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Wheel Arrangement of a Rocker-bogie Mechanism with Omni-directional Wheels for Reduced DOF Design

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Abstract— **Wheeled mobile mechanisms are essentially unsuitable for moving over rough terrain, but the rocker bogie mechanism is known as a six-wheeled mobile mechanism with high ground adaptability that solves this problem. However, this mechanism requires a large number of degrees of freedom (DOF), at least 10 DOF, or 12 DOF in the case of an omni-directional moving function. This contains problems in terms of control system configuration, mechanism development, and energy efficiency. In this study, the number of DOFs is reduced to a maximum of 6 DOFs and a minimum of 4 DOFs by applying omni-directional wheels to the rocker bogie mechanism. First, we examined how the two main types of omni-directional wheels should be arranged in relation to the six wheels. Based on the results, an actual machine was developed for evaluation, and its effectiveness was confirmed through step over experiment on several types of stairs.**

I. Introduction

Various types of mobile machines on land have been realized, but most of them are mainly classified into two types: legged machines and wheeled machines. Legged machine has high adaptability to the terrain because it can move with discrete selection of ground contact points. However, because it requires a large number of DOF, there are issues that increase the complexity of control system and mechanical structure [1]-[3]. On the other hand, wheeled machine has advantage of high speed and efficient movement because of its simple structure. However, its performance is limited to a leveled terrain.

Several machines have been proposed as a method to improve the poor ground adaptability of wheeled machine.

First, Nakajima et al. proposed a mechanism called RT-Mover, which has four DOF for wheel drive, two DOF for steering, and two DOF around the roll axis, for a total of eight DOF [4]-[6]. This mechanism has the characteristics of a so-called leg-wheeled machine, which moves like a normal wheeled machine on leveled ground and uses the wheels like a legged machine by using the DOF of the roll axis only when stepping over a step.

As another example, Ishikawa et al. also developed a leg-wheel mechanism with four spherical spring tires made of nickel-titanium, a shape memory alloy [7]. This mechanism has a DOF around the horizontal axis for each wheel to lift up itself as swing leg, allowing the wheel to be put on a step when stepping over a step. However, when one wheel is in the swing mode, i.e., supported by only three wheels, there is a risk that the robot may fall over. Therefore, the robot is designed to maintain its center of gravity within the support leg triangle by providing DOF around the vertical axis that connects the body into two sections.

Among similar studies, the rocker-bogie mechanism is particularly noteworthy [8]. The details of this mechanism will be described later, but it has been put to practical use as a planetary rover, etc., as a mechanism with high ground adaptability. However, because this mechanism requires many DOF, the control system and mechanical structure become complex, as is the case of the legged machine. Various studies have been conducted to improve this problem.

Several studies have been conducted based on the rocker bogie mechanism with various modifications. One is a mechanism in which the front wheels of the bogie part are replaced with crawlers. The purpose of this study is to further enhance the ground adaptability, which is achieved by adjusting the angle of the crawler [9]. The other research aimed to solve the mentioned problem caused by the large number of DOF. By using springs, a rocker-bogie mechanism is realized with only two DOF [10]. However, it cannot be said to be practical, because it does not have a steering function.

In this study, we propose a new rocker-bogie mechanism that applies the concept of design with reduced DOF to solve the problems caused by the many numbers of DOF. Specifically, omni-directional wheel that does not require DOF around a vertical axis is applied as a wheel of the rocker-bogie mechanism. As a mobile mechanism using omni-directional moving wheels, Chugo et al. developed a mobile mechanism with step-over ability with different structure[11]. The optimum of wheel arrangement for the omni-directional wheels, of which there are two main types, was investigated. To verify the adaptability of the prototype rocker-bogie mechanism to ground conditions, a step traversing experiment was conducted. The results are also reported.

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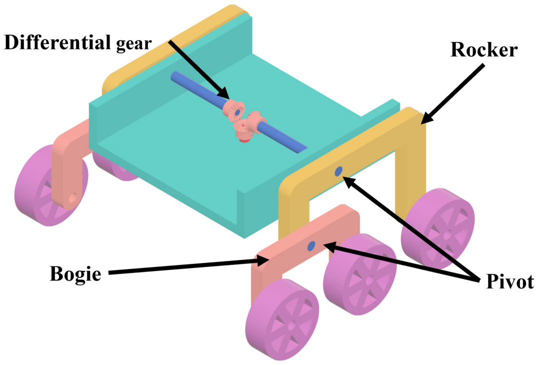

Figure 1. Rocker bogie mechanism

The paper is organized as follows Section 2 describes the basic concept of the new rocker bogie mechanism and its wheel arrangement; Section 3 describes the inverse kinematics of the proposed rocker bogie mechanism Section 4 describes the details of the mechanism developed for evaluation Section 5 presents method and results of the experiment and a discussion Finally, Section 6 presents conclusions and future issues.

II. Reduced DOF with Omni-directional Wheels

A. Rocker-Bogie Mechanism

The basic structure of the rocker-bogie mechanism is shown in Fig. 1. This mechanism was developed by NASA in the 1980s for use on Mars rovers. There are two types of links called rocker and bogie on each side of the body, and one wheel is attached to the one end of the rocker and one wheel to each end of the bogie, making a total of six wheels. The rotational axis in the center of the rocker is connected to the body as a passive joint, and the rotational axis in the center of the bogie is connected to another end of the rocker also as a passive joint. This mechanism allows the distance and height between each wheel to be varied relative to the ground surface, making it easy for all six wheels to always be on the ground. This is the reason why the rocker bogie structure has high ground adaptability.

However, this mechanism is limited to straight-line movement only, and steering is not possible. To achieve steering, active joint around the vertical axis must be added to some of the wheels. At least, this joint must be added to four wheels in the front and rear position. In this case, in addition to movements similar to those of an ordinary car, a pivot turn is possible. If the active joints are also added to the center two wheels, the mechanism can move in all directions in addition to the above-mentioned movements. Therefore, a typical rocker- bogie mechanism requires a minimum of 10 DOF, and 12 DOF for more free motion, which is a large number of DOF.

If the rocker is actually connected to the mechanism body by passive joints, the problem is caused that the orientation of the mechanism body is not uniquely fixed. Generally, some kind of differential device is used to solve this problem. For example, in the mechanism shown in Fig. 1, the shafts extending from the left and right rocker to the center of the mechanism body is fixed to the rockers, and they are connected by differential gearbox at the center of the mechanism body. This mechanism maintains the mechanism body orientation as an average of them of the left and right rockers.

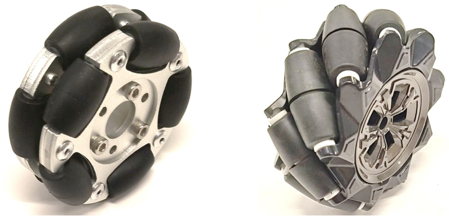

Figure 2. Omni-directional wheels *(a. Omni wheel, b. Mecanum wheel)*

B. Omni-directional Wheel

Omni-directional wheels, as the name suggests, were developed to realize omni-directional movement, and there are two main types: omni wheel and mecanum wheel shown in Fig. 2.

In the omni wheel, small free rollers are arranged perpendicular to the axis of rotation of the wheel, and the wheel is designed to slide sideways. By arranging three or four of these wheels in a radial pattern, omni-directional movement can be achieved.

On the other hand, the mecanum wheel has free rollers inclined at 45° angle to the wheels and can generate 45° oblique force against the rotation of the wheels. In this case, four wheels are arranged as in a car, with a pair of wheels on the left/right and front/rear with different inclination directions respectively.

The point to note here is a feature common to both types of wheels. In the case of general wheel, some DOFs around the vertical axis are necessary for steering. In contrast, omni-directional wheels can be steered without requiring this DOF. Therefore, this study attempts to realize a rocker-bogie mechanism that includes a steering function with a minimum number of DOF by applying omni-directional wheels as wheels of rocker-bogie mechanism.

C. Consideration of Wheel Arrangement

It is necessary to consider how to arrange the two types of omni-directional wheels mentioned above for the six wheels of the rocker-bogie mechanism. First, as mentioned above, the omni wheel requires the wheels to be arranged in a radial pattern. This condition is not compatible with a rocker-bogie mechanism in which all wheels are parallel. Therefore, it is impossible to apply the omni wheel to all six wheels. Necessarily, mecanum wheels must be used for some of the wheels. As mentioned above, in the case of the mecanum wheel, it is required to use four wheels, and each pair of wheels on the left and right must have wheels with different inclination directions. The same rule must be applied to the pair of wheels in the front and rear. Therefore, it is reasonable to use mecanum wheels for at least four wheels of the rocker-bogie mechanism, in the front and rear. On the other hand, the center wheel can theoretically be applied to either wheel, which will be discussed later.

Regardless of which wheel is used as the center wheel, it is not necessary to use these wheels active joint, because only

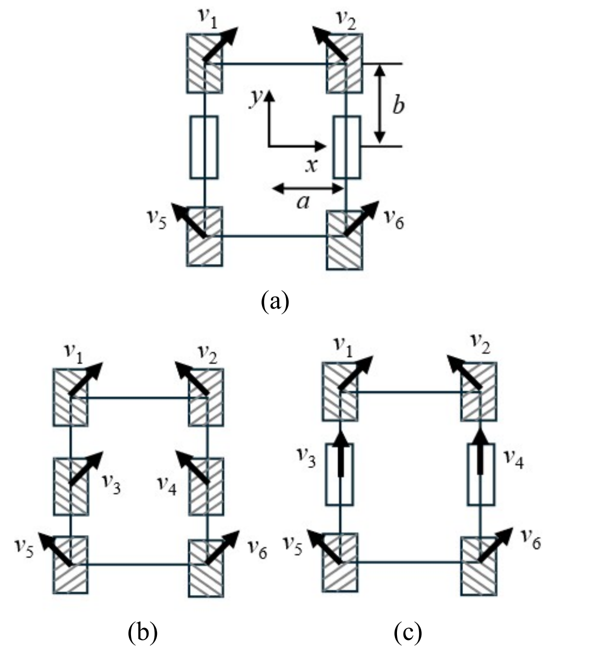

Figure 3. Definition of the coordinate system and parameters

four mecanum wheels in front and rear can be used as an omni-directional mechanism. In other words, a possibility remained to configure the center wheel as a passive wheel.

Therefore, the number of active DOFs is a minimum of 4 and a maximum of 6 DOFs, which is a significant reduction in the number of DOFs compared to a general rocker-bogie mechanism.

III. Inverse Kinematics of New Rocker-bogie

This section, we consider the inverse kinematics of this mechanism for the case where a mecanum wheel or omni wheel is used as the center wheel. Fig.3 shows definition of the coordinate system and parameters.

v_1 to v_6 are the peripheral velocities generated by each wheel. However, v_3 and v_4 are not shown in Fig.3 (a) because the direction of the velocity vector differs depending on the wheel types used. The positional relationship of the wheels is defined as a and b.

The front and rear four wheels are determined to use mecanum wheels, and their inverse kinematics are shown by the following equations.

Where v_x, v_y are the x and y components of the velocity vector of the mechanism body and ω is the angular velocity around the yaw angle.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_5 \\ v_6 \end{bmatrix} = \begin{bmatrix} 1 & 1 & -(a+b) \\ -1 & 1 & a+b \\ -1 & 1 & -(a+b) \\ 1 & 1 & a+b \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \tag{1}$$

When a mecanum wheel is used as the center wheel, the inclination of the left and right free rollers must be opposite to each other. Therefore, the rule of the inclination must match either the front or the rear wheels. When the rule is matched to the front wheels, the direction of the peripheral velocity is as shown in Fig.3(b), and the inverse kinematics of the center two wheels is shown by the following equation.

$$\begin{bmatrix} v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & -a \\ -1 & 1 & a \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \tag{2}$$

Conversely, when the rule is matched to the rear wheels, the following equation is obtained.

$$\begin{bmatrix} v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} -1 & 1 & -a \\ 1 & 1 & a \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \tag{3}$$

Next, when omni wheels are used as the center wheels, the direction of the peripheral velocity is as shown in Fig. 3(c), and the inverse kinematics of the center two wheels is shown by the following equation.

$$\begin{bmatrix} v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & -a \\ 0 & 1 & a \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \tag{4}$$

From the result of these peripheral velocities, the angular velocity that should be generated in the angular wheel can be obtained.

IV. Prototype Machine for Experiment

To verify the effectiveness of the above design guidelines, a rocker-bogie mechanism was actually developed to confirm the validity. The appearance of the developed mechanism is shown in Fig. 4. The mechanism design and control system are described below.

A. Mechanical Design

As mentioned above, either a mecanum wheel or an omni wheel can be used as the center wheel, but the omni wheel is applied in this experiment. There are two main reasons for this. First, the purpose of using omni-directional wheels is not to realize omni-directional movement, but to reduce the number of DOF. At least on rough terrain, it is not intended to move in all directions, but rather to move like as a car. In this sense, an omni wheel with high efficiency in the straight direction is appropriate. Second, if the mecanum wheel is placed as the center wheel, the inclination rules of the free rollers must match the rules of either the front or rear wheels. Since this would be considered mechanically unbalanced, it was decided that mecanum wheel should not be applied to the center wheel.

MDF boards were used for the rocker and bogie components, and 3D printed parts were used for the connections of the various parts. The range of motion of the bogie is approximately 60 degrees when the front side wheel is raised and approximately 30 degrees when it is lowered. Similarly, the range of motion for the rocker is approximately 30 degrees when the connected wheel is raised and approximately 10 degrees when it is lowered. Other parameters are shown in Table Ⅰ.

A 17W (12V) DC coreless motor with a built-in gearbox and optical encoder was used to drive each wheel. To simplify the mechanism, output shaft of the gearbox is directly connected to the wheel. Since the center wheel must be tested for active and passive joints, it is designed to be easily switched between them.

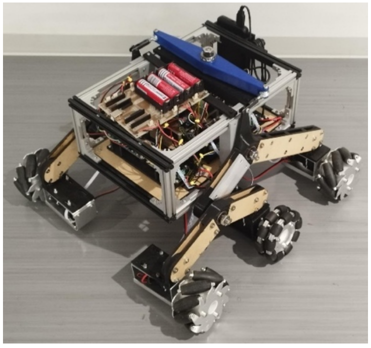

Figure 4. Rocker-bogie mechanism with omni-directional wheels

TABLE I. SPECIFICATION OF PROTOTYPE MODEL

Specifications	Length
Full length	500 mm
Full width	420 mm
Full height	380 mm
Tread	400 mm
Wheelbase	200 mm
Diameter of omni wheel	100 mm
Diameter of mecanum wheel	100 mm

To solve the problem of the mechanism body orientation not being uniquely fixed, arms extending from the left and right rockers, called differential arms, were connected above the body. This mechanism allows the movement of the left and right arms to be transmitted to the body and its orientation to be determined.

B. Control System

For speed control of DC motors, an exclusive microcontroller is used for each motor individually. 2-phase signals from the optical encoder are connected to the external interrupt terminal of the microcontroller, and the speed is detected by software counting. Simple PI control is used as the control law for speed control.

Except of these microcontrollers, another microcontroller is prepared to calculate the angular velocity of each wheel based on inverse kinematics. The calculated data is then sent to the microcontrollers for speed control via I^2C communication.

In addition, a controller equipped with two joysticks was provided for manual operation in the experiment. The velocity vector and the angular velocity around the yaw angle of the rocker-bogie mechanism can be controlled by operating these joysticks. The microcontroller in the manual controller and the microcontroller for inverse kinematics calculation described above are connected via ZigBee which is known as a wireless communication.

All of the above control circuits and necessary power supplies are mounted on the mechanism body, which means the rocker-bogie mechanism is self-contained type. Fig. 5 shows a system configuration diagram summarizing the above.

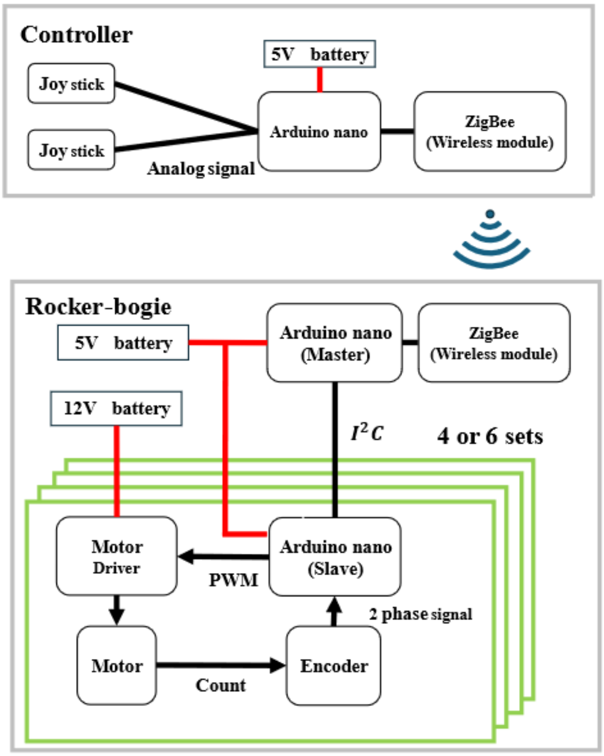

Figure 5. Configulation of the control systems

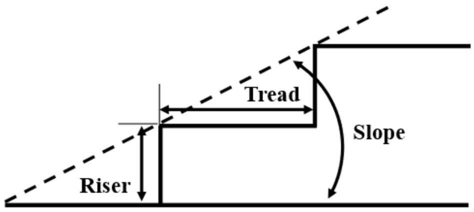

Figure 6. Parameters definitions in stairs

TABLE II. CONDITION OF STAIRS FOR EXPERIMENT

ID	Riser	Tread	Slope
12-36	12 mm	36 mm	18.4 deg.
24-72	24 mm	72 mm	
12-24	12 mm	24 mm	26.6 deg.
24-48	24 mm	48 mm	

V. PROTOTYPE MACHINE FOR EXPERIMENT

A. Experimental Method

To verify the adaptability of the developed rocker-bogie mechanism to ground, several types of stairs were prepared and tested trying to step over them. First, two types of staircase shapes were set for the riser height: 12 mm and 24 mm. The lengths of the treads were set to be 1:2 and 1:3 in relation to the riser, so that the angle of inclination would be two types. The inclination angles are approximately 18.4 and

26.6 degrees, respectively. (See Fig.6 for definitions of riser and tread). Four combinations are shown in Table. Ⅱ, ID is a name given for convenience to indicate a unique combination among the four combinations.

For this environment, experiment was conducted using a combination of the following two conditions.

- When the center wheel was set to active and passive joints
- When entering the staircase in forward and backward motion

It is required to note for the forward and backward, generally the bogie side is defined as forward in a rocker-bogie mechanism.

Thus, in total, the experiment consists of 16 different patterns. The experiments were conducted by one operator using the manual controller. For each of the 16 conditions, five runs were conducted, and the number of successful steps was counted.

The appearance of the stairs ID 24-48 actually built for the experiment is shown in Fig. 7 (a) In addition, a 6WD machine is shown trying to step over the stairs ID 12-24 from the front in Fig. 7 (b)

B. Experimental Results and Discussion

The experimental results are shown in Table III. When the passive wheels are applied as center wheels, i.e., four-wheel drive (4WD), it was impossible to step over at all in all conditions. On the other hand, when active wheels are applied, i.e., six-wheel drive (6WD), the vehicle showed high performance in all environments except for the most severe environment ID 24-48.

These results show that there is a clear difference in the ability to step over uneven terrain between the 4WD and 6WD cases, indicating the importance of the center wheels. However, since the same motor was used to drive each wheel in both cases, the 6WD had an advantage in overall motor output and torque, which may have influenced the results.

The difference in the experimental results between the case of forward entry and the case of backward entry was very slight. In addition to this, no clear difference in behavior was observed as far as visual inspection was concerned.

Figure 7. Experimental environment.*(a. stairs ID24-48, b. Rocker-bogie on the stairs ID12-24)*

TABLE III. EXPERIMENTAL RESULTS

ID	4WD		6WD	
	Forward	**Back**	**Forward**	**Back**
12-36	0	0	5	5
24-72	0	0	5	5
12-24	0	0	5	4
24-48	0	0	0	0

VI. CONCLUSION

From the experimental results, it was found that number of DOF could be significantly reduced to a maximum of 6 and a minimum of 4 by placing omni-directional wheels on the rocker-bogie mechanism, without reducing moving functionality. However, 4 DOF are not sufficient for ground adaptability, and 6 DOF are practical.

The prototype model developed for the verification experiment was not sufficient in terms of practical use and needs to be improved mainly in terms of the mechanism. Most of the prototype's parts were fabricated using MDF boards and 3D printers, but their rigidity is not sufficient and needs to be replaced with any metal parts. In addition, the current design prioritizes simplification of the mechanism, so the wheels are connected directly to the motor. This means that obstacles may hit the motor in more complex terrain, because the motor is not sufficiently separated from the ground. To solve this problem, mechanical improvements are needed to place the motor in a higher position using some kind of power transmission mechanism and to separate the distance between the motor and the ground.

Then, the most important improvement is the omni-directional wheels. The omni-directional wheels in use are commercially available wheels, which may slip even in directions where friction is necessary. In addition, there is a possibility that soil, stones, etc. may get caught between the freewheel and the frame and interfere with the function of the freewheel. To solve this problem, it is desirable to develop a new omni-directional wheel suitable for rough terrain.

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