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Analysis method of climbing stairs with the rocker-bogie mechanism †

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Abstract

An analysis method to make the rocker bogie mechanism can climb up a stair is achieved in this paper. To verify whether the rocker bogie, with certain lengths of the linkages and radii of the wheels, could climb up a target stair or not, a kinematic analysis and its posture are determined. The trace of the center of mass of the rocker bogie was considered and the situation that three wheels contact the front side of the stair is analyzed. With this two analyses, the stair climbability graph (SCG) determined with the length and the height of a stair was drawn. The SCG shows the climbable stair group for the rocker bogie with certain size. Two prototypes of rocker bogie which has different lengths of linkages were designed and tested on two different stairs. As same result of the SCG, the first prototype rocker bogie with small rocker linkage can climb up the stair (length 450 mm and height 150 mm) but cannot climb up the other stair (length 300 mm and height 175 mm). The second prototype rocker bogie with large rocker linkage can climb up both stairs.

Keywords: Rocker bogie; Wheel type mobile robot; Stair climbing; Kinematic analysis

1. Introduction

The rocker bogie mechanism is the most popular linkage mechanism for a wheel robot which has 6 actuated wheels. The rocker bogie's main frame has two linkages on each side that are called the "rocker"(see Fig. 1). One end of the rocker is connected to the rear wheel, and the other end is connected to a small linkage which is called the "bogie". The bogie is connected with the front wheel and the middle wheel. The rocker and the bogie are connected with the passive joint, so that the six wheels contact the ground at all times without any actuators. With this suspension mechanism, the rocker bogie demonstrates great mobility on rough terrain and it can climb up an obstacle twice larger than the wheel diameter [1]. Therefore, the rocker bogie shows strong mobility on unexpected terrain and it is used in the "Sojourner" which explores the unencountered terrain of the Mars.

However, the rocker bogie does not demonstrate good maneuverability on stair-climbing because it is based on the wheel mechanism. While the track mechanism is designed to contact the edge of a stair at all times and climb up the stair smoothly, the wheel mechanism must contact the front side of a stair and climb it up vertically.

It is sometimes not easy to obtain enough normal force to climb up a stair when the wheel contacts the front side of the stair, so the wheel mechanism cannot ensure high maneuverability on stair-climbing. For this reason, several researches have investigated ways to improve its stair-climbing ability. One way is to set the maximum allowable angle of the bogie in order to improve the climbing ability of the rocker bogie [2]. By attaching a small pin to the pivot joint, the bogie is disallowed to rotate freely for all angles. In this model, the middle wheel does not contact the ground while climbing up a high slope. For this reason, the normal force of the front wheel and rear wheel increases, and the robot receives more traction force for climbing. However, this research was investigated and optimized only for certain type of stair, and the robot was unfit to perform in every stair in reality.

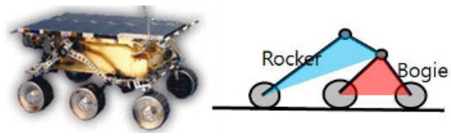

Fig. 1. Sojourner and the rocker bogie mechanism.

The optimal design to make the rocker bogie's path to similar to the slop of the stairs was explored to improve its climbing ability [3]. By optimizing the length of the linkage and the size of the wheels, the difference between the trace of the center of mass and the slope of the stairs was minimized. Three different sizes of stairs were analyzed on the optimization, so that the result of the study could be applied to different types of stairs in reality. However, before adopting the optimization process, it was assumed that the robot has to be small enough

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for two wheels to contact the horizontal plane of the stair at all times, which was too a strong assumption for its climbing ability. As for the climbing ability, if two wheels always contact the ground, it is easy to climb up a stair because the rocker bogie can get enough normal force and friction force for climbing. However, not every rocker bogie has its two wheels contacting the ground at all times, and this is why the study cannot be extended to the general climbing ability of rocker bogies with different sizes.

In this paper, two metrics are considered which are closely related to the rocker bogie's climbing ability. One metric is the contact angle between the center of mass and the ground which is related to the robot's flip-over. The other metric is whether there is a state of the three wheels of the rocker bogie simultaneously contacting the side of the stair, which causes zero normal force for the robot. By using a geometric analysis, two metrics are considered in order to plot the stair climbability group graph for the rocker bogie with a certain size. In addition, two prototypes of the rocker bogie were made to test the possible stair group graph and experiments were performed accordingly.

This paper includes section 2 illustrating the definition of a stair as well as a kinematic analysis of the rocker bogie and a description of the stair possible group graph. In section 3, two prototypes of the rocker bogie are designed and experiments were performed on two different types of the stairs. Lastly, conclusions are briefly discussed in section 4.

2. Analysis

2.1 The definition of a stair

Before starting an analysis of the stair-climbing ability of the rocker bogie, the definition of a stair needs to be specified. A stair can be specified by its length, height and width. By the standard of building construction in Korea, a stair length has to be larger than 260 mm, a stair height has to be lower than 180 mm, and a stair width has to be larger than 1,200 mm. Taking into account of the standard, the length of the stair in this study was set between 260 mm and 500 mm, and its height between 50 mm and 180 mm. If a stair is longer than 500 mm, it is too long and can be regarded as a step rather than a stair. The rocker bogie mechanism can overcome a step more easily than a stair, and therefore analyzing a stair which is longer than 500 mm is meaningless. Similarly, if a stair is lower than 50 mm in its height, it is too an easy task for the rocker bogie mechanism, which makes an analysis equally meaningless. As for the width, it does not need to be considered as the analysis will be carried out in a 2D motion. Fig. 2 shows the stairs graphed by its length and height. Each dot in the graph is representing a stair with corresponding the length and the height. If the length is big and the height is small, the stair has a low slope which makes it easy to climb up (Fig. 2 the green area A). In contrast, if the length is small and the height is big, the stair has a high slope which makes it hard to climb up (Fig. 2 the red area B). For analyzing the climbing

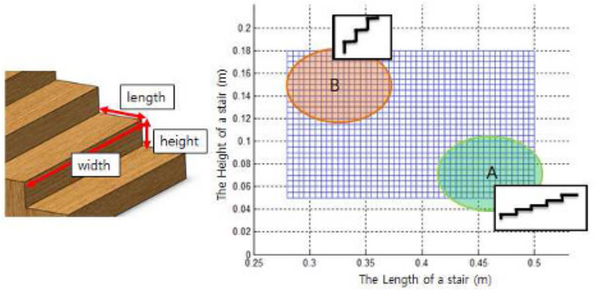
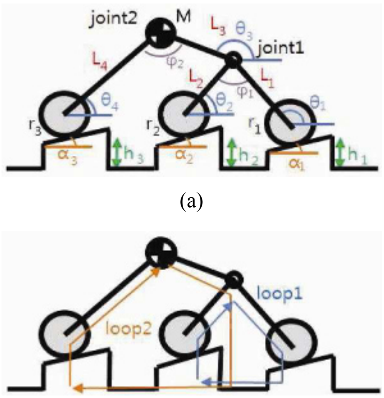


Fig. 2. The stair classified graph by its length and height.



(a)

(b)

Fig. 3. (a) Simple modeling of the rocker bogie mechanism on rough terrain; (b) two closed loops on the rocker bogie.

ability of the rocker bogie, all the stairs in Fig. 2 need to be considered.

2.2 The kinematic analyses

A kinematic analysis is performed to determine the posture of the rocker-bogie when it climbs up a stair. Fig. 3 shows a simple model of the rocker bogie. For the given contact heights (h_1, h_2, h_3), and contact angles (α_1, α_2, α_3), the posture of the rocker bogie can be calculated. For stair-climbing, the contact height would be a multiple value of the stair height and the contact angle would be 0 degree or 90 degrees. From the geometry, two angle equations can be derived.

$$\theta_1 = \theta_2 + \varphi_1 \tag{1}$$
$$\theta_3 = \theta_4 + \varphi_2 \,. \tag{2}$$

The θi representing the angle between the ground and linkage i of the rocker bogie, $\varphi 1$ is the angle between linkage 1 and linkage 2 and $\varphi 2$ is the angle between linkage 3 and linkage 4. With the two closed loops on the rocker bogie (Fig. 3(b)), another two equations can be acquired.

$$\begin{aligned} & h_1 + r_1 \cos\alpha_1 + l_1 \sin\theta_1 \\ & -h_2 - r_2 \cos\alpha_2 - l_2 \sin\theta_2 = 0 \end{aligned} \tag{3}$$

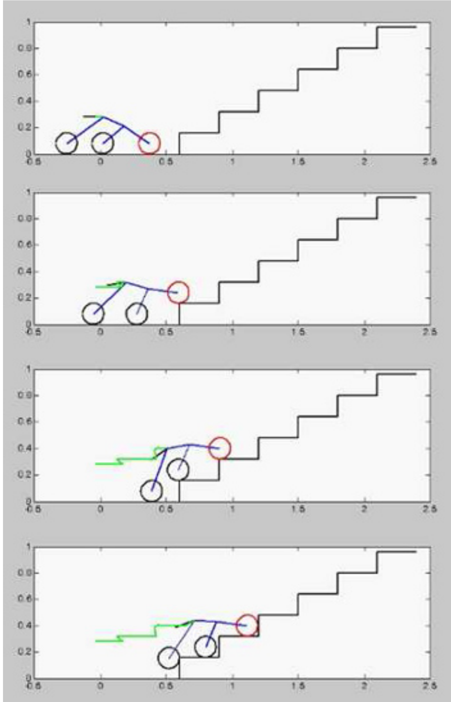


Fig. 4. The schematic of the rocker bogie when it climbing up a stair.

$$h_1 + r_1\cos\alpha_1 + l_1\sin\theta_1 + l_3\sin\theta_3 \\ -h_3 - r_3\cos\alpha_3 - l_4\sin\theta_4 = 0\,. \tag{4}$$

The r_1, r_2, r_3 are the radius of the wheels, respectively. The length of the linkage1 between the first wheel and the joint 1 is l_1, the length of the linkage 2 between the middle wheel and joint 1 is l_2, the length of the linkage 3 between joint 1 and joint 2 is l_3, and the length of the linkage 4 between the rear wheel and joint 2 is l_4. M is the total mass of the rocker bogie. With Eqs. (1)-(4), all angles between the ground and the linkages can be calculated.

$$\theta_1 = \sin^{-1}\frac{r_1\cos\alpha_1 + h_1 - r_2\cos\alpha_2 - h_2}{\sqrt{(l_1 - l_2\cos\varphi_1)^2 + (l_2\sin\varphi_1)^2}} \\ -\tan^{-1}\frac{l_2\sin\varphi_1}{l_1 - l_2\cos\varphi_1} \tag{5}$$

$$\theta_3 = \sin^{-1}\frac{r_1\cos\alpha_1 + h_1 + l_1\sin\theta_1 - r_3\cos\alpha_3 - h_3}{\sqrt{(l_3 - l_4\cos\varphi_2)^2 + (l_4\sin\varphi_2)^2}} \\ -\tan^{-1}\frac{l_4\sin\varphi_2}{l_3 - l_4\cos\varphi_2}\,. \tag{6}$$

After radii of the wheels of the rocker bogie and the lengths of the linkages are set, with given contact heights and angles, the kinematic of the rocker bogie can be calculated. Therefore, with this kinematic analysis, the posture of the rocker bogie can be analyzed during its climbing up a stair. Fig. 4 shows the schematic of the rocker bogie when it climbs up a stair by MATLAB. As the first wheel (the red wheel in Fig. 4) moves along the stair, the positions of the linkages, the second wheel, and the third wheel are settled by a geometric condition.

2.3 An analysis of the center of mass position

By analyzing the movement of the center of mass during climbing up a stair, climbability of the rocker bogie can be determined. When the rocker bogie climbs up a stair, θ_4, the angle between the ground and linkage 4 (θ_4 in Fig. 3), is changed. If θ_4 is smaller than 90 degrees, the rocker bogie can maintain its posture and does not flip over. However, if θ_4 becomes bigger than 90 degrees, the moment of the center of mass becomes bigger than zero and it causes the rocker bogie flip over (See Figs. 5(a) and 5(b)).

To climb up a stair with the rocker bogie, θ_4 always has to be smaller than 90 degrees. Since the rocker bogie will have some vibration or unexpected movement during climbing up, θ_4 has to be no bigger than 81 degrees, with a 10% safe margin. Using the kinematic analysis, the change of θ_4 during the climbing can be calculated. If there is at least one point at which θ_4 becomes bigger than 81 degrees, it is concluded that the rocker bogie would flip over and would not be able to climb up the stair. With this analysis, whether or not the rocker bogie can climb up a certain stair can be determined.

If the analysis is generalized to every other possible stairs, the stairs can be classified into two main groups. One group is those that the rocker bogie can climb up without making θ_4 bigger than 81 degrees and the other groups is those that the rocker bogie can climb up without making θ_4 smaller than 81 degrees. By changing the lengths of the rocker bogie, the stairs belonging to each group can also change.

Fig. 5(c) shows the trace of the rocker bogie and the angle change of linkage 4. By analyzing the rocker bogie's geometry condition, the maximum angle during climbing up a certain stair can be calculated. As the length and the height of a stair change, the maximum angle of linkage 4 changes. Based on the maximum angle of linkage 4, the stair graph dividing the two groups of stairs can be drawn, as shown in Fig. 5(d).

The blue grids of the graph in Fig. 5(d) represent the stairs of which the maximum angle is lower than 81 degrees, and the red grids represent the stairs of which the maximum angle is larger than 81 degrees. The graph can be drawn with a given length of the linkage and of the radius of the wheel. For every graph, the rocker bogie with a certain size would be able to climb up for the stairs belonging to the blue girds, while it would flip over and not be able to climb up for the stairs belonging to the red grids.

2.4 An analysis of the situation where three wheels contact the front side of the stair

The situation that the rocker bogie cannot climb up can be occurred depending on the stair length and height. By the geometric condition described above, when the first wheel is placed at a certain point of the stair, the points at which the second and the third wheels would be placed are determined

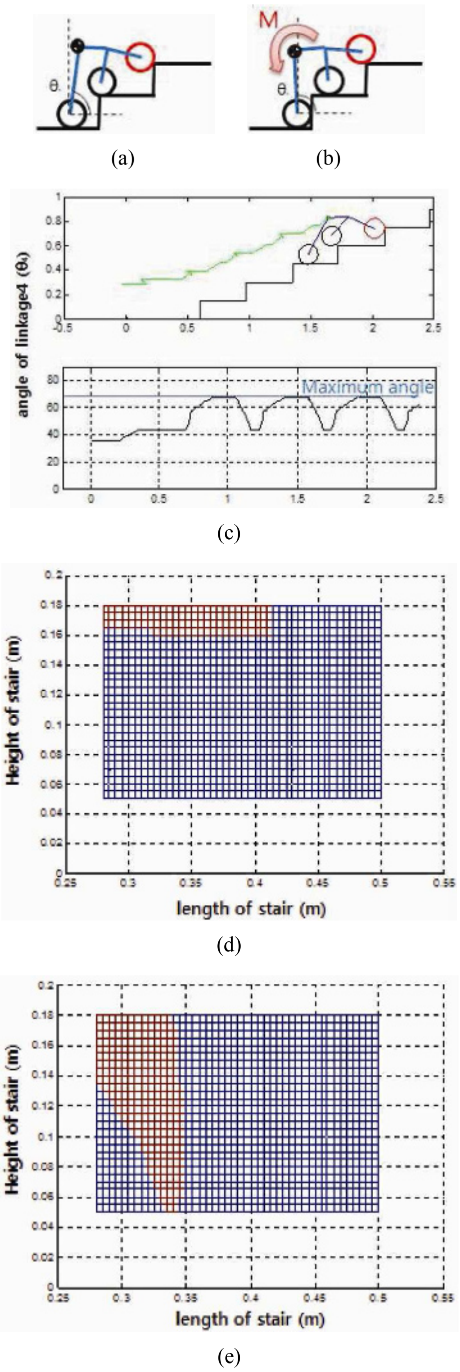


Fig. 5. Two state of the rocker bogie where the θ_4 is (a) smaller than 90 degree; (b) large than 90 degree; (c) the trace of the center of mass and the θ_4 change during climbing up a stair; (d) The classification of stairs, based on whether the rocker bogie overturned while climbing up a stair (the red area) or not (the blue area); (e) The classification of stairs, based on whether the three wheels of the rocker bogie contacted the vertical face at the same time (the red area) or not (the blue area).

automatically. However, as there are many different kinds of stairs in reality, in an extreme case, the situation where three wheels simultaneously contact the front side of the stair can occur. When this is the case, the rocker bogie cannot climb up the stair. No matter how big the coefficient of friction is, the rocker bogie cannot receive any normal force from the stair and cannot receive the force to climb up. For this reason, determining whether or not this particularly troublesome situation would occur is paramount importance to analyzing the climb ability of the rocker bogie.

Fig. 5(e) shows the cases in which the three wheels simultaneously contact the stair during climbing. The red grids represent the stairs of which the three wheels simultaneously contact the front sides. In other words, the rocker bogie cannot climb up the stairs belonging to the red grids, while it can climb up those belonging to the blue grids.

By combining these two graphs, "the stair climbability graph (SCG)" can be drawn. On the SCG, for a certain length of the linkage, a stair that makes the CM degree bigger than 81, or that makes the rocker bogie wheels contact the front side at same time are marked as red dots. With this analysis, it is possible to decide whether the rocker bogie would be able to climb up the target stair. If the target stair is marked as red in the SPG, the lengths of the linkages should be changed in order for the rocker bogie to climb up the stair.

3. Experimentation

Two rocker bogie robots with different sizes were designed to probate the analysis and the prototypes are shown in Fig. 6. Fig. 6(a) is the rocker bogie mechanism with a small rocker linkage (referred to as the small rocker bogie hereafter) and Fig. 6(b) is the rocker bogie mechanism with large rocker linkage (referred to as the large rocker bogie hereafter). Suppose that the mass of the linkages are too small compare to the main body, the center of mass of two robots are said to be placed on a pivot joints. The lengths of the linkages for the two different systems are written in Table 1.

With these lengths of the linkages, two SCGs can be drawn.

Table 1. Length of two prototypes.

Length(mm)	Small rocker bogie	Large rocker-bogie
L1	210	210
L2	210	210
L3	170	170
L4	340	570

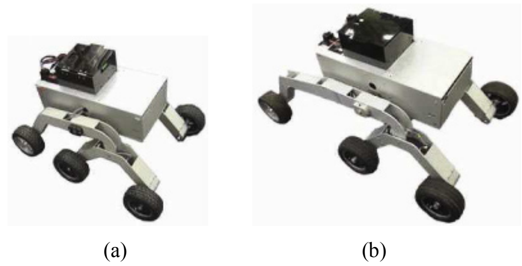


Fig. 6. prototype of (a) the small rocker bogie; (b) the large rocker bogie.

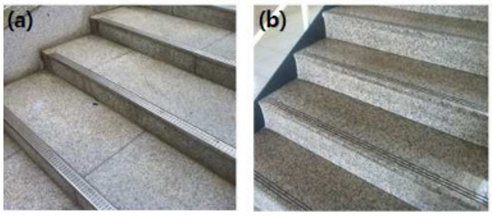
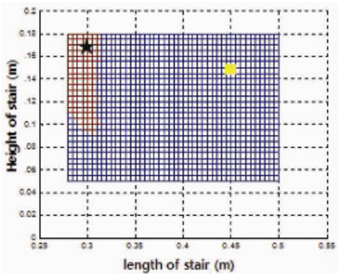
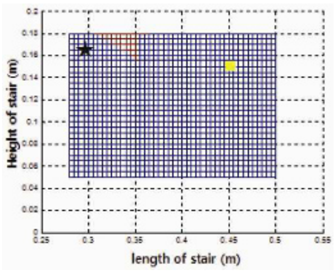


Fig. 7. The picture of two states of stairs: (a) length 450 mm, height 150 mm; (b) length 300 mm, height 175 mm.



(a)



(b)

Fig. 8. The stair possible graph of (a) the small rocker bogie; (b) the large rocker bogie. The yellow square is the stair with 450 mm length and 150 mm height, the black star is the stair with 300 m length and 175 mm height.

Fig. 8 shows the SCG of the small rocker bogie (Fig. 8(a)) and the large rocker bogie (Fig. 8(b)). As can be seen in the SPG, the small rocker bogie has more red dots than the large rocker bogie.

To operate the rocker bogies, six direct current (DC) motors (RE-30, Maxon, Switzerland) and six DC drivers (NT-DC20A, NTREX, Korea, AM-DC1-3D, NEWTC, Korea) were used on each wheel. The rocker bogies were controlled by the operator using an Arduino Mega (Italy) and Wii wireless classic controller (Nintendo, Japan). Two different rocker bogies were tested regarding their climbing ability for two different stairs.

The first stair is shown in Fig. 7(a), which is 450 mm in length and 150 mm in height and has 18.5 of a slope degree. It is marked as the yellow square in Fig. 8. On both of the graphs in Fig. 8, the yellow square mark is on the blue area which indicates that the stair can be climbed by the small and the large rocker bogies. In the experiment, since the length of the stair can support two wheels at a time, the rocker bogies do not encounter the situation when the three wheels simultaneously contact the front side of the stair. Therefore, both the small and the large rocker bogies can climb up the stair without failing.

Table 2. length of two prototypes.

Stair length(mm)	Stair height(mm)	Analyze		Experiment	
		small	large	small	large
450	150	O	O	O	O
300	175	X	O	X	O

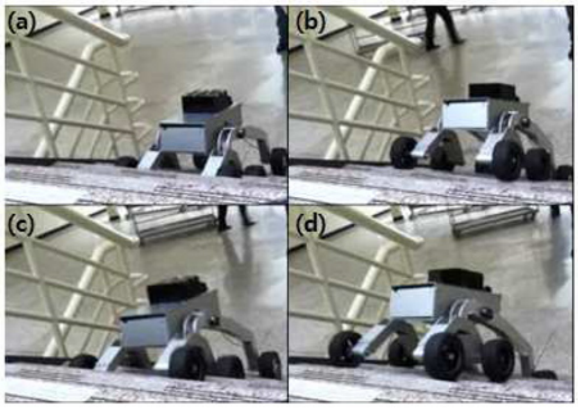


Fig. 9. the picture of the large rocker bogie climbs up the stair with length 300 mm and height 175 mm.

The second stair is shown in Fig. 7(b) and it is 300 mm in length and 175 mm in height and has 30.3 of a slope degree. The stair is marked as a black star in Fig. 8. The stair has a shorter length and a bigger height than the first stair, so it is hard to overcome. On Fig. 8, the black stair is marked in the red area in the SCG for the small rocker bogie whereas it is marked in the blue area in the SCG for the large rocker bogie. Since the length of the stair is too small to support two wheels at a time, the situation where the three wheels simultaneously contact the front sides of the stair easily occurs. This makes the rocker bogie lose its normal force to carry its weight. In the experiment, the small rocker bogie did not climb up the stair because the three wheels contacted the front sides of the stair at the same time. On the other hand, the large rocker bogie could climb up the stair, because the three wheels did not contact the front sides of the stair at the same time.

4. Conclusions

An analysis of the conditions for the rocker bogies to climb up stairs was discussed in this paper. With certain lengths of the linkages and radii of the wheels, a kinematic analysis was performed when the rocker bogies climbs up the stairs. The center of mass of the rocker bogies was considered and the situation where three wheels simultaneously contact the front sides of the stair was analyzed. By using two analyses, the possibility of climbing up the stair was determined with the lengths and heights. By extending and generalizing the analysis to the lengths and heights of the stairs available in everyday life, the stair climbability graph (SCG) can be drawn. The prototypes of the two rocker bogies which have different lengths of the linkage were designed and tested on two different stairs. As has been reiterated from the result of the analysis, the small rocker bogie could overcome the stair with a length of 450 mm and a height of 150 mm but could not overcome the stair with a length of 300 mm and a height of 175 mm. On the other hand, the large rocker bogie could overcome both stairs. Therefore, the analysis in this paper enables an operator to determine a rocker bogie's possibility of overcoming a stair with a given length of its linkage and the radius of the wheel. If the target stair is marked as red in the SPG, the rocker bogie could climb up the stair by changing its lengths of the linkages that make a blue dot in SCG.

Acknowledgment

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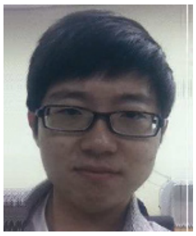

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