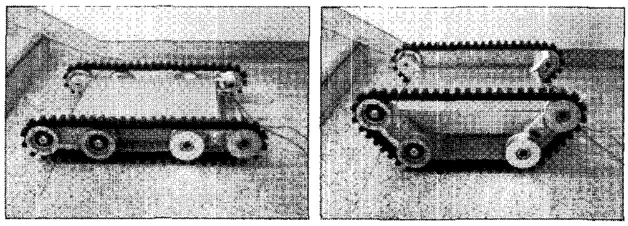


Fig.11 Turning

4.2.3 Climbing Stairs

In mode 1, the system slipped and could not climb the first step, which is in agreement with the theoretical evaluation. However, it could climb the first step in mode 2, after which it was transformed back into mode 1. It then ascended the remaining stairs as if proceeding up a normal slope. Figure 12 shows the phases of climbing the stairs in sequence. The system traveled with a velocity of 0.25 m/s, as predicted.

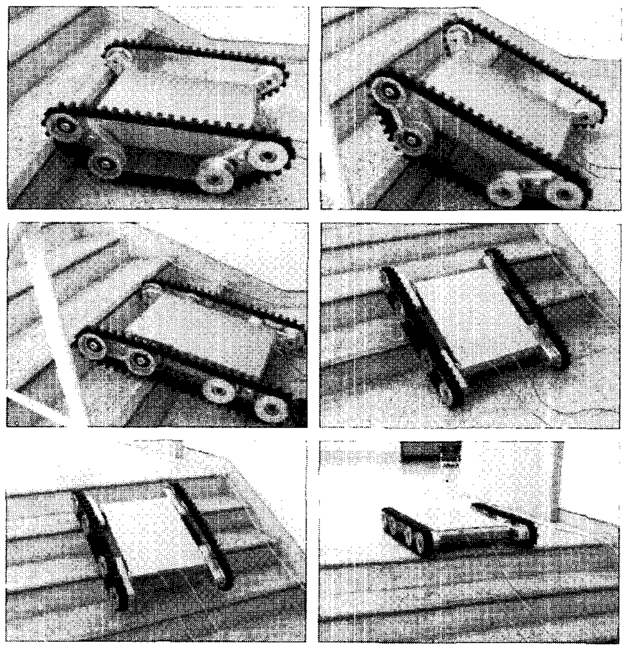


Fig. 12 Climbing stairs

In Table 2, the proposed system is compared to the Packbot (iRobot Corp.) and Robhaz (KIST), which are leading rescue robots. The proposed system proved to be effective, making it a possibility for use in rescue activities.

Table 2 Comparison with other systems

	Packbot	Robhaz	Proposed system
Size [mm]	879 (L) 513 (W) 178 (H)	740 (L) 470 (W) 290 (H)	800 (L) 560 (W) 150 (H)
Weight [kg]	24	39	34
Friction moment for turning [Nm]	17.15	20.58	9.2
Velocity [m/s]	2.2 – 3.7	2.0	2.0
Climbing stairs	Possible	Possible	Possible
Preparing to turnover	Possible	Impossible	Possible

5. Conclusions

We proposed a new type of single-track driving mechanism capable of transforming into various geometries for use as a rescue robot. The performance indices and design variables were evaluated for climbing stairs. The mechanism had a symmetric configuration so that the robot could advance in two directions, allowing it to remain operable when overturned. By transforming its geometry, the robot could reduce energy consumption in steering and rotating and also maximize its ability to overcome obstacles such as stairs. The feasibility of the proposed driving mechanism for use as a rescue robot was confirmed through various tests.

Although the task of climbing stairs was emphasized in this paper, future work will be performed on maneuvering the robot over various types of terrain. Also, sensors such as cameras, microphones and manipulators will be added to the robot to enhance its rescue capabilities.

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