Development of Innovative Wheel Modules for Indoor Powered Wheelchairs

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***Abstract*— It is crucial for wheelchairs to overcome small interior space constraints and increase their mobility. Thus, this paper aims to develop wheel modules for indoor powered wheelchairs to allow them to move sideways. The wheel module uses one motor to achieve the two-degree-of-freedom motion, moving forward and turning, by taking advantage of the one-way bearing. A wheelchair equipped with two steering castors and two proposed wheel modules can indeed move in any direction. Compared to the omni-wheel design, the wheel module proposed in this research is energy-saving and straightforward to control.**

I. Introduction

It will be convenient for a powered wheelchair to move sideways, for example, in a kitchen where the sink, the top, and the stove are all on the same side. If a powered wheelchair cannot move sideways, the wheelchair's user needs to make several turns to take the vegetable from the sink and put it into the pan on the stove to cook. Therefore, a powered wheelchair with the capability of moving sideways is necessary.

There are several wheel designs for a powered wheelchair. One of the most popular designs is the differential drive, consisting of two wheels with independent motors. In addition, one or two castor wheels are also needed for stability. Both Mori et al. [1] and Takahashi et al.[2] adopted this design with two differential wheels as the front wheels and a castor wheel as the rear wheel. On the other hand, Fioretti et al. [3] used a similar design except exchanging the differential wheels as the rear wheels and a caster wheel as the front wheel. Although this design is advantageous in controlling and maneuvering wheelchairs easily, it does not allow them to move sideways. Some researchers provided different approaches in operating powered wheelchairs. One intuitive idea is the use of omni wheels, which allows a cart to move in any direction by adjusting the power of each wheel. As a result, the wheels are used in the occasions such as robot soccer. Although the wheelchair with this type of wheel can move in any direction, including sideways, it apparently costs a great deal of energy. This is because some of the power of one wheel may be cancelled out by the other in achieving the desired motion. Power loss may not be an area of concern for robot soccer, as the duration of a game may last only tens of minutes. However, the power consumption for a wheelchair is important because it determines how often the wheelchair needs to be recharged. Hence, fewer powered wheelchair companies adopt omni wheels in their designs.

Wada [4] adopted a design using two omni wheels and two regular wheels to build a four-wheel-drive (4WD) wheelchair. This design allows the wheelchair to roll freely from side to side but not sideways. On the other hand, some mobile robots used innovative wheel module design, such as the Vuton [4] and VmaxCarrier [5]. However, the wheel module consisting of multiple wheels is not adequate for wheelchair applications.

As discussed above, an energy-saving powered wheelchair with side movement capability is needed. Thus, this research aims to particularly develop a wheel module that can provide an energy-saving powered wheelchair to move sideways.

II. Design of the Wheel Module

The design requirements are as follows. First, the wheelchair should directly move in any direction. Second, the wheel module must be light and simple. Third, each module should carry at least 40 kgf while moving on a flat, indoor surface. Keeping these requirements in mind, we designed an integrated moving and turning wheel module with small-sized wheels and a lightweight motor. The idea is to use the minimum number of motors in each wheel module to make the module be able to move forward and turn. If we can allow each wheel module of a wheelchair to aim and move in any direction, we can achieve the task of making the wheelchair move sideways.

Illustrations on how the wheelchair with the proposed wheel module operates are shown in Figs. 1 and 2. In Fig. 1, we use two independent motors to control the directions of the two steering castors and the proposed wheel module to allow the wheelchair to move forward or turn. When the wheelchair needs to move sideways, we shall change the directions of the castors and the wheel modules along the side direction and use the wheel module to drive the wheelchair and move sideways, as illustrated in Fig. 2. Furthermore, we can find from Figs. 1 and 2 that the wheel module needs to have the capability to turn and change its direction. Usually, this can be done by using two motors for each module. However, in this research, we designed the wheel module using only one motor to reduce cost and complexity. One key component that we used is the one-way bearing – a bearing whose inner ring can be engaged or disengaged with the outer ring depending on the rotation direction of the inner ring. Using this particular component allows us to create the unique motion of the wheel module. In

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this research, we developed three generations of the wheel modules presented as follows.

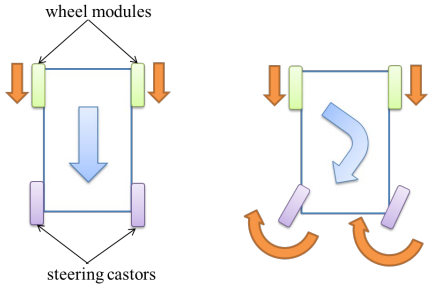

Figure 1. The wheelchair viewed from the top is (a) moving forward; (b) turning.

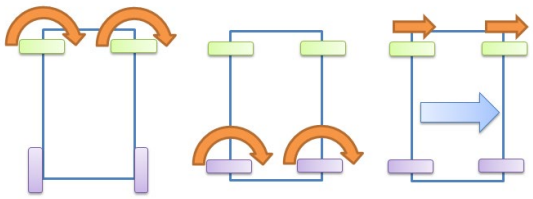

Figure 2. The wheelchair viewed from the top is (a) orienting the real wheel modules; (b) orienting the castors; (c) moving sideways.

A. First-Generation Wheel Module

The first-generation wheel module design is shown in Fig. 3. This design employs only one gearhead motor with an encoder at the end to obtain the motor's angular position. Further, a worm and a worm gear reduce the speed of the motor. While the left roller is directly attached to the worm gear, the right one is rather indirectly attached through a one-way bearing. When the motor drives the worm in the direction so that the one-way bearing is engaged, both wheels rotate in the same direction (as shown in Fig. 4), and the wheel module will move forward. On the other hand, when the motor drives the worm in the other direction so that the one-way bearing is not engaged, the right wheel stays still while the left rotates, causing the wheel module to turn.

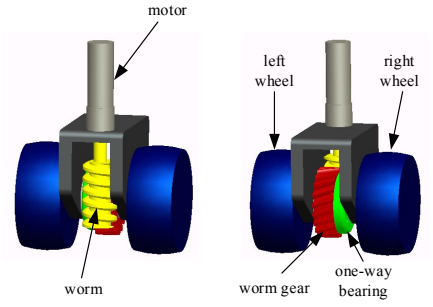

Figure 3. The first-generation wheel module's (a) front side; (b) backside

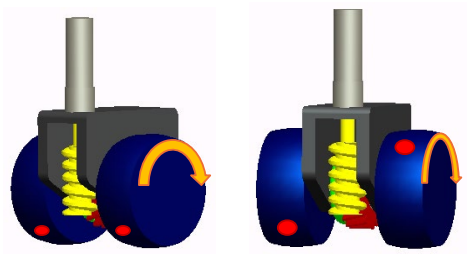

Figure 4. (a) Both wheels rotate in the same direction; (b) the right wheel stays still, and the left rotates, so the wheel module turns. Because this module is viewed from the front, the wheel on the left is the right wheel.

The motor used in our design was a 24 V DC servo gearhead motor with a 5.5 kgf-cm rated torque. The worm gear further provides a 1/10 speed reduction so that the rated torque for the driveshaft can be as high as 55 kgf-cm. Our design target is that each wheel module should be able to carry 40 kgf. The diameter of the roller was 125 mm, and the maximum static friction coefficient between the roller and the floor was assumed to be 0.2. Then, the torque required for the driveshaft can be estimated as follows:

$$40 \times 0.2 \times 6.25 = 50 \text{ kgf-cm}, \quad (1)$$

which is less than the rated torque provided by the motor and the worm gear, making the selected motor appropriate for this application.

B. Second-Generation Wheel Module

The second-generation wheel module design is shown in Fig. 5. This particular wheel module design differs from the previous version as this aims to remove the heavy worm and the worm gear by using a gearhead motor with a high gear ratio. A pair of spiral bevel gears were used for transmitting the power to the shaft. Furthermore, a one-way bearing was attached to one of the wheels so that when it is engaged, the wheel module moves forward, as illustrated in Fig. 5. As the motor rotates in the reversed direction (as shown in Fig. 6), the one-way bearing is disengaged, and the wheel module turns.

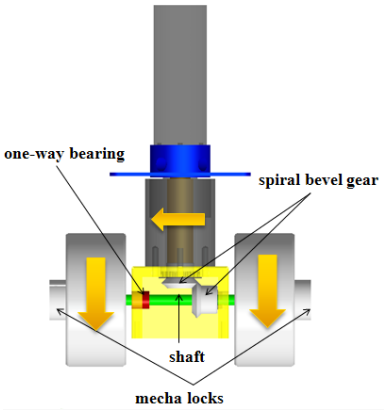

Figure 5. The second-generation wheel module's design. When the one-way bearing is engaged, both wheels rotate as the arrows indicate.

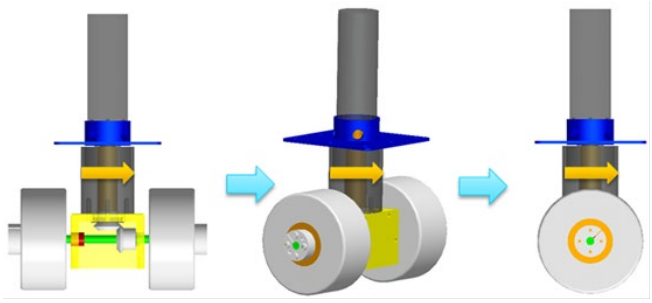

Figure 6. For the second-generation wheel module design, when the one-way bearing is disengaged, the wheel module turns.

D. Third-Generation Wheel Module

The previous two wheel module designs adopted two wheels per module. To further reduce the cost and weight of the wheel module, we redesigned the wheel module where one wheel is removed. The third-generation design of the wheel module is shown in Fig. 7. The design includes two shafts (shaft 1 and shaft 2), a pair of spiral bevel gears, and a set of timing belts and pulleys. We then attached the one-way bearing to shaft 1 in Fig. 7. When the one-way bearing is engaged, as illustrated in Fig. 8, the motor power goes through the bevel gears, shaft 1, the one-way bearing, the timing belt, and shaft 2 to the wheel so that the wheel module moves forward.

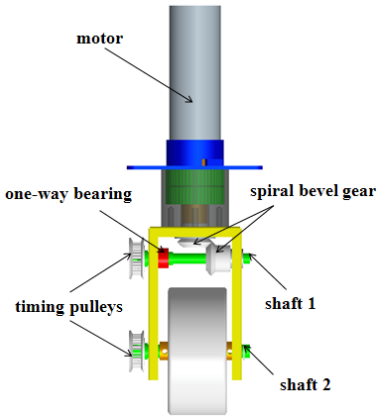

Figure 7. The design of the third-generation wheel module.

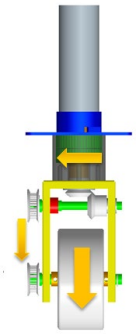

Figure 8. For the third-generation wheel module, when the one-way bearing is engaged, the wheel rotates.

If, for some reason, the wheel gets stuck while the wheel module is moving forward, the wheel module will stay still and will not turn because the one-way bearing is still engaged.

On the other hand, when the motor rotates in the other direction (as illustrated in Fig. 9), the one-way bearing is disengaged, and no power can be transmitted to both shaft 2 and the wheel. However, the spiral bevel gear on shaft 1 spins around the spiral bevel gear attached to the motor, causing the wheel module to turn.

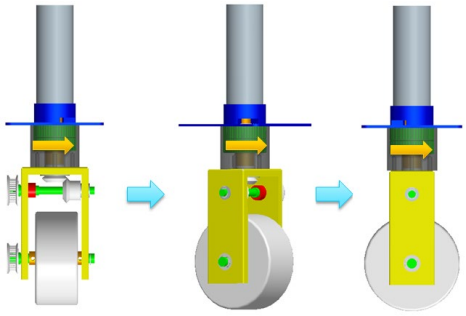

Figure 9. For the third-generation wheel module design, when the one-way bearing is disengaged, the wheel module turns.

III. PROTOTYPES OF THE WHEEL MODULES

A. Prototype of the First-Generation Wheel Module

The complete integrated moving and turning wheel module is shown in Fig. 10. The weight of the module was 2259 g, which included a 220-g motor. According to our preliminary tests, the module can perform moving and turning as we designed. In addition, the results verified the feasibility of the integrated moving and turning wheel module and did show some room for improvement on the weight of the mechanism.

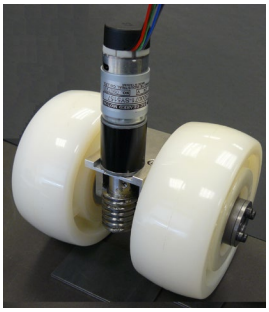

Figure 10. Prototype of the first-generation wheel module.

B. Prototype of the Second-Generation Wheel Module

The prototype of the second-generation wheel module is shown in Fig. 11, which worked as we expected. However, the disadvantage we found was that the wheels could not rotate as the wheel module turned, which caused the wheels to slide on the floor.

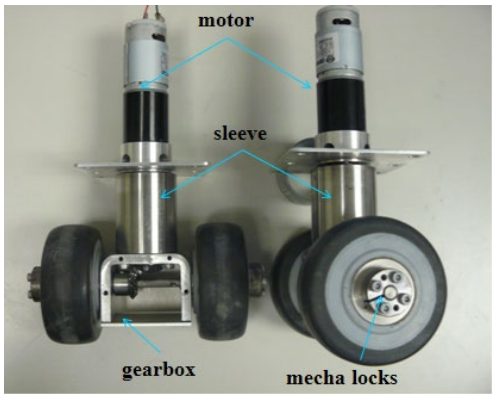

Figure 11. Prototype of the second-generation wheel module.

C. *Prototype of the Third-Generation Wheel Module*

The prototype of the third-generation wheel module is shown in Fig. 12, which also worked as we expected. The wheel still could not rotate when the wheel module turned, and it turned around its contact point with the floor. Noteworthily, no sliding occurred on the wheel.

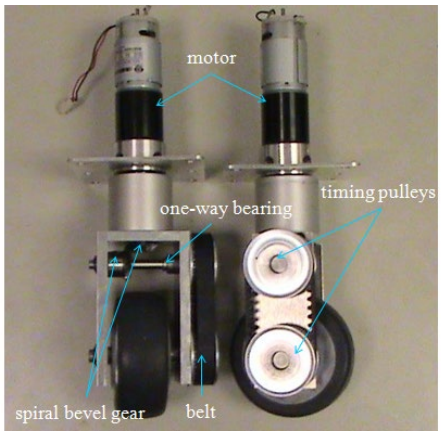

Figure 12. Prototype of the third-generation wheel module.

IV. Experimental Results on the Wheelchair

Because the wheel module was developed for the powered wheelchair, we installed two third-generation wheel modules as the rear wheels on a wheelchair platform to test its movement. The whole process is shown in Fig. 13. During the process, we controlled the wheel modules so that the wheelchair initially moved straight. Then, we turned the wheel modules 90˚and allowed the wheelchair to move sideways. According to the test results, the wheelchair moved as depicted in Fig. 2. Only rear wheels were powered, so while rear wheels moved sideways, the front castors followed without causing obvious rotation of the wheelchair. Fig. 13 demonstrates the feasibility of moving forward and sideways in a powered wheelchair with the proposed wheel modules.

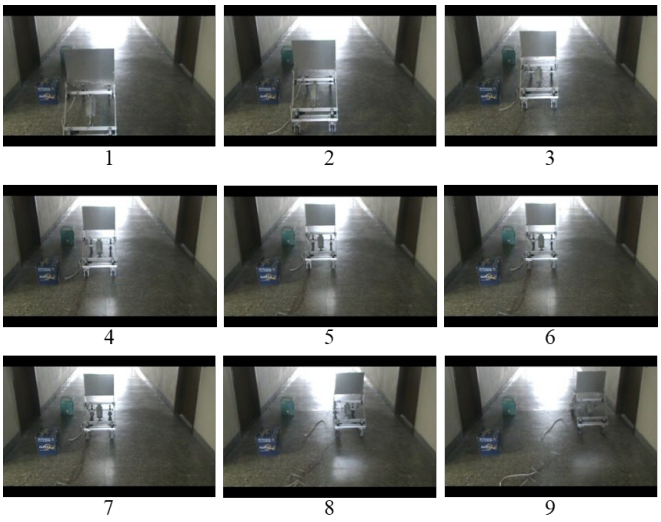

Figure 13. The wheelchair with the third-generation wheel modules moved forward and sideways.

V. Conclusion

Powered wheelchairs are getting popular for disabled, elderly people as they provide good maneuverability with less effort. However, they cannot simply move sideways or in any other direction. In crowded spaces like kitchens or restrooms, the need for a wheelchair to move sideways is essential. Therefore, in this research, we proposed three generations of wheel modules that address the issue. The wheel modules require only one motor but can already perform both moving and turning through a one-way bearing component. The preliminary test results demonstrated that the wheelchair with the wheel modules achieved forward and steering functions. Moreover, the proposed wheel modules save energy and have simpler control compared to the omni-wheel design.

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