A Study of the Mobile Robot with wheels that can climb stairs
- Detection of the stairs, and optimization of expandable wheels -

Takao ABE  Hiroki MURA TA  Ryuta MASUZAKI  Toshihiro IRIE
College of Science and Technology, Nihon University
7-24-1 Narashinodai Funabashi Chiba JAPAN 274-8501
Email: takaoabeko@gmail.com

Abstract - In general, legs and crawlers are used as a robot to climb stairs. But, driving performance of these robots in the plains is lower than the wheel robot. The robot of this research runs level ground like a wheel and gets over a step with the wheel which unfolded.

In this paper, we introduce a expandable wheel system, and it’s described how to control for wheel expansion on the stairs. The control method has to be optimized. It is the first report to which we did a basic analysis.

I. INTRODUCTION

It is important to get the infrastructure in aging society in the future. However it is difficult to let infrastructure support rapidly. Therefore this study pays attention to a barrier-free problem and aims at the realization of the mobile robot which can move on stairs and level ground. As a result, Wheelchairs can move on the place where barrier-free measures are difficult.

In general, legs and crawlers are used as a robot to climb stairs. However, driving performance of these robots in the plains is lower than the wheel robot [1]. The robot of this study has the ability of the wheel and can climb the stairs by unfolding a wheel. Therefore the robot can perform appropriate movement on the level ground and the stairs.

The transformation mechanism is complicated, but it is practicable and production is possible [2]. This study shows that a transformation wheel is practical.

II. THE MECHANISM OF THE WHEEL

We devised two wheel shapes to realize a robot. The wheel shape is shown in Fig.1. The left side of Fig.1 is an oval type (OVAL). And the right side is a comma-shaped bead type (COMMA). Both wheels consist of a frame and four small wheels.

Arms are short, so an OVAL is strong because it is hard to take a moment of force. An OVAL can't support an axis at both sides, but small wheels can turn freely.

On the other hand, a COMMA can support an axis at both sides, but small wheel can’t turn freely. And a COMMA’s distance of the movement is large, because arms of small wheels are long. Both wheels are characteristic each in this way. Therefore, it is necessary to examine the most suitable shape.

We produced a prototype of an OVAL. The prototype is shown in Fig.2. This wheel runs with a circle on the level ground. When climb stairs, the wheel is unfolded.

This wheel is driven with motors. There are motors for running and for the transformation.

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1Arms show the length from center to point of the small wheels.
III. THE RELATIONS OF THE WHEEL ANGLE QUANTITY OF THE UNFOLDING

This study aims to adjust to both the plain and the stairs, so the wheel unfolds after it runs in the plain. When it unfolded, the wheel is not a good position every time. It is shown in Fig.3. It is necessary to let the position suitable for stairs movement do it.

We thought that adjusted it by running it in the state that transformed a wheel. Therefore we performed analysis by the simulation.

![Fig.2. When runs on the level ground](image)

A. An OVAL

Each parameter of the wheel are shown in Fig.4.

![Fig.3. Comparison when it unfolded](image)

![Fig.4. The parameter of the transformation wheel](image)

\[ l \] : The aim distance to the good position
\[ r \] : A wheel radius
\[ \phi \] : The initial angle of the wheel
\[ x \] : Movement distance by the wheel turn
\[ \alpha \] : The rotary angle of the small wheels

We assume the revolving amount of the wheel \( \theta \). Eq.(1) is provided from \( \theta \) and \( \phi \).

\[
\frac{\pi}{2} s = \theta + \phi \quad (s = 0, 1, 2, \cdots) \quad (1)
\]

The relations of aim movement distance and the movement distance by the turn of the wheel become Eq.(2).

\[
l = x + f(\phi) \quad (2)
\]

\( f(\phi) \) : Horizontal movement distance by the transformation

Fig.5 is relations of the movement distance by the transformation that we found from simulation. Substituting the movement distance from Fig.5 into \( f(\phi) \). We get \( x \).

![Fig.5. Relations of the movement distance by the transformation](image)

And \( x \) can be expressed by Eq.(3).

\[
x = r_i \left( \theta + \phi \right) \quad (3)
\]

\( r_i \) : A temporary radius when a wheel transformed it

We get Eq.(4) to demand \( r_i \) from Eq.(3) and Eq.(1).

\[
r_i = \frac{2x}{\pi s} \quad (4)
\]

We divide both sides of Eq.(4) by \( r \), Eq(4) become Eq.(5).

\[
\frac{r_i}{r} = \frac{2x}{\pi s} \quad (5)
\]

While a wheel makes it 1 rotation, it becomes the same state four times. 1/4 rotations are assumed to be single-unit, it shows whether \( s \) is times how many. And \( s \) is an integer of the plus.

Fig.6 is relations of \( r \), \( r_i \) and \( \alpha \) which we found from simulation. We find \( \alpha \) from Eq.(5) and Fig.6.
One example of the result of the simulation is shown in Fig.7. As Fig.7-① shows, we transform small wheels 75° from a state of an initial angle of 45° and make it Fig.7-②. After having run, the wheel becomes s=1 in Fig.7-③ and s=2 in Fig.7-④. Then we transform small wheels 90° and become the most suitable position. We confirmed that the wheel is able to adjust a position in front of the stairs.

**Fig.7. An analysis result in the an OVAL**

**B. A COMMA**
We examine a COMMA like an OVAL. The greatest angle difference from the most suitable position is 45°. This movement is shown in Fig.8.

**Fig.8. An analysis result in the a COMMA**
The wheel moved without a problem on simulation. It is because the distance of the movement of small wheels of a COMMA is large. Therefore, it is not necessary to let the position suitable for stairs movement do it.

**IV. A RESULT OF SIMULATION**
We judged that COMMA was easy to climb the stairs and simulated COMMA. The simulation performed transformation and stairs movement. The results are shown in Fig.9~Fig.16.

**A. THE TRANSFORMATION**
This chapter reports on the simulation of transformation. The transformation is started by the transformation motor, and the
running motor has been rotating one second later.

Fig.9 and Fig.10 are a change of the torque of motors at the time of the transformation. The torque of running is assumed to be \( T_r \). And the torque of transformation is assumed to be \( T_t \).

![Fig.9. The torque of the running motor (\( T_r \))](image)

![Fig.10. The torque of the transformation motor (\( T_t \))](image)

When the running motor begins a turn, the burden of transformation motor shrinks.

Fig.11 and Fig.12 are a change of the rotary angle of motors at the time of the transformation.

![Fig.11. The angle change of the running motor](image)

![Fig.12. The angle change of the transformation motor](image)

Running motor is the same as the targeted value. Transformation motor is delayed a little than the targeted value first. Afterwards, because transformation motor becomes it as well as the targeted value, it is unquestionable. It is because center of gravity was moved by rotating the running motor.

**B. THE RUNNING OF STAIRS**

This chapter reports on the simulation of stairs movement. This simulation is started from the state that finished being transformed.

Fig.13 and Fig.14 are a change of the torque of motors at the time of the movement in the stairs. The torque of running is assumed to be \( T_r \). And the torque of transformation is assumed to be \( T_t \).

![Fig.13. The torque of the running motor (\( T_r \))](image)

![Fig.14. The torque of the transformation motor (\( T_t \))](image)
The change in the torque when mounting the stairs was able to be confirmed. Fig.15 and Fig.16 are a change of the rotary angle of motors at the time of the movement in the stairs.

V. OPTIMIZATION IN A ROUTE

We stated that the robot has the good position to climb stairs at 3 chapters. And, we don’t hope that there is a difference in the left and right for the initial angle $\phi$ of the wheel. We said that a COMMA didn’t have to be adjusted, but it is the best when adjusting it.

Therefore, right and left $\phi$ is arranged, and the robot is made good position. As an adjustment method, the route of the robot is designed. We adjust it by changing amount $K$ of the rotation of a right and left wheel. $K$ is Eq.(6).

$$K = \frac{\theta}{2\pi} \tag{6}$$

This time, we examine it by an easy model. The model is shown in Fig.17. Please refer to Fig.4 for the parameter of the wheel.

There are a lot of routes when the robot moves from $P_0$ to $P$. It is necessary to choose the shortest, best one in these routes.

The motion equation of this model is Eq.(7).

$$\begin{bmatrix} x \\ y \\ \psi \end{bmatrix} = \begin{bmatrix} \frac{\cos \theta}{\sin \theta} & \frac{\cos \theta}{\sin \theta} \\ 2 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \text{ror} \text{R} \\ \text{ror} \text{L} \end{bmatrix} \tag{7}$$

Regulating system to run in the best route is shown in Fig.18. The speed instruction, target coordinates, and the angle of the target are input. Coordinates of the input are generated with the curve. This value and the angle of the model is used as a parameter of feedback.

The motor of running is following to the angle of the target. The transformation motor deviates from the targeted value a little. But, gaps are less than five degrees. Therefore, it is a range that can be allowed.
Fig.18. The control system

The simulation result is shown in Fig.19 and Table 1. As for case 1 and case 2, the shape of curve is different.

![Comparison of a route of a simulation](image)

**Table 1 result of simulation**

<table>
<thead>
<tr>
<th></th>
<th>x [m]</th>
<th>y [m]</th>
<th>$\psi$ [°]</th>
<th>$K$ [times]</th>
<th>$\phi$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>case1</td>
<td>10.5</td>
<td>5.0</td>
<td>0</td>
<td>19.0025</td>
<td>0.9</td>
</tr>
<tr>
<td>case2</td>
<td>10.5</td>
<td>5.0</td>
<td>0</td>
<td>19.0976</td>
<td>-14.1</td>
</tr>
</tbody>
</table>

The angle $\phi$ of the wheel became 0.9° for case1, and became -14.1° for case2. It was able to be confirmed that $\phi$ changed depending on the route. Therefore, $\theta$ and $\phi$ are made a given value in the target point. And, the robot is led to a good position to mount the stairs.

We will make the function to make the best route from each parameter of the robot in the future.

We did the introduction to make the best route. We will make the function to make the best route from each parameter of the robot and calculate the best route in the future.

We should think about the system that can control on the best route automatically by combining various sensors with the robot.

**VI. CONCLUSION**

We produced a prototype of an OVAL, and confirmed that the prototype could perform running and transformation.

A COMMA is suitable for stairs movement than an OVAL. Because it is not necessary to let the position suitable for stairs movement do it. And a COMMA was simulated. Therefore, it can be said that the transformation wheel can be practicably produced.

**VII. REFERENCES**
