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Research Article

Collision-Detecting Device for Omnidirectional Electric Wheelchair

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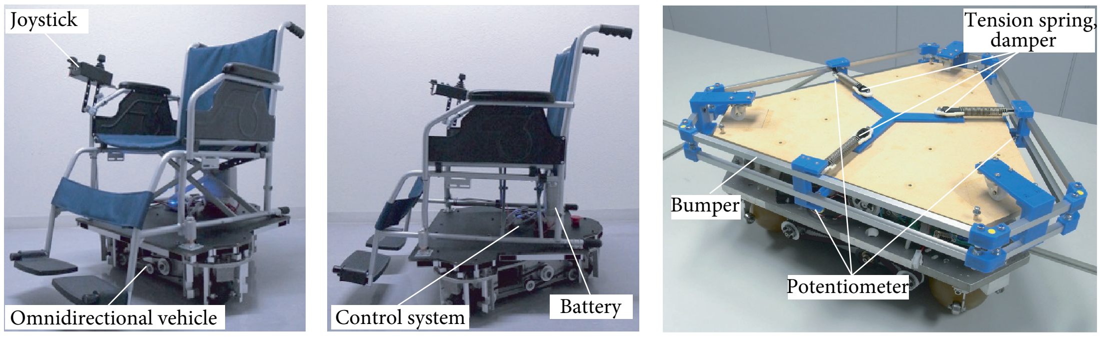
An electric wheelchair is the device to support the self-movement of the elderly and people with physical disabilities. In this paper, a prototype design of an electric wheelchair with a high level of mobility and safety is presented. The electric wheelchair has a high level of mobility by employing an omnidirectional mechanism. Large numbers of mechanisms have been developed to realize omnidirectional motion. However, they have various drawbacks such as a complicated mechanism and difficulty of employment for practical use. Although the ball wheel drive mechanism is simple, it realizes stable motion when negotiating a step, gap, or slope. The high level of mobility enhances the freedom of users while increasing the risk of collision with obstacles or walls. To prevent collisions with obstacles, some electric wheelchairs are equipped with infrared sensors, ultrasonic sensors, laser range finders, or machine vision. However, since these devices are expensive, it will be difficult for them to be widely used with electric wheelchairs. We have developed a prototype design of collision-detecting device with inexpensive sensors. This device detects the occurrence of collisions and can calculate the direction of the colliding object. A prototype has been developed to perform motion experiments and verify the accuracy of the device. The results of experiments are also presented in this paper.

1. Introduction

The reduced physical functions associated with aging or disability make independent living more difficult. Lower extremity function ability limits the scope to take part in vocational and educational opportunities and many also negatively affect self-esteem. If people with reduced physical functions cannot receive support, they may become bedridden. A wheelchair can compensate for a lower extremity function, by allowing users to move freely by themselves. An electric wheelchair is the device to support the self-movement of the elderly and people with physical disabilities. Previous research topics based on electric wheelchairs can be classified into projects to develop increasing a high level of mobility and projects to add intelligent functions to wheelchairs.

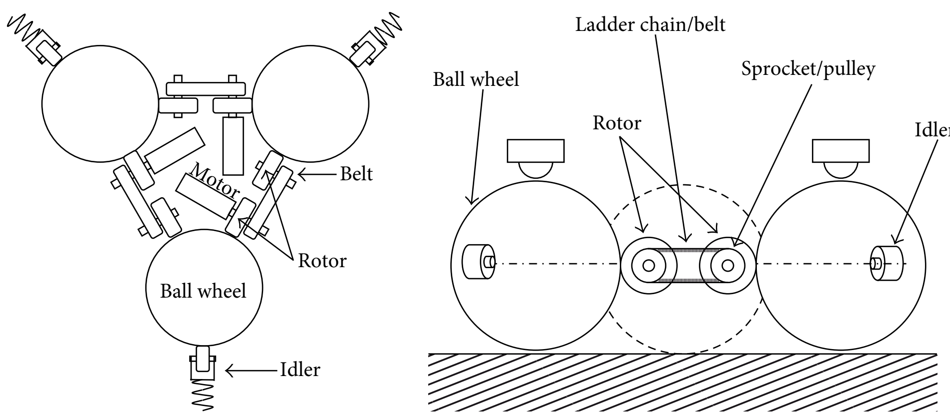
The conventional wheel-type mechanism needs to switch the drive when negotiating narrow spaces. An omnidirectional vehicle has no limits to its direction of motion and is expected to have a wide range of applications. Omnidirectional vehicles are an active area of research in robotics and a numerous mechanisms have been developed. To realize omnidirectional motion, vehicles so far have been equipped with an omniwheel consisting of a large number of free rollers [1] or a spherical ball wheel [2–5]. Several vehicles have been developed for use as electric wheelchairs [5]. However, they must be tested for practical use.

Various input methods are used with electric wheelchairs. The traditional input method is the joystick. Voice recognition [6] and eye- and head-tracking [7–9] have often been used. Intelligent functions must be based on safety. However, the unintended motion of electric wheelchairs may be caused by user errors. To ensure the safety of users, many studies have focused on the avoidance of obstacles by detecting potential hazards in the local environment. The sensors that have been used by electric wheelchairs are ultrasonic sensors, infrared sensors, laser range finders, and force feedback joysticks



(a) Omnidirectional electric wheelchair (b) Collision detecting device

FIGURE 1: Photographs of the prototype.



(a) Top view (b) Side view

FIGURE 2: Structure of ball wheel drive mechanism.

TABLE 1: Specifications of ball wheel drive mechanism.

Length	200 mm × 650 mm
Width	650 mm
Weight	40 kg
Payload	200 kg
Ball wheel's diameter	98 mm
Ball wheel's material	Urethane shore 90
Rotor's diameter	40 mm
Rotor's width	20 mm
Rotor's material	MC nylon
DC motor's output	100 W × 3
Battery	24 V
Control system	Arduino (ATmega328P)
Controller	Joystick

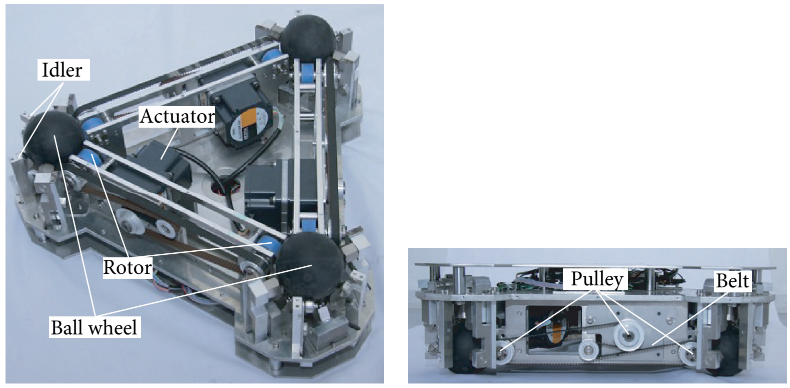
[10–16]. In recent years, machine vision systems have been developed that use an omnidirectional camera system [17, 18], a fisheye camera system [19], or a stereo omnidirectional system [20] based on computer vision technology.

These systems cannot only help avoid collisions, but also enable the realization of additional intelligent functions such as autonomous and semiautonomous wheelchairs. However, there are still many problems to be solved. Because inexpensive and reliable systems are required in the fields of public health and welfare, as reported in this paper, we have developed an omnidirectional wheelchair with a ball wheel drive mechanism. As a measure to ensure its safety, we have also developed a collision-detecting device without expensive sensors.

2. Outline of Prototype

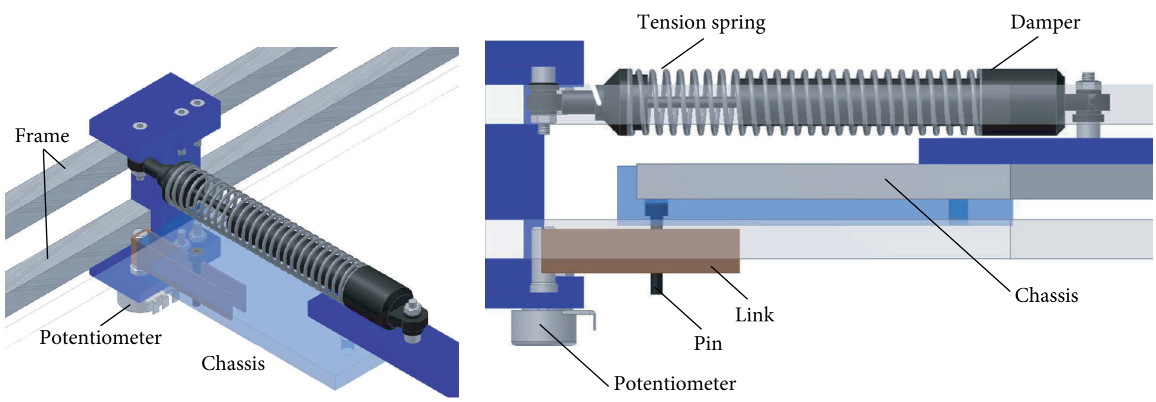
Photographs of the prototype are shown in Figure 1(a). The drive unit of the prototype employs a ball wheel drive mechanism with the following features: (1) the ball wheel is a suitable shape for omnidirectional motion and do not generate vibration or noise, and (2) a high level of ability for negotiating a step, gap, or slope. The input device of the prototype is a joystick using Arduino chipset. A battery (Ni-MH, 24 [V], 6.7 [Ahr]) and control unit are mounted on the body. The user can move in any direction by operating the joystick.

Figure 1(b) shows the prototype collision-detecting device on the body of the vehicle. The role of this device is not to avoid collisions but to detect them. Although various types of sensors and cameras have been used to improve collision avoidance performance, it is not realistic to install



(a) Perspective view (b) Side view

Figure 3: Whole view of ball wheel drive mechanism.



(a) Perspective view (b) Side view

Figure 4: Sensor unit of collision detecting device.

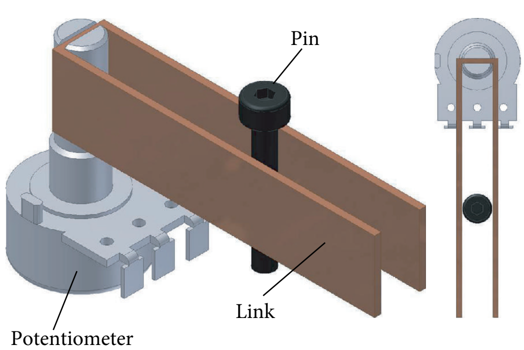


Figure 5: Detecting of the displacement.

these expensive devices in welfare equipment such as electric wheelchairs. We proposed a new device that can physically detect a collision and contribute to improve operation safety. Collision detection is realized by installing a bumper around the wheelchair. When the bumper collides with an obstacle, the obstacles does not come in contact with the main body of the wheelchair. The bumper can move omnidirectionally in the horizontal plane with the vehicle body. The device can calculate the collision direction from the measured displacement (position and orientation) of the bumper from the initial position. To measure the displacement, the device is equipped with three potentiometers. Moreover, so that the bumper can rerun to its initial position, the device is equipped with three tension springs and dampers. The collision-detecting device is composed of low-cost sensors.

3. Ball Wheel Drive Mechanism

We have developed a holonomic omnidirectional vehicle with a simple mechanism consisting of three ball wheels and three actuators [2]. The layout of the mechanical parts is shown in Figure 2. Each actuator can drive two rotors simultaneously by using pulleys and belts. The rotation of each ball wheel is supported by two rollers. The mechanism does not cause overconstraint, because the number of actuators is equal to the number of degrees of freedom of motion on a flat surface.

Photographs of the prototype omnidirectional vehicle with the ball wheel drive mechanism are shown in Figure 3 and the specifications of the vehicle are shown in Table 1.

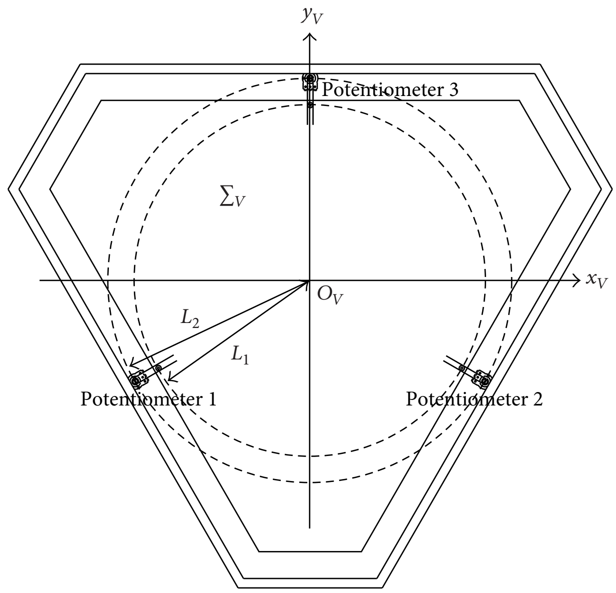
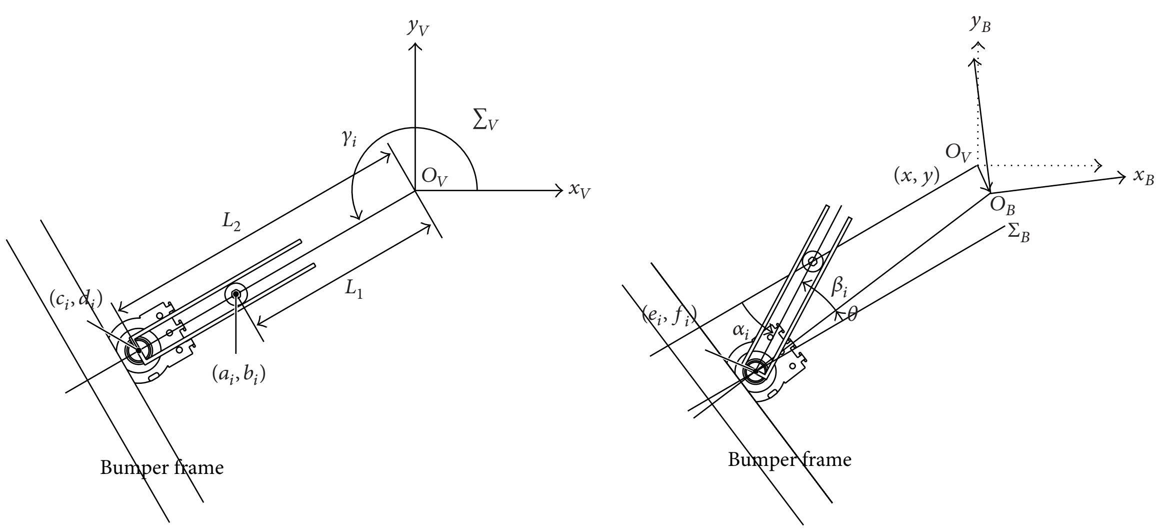


FIGURE 6: Layout of the sensor unit.



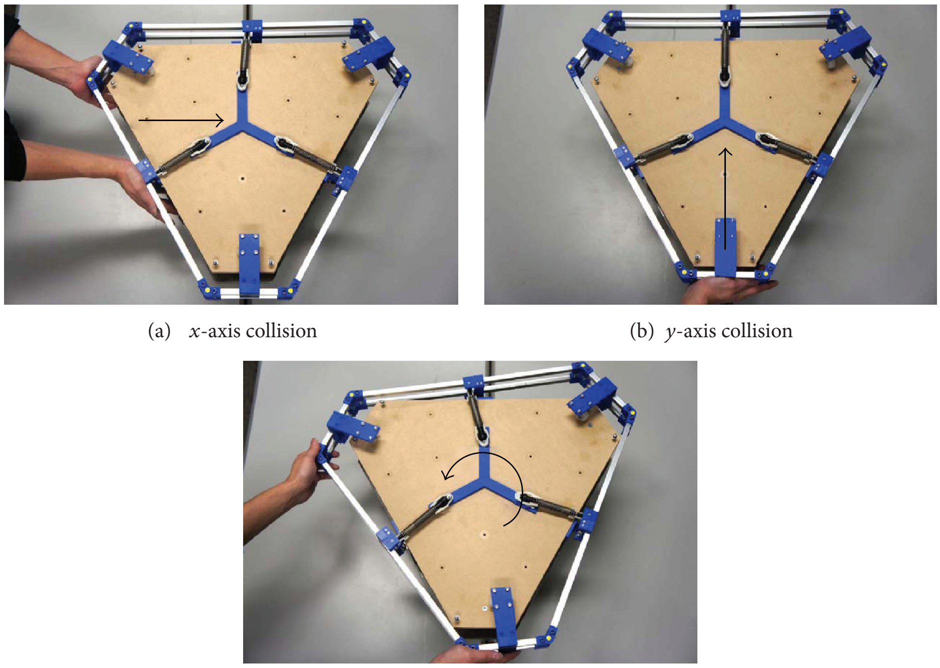
(a) Initial position (b) Change of position

FIGURE 7: Bumper movement by collision.

The ability to negotiate more difficult terrain steps, gaps, and slopes is confirmed by motion experiments with an adult of approximately 56 kg in the wheelchair. The omnidirectional vehicle with the ball wheel drive mechanism was able to (1) overcome a step of 14 mm, (2) traverse a gap of 50 mm, and (3) climb a slope of 15 deg. These abilities are necessary for practical use and allow the electric wheelchair to be used an indoor environment.

4. Collision-Detecting Device

4.1. Concept of Collision-Detecting Device. The basic part of the collision-detecting device is the frame surrounding the vehicle body. Each potentiometer in the device is arranged on the long side of the bumper and can measure different directions. A sensor unit consisting of a potentiometer, a tension spring, and a damper is installed on the frame, as shown in Figure 4(a). A rotary knob is attached to a link with a slit, as shown in Figure 5. When the bumper is moved by a collision, it causes the link to rotate around the pin. The arrangement of the link and pin is shown in Figure 4(b). Using each measurement value, the system can calculate the position and orientation of the bumper. After the collision, the bumper returns to the initial position, and the force for which is provided by a tension spring connected to the bumper and the vehicle body. To support the smooth



(a) x-axis collision (b) y-axis collision (c) θ-axis collision

FIGURE 8: Input displacement.

movement of the bumper in the horizontal plane, a free caster is installed on each short side of the bumper. The free caster rotates passively on the vehicle chassis to realize the smooth motion of the bumper.

4.2. Kinematics. We defined the fixed coordinate Σ_V of the vehicle as shown in Figure 6, in which L_1 and L_2 are the distances from the vehicle center o_V to the pin and potentiometer, respectively. (a_i, b_i) and (c_i, d_i) in Figure 7(a) designate the center positions of each pin and potentiometer, respectively ($i = 1, 2, 3$). First, to evaluate the motion of the bumper, we define the initial position. Define Σ_B as the fixed coordinate of the bumper. In the initial condition, o_B coincides with o_V which is the origin of the vehicle coordinate. The rotation angles γ_i are formed by pin i and the vehicle coordinate. Here, counterclockwise rotation is assumed to be positive. The positions of pin i and potentiometer i are as fellows:

$$\begin{aligned} (a_i, b_i) &= (L_1 \cos\gamma_i, L_1 \sin\gamma_i) \\ (c_i, d_i) &= (L_2 \cos\gamma_i, L_2 \sin\gamma_i). \end{aligned} \tag{1}$$

It is assumed that the bumper is moved by a collision in Figure 7(b), meaning that the fixed coordinate Σ_B of the bumper is displaced relative to the vehicle coordinate Σ_V (position x: x_V-axis, y: y_V-axis, orientation θ: o_V). The center of each potentiometers (e_i, f_i) is given by

$$(e_i, f_i) = (c_i \cos\theta - d_i \sin\theta + x, c_i \sin\theta + d_i \cos\theta + y). \tag{2}$$

Let $\gamma_i + \alpha_i$ be the rotation angle from the x_B-axis to the line segment joining the pin and potentiometer center. Here, α_i is the sum of the bumper rotation angle θ and potentiometer rotation angle β_i. The relationships between γ_i and α_i are

$$\tan(\gamma_i + \alpha_i) = \frac{f_i - b_i}{e_i - a_i}. \tag{3}$$

In the case that $\gamma_1 = (1/2 + 2/3)\pi$, $\gamma_2 = (1/2 + 4/3)\pi$, and where $\gamma_3 = 1/2\pi$, we obtain

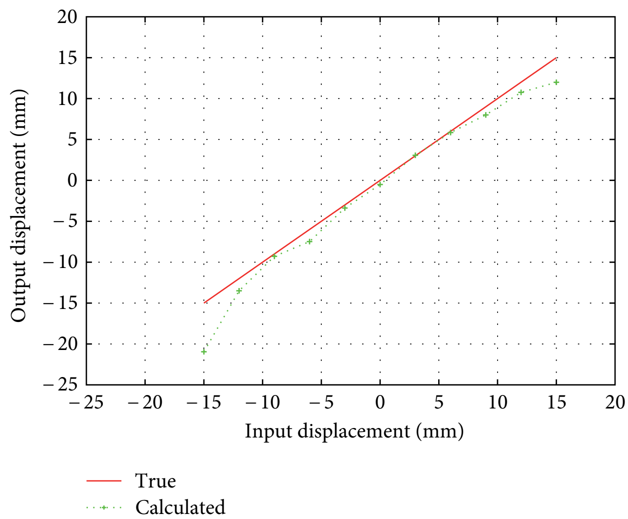
$$\begin{aligned} \tan(\alpha_1) = z_1 &\fallingdotseq \frac{x - \sqrt{3}y + 2L_2\theta}{-\sqrt{3}x - y + 2(L_2 - L_1)} \\ \tan(\alpha_2) = z_2 &\fallingdotseq \frac{x + \sqrt{3}y + 2L_2\theta}{\sqrt{3}x - y - 2(L_2 - L_1)} \\ \tan(\alpha_3) = z_3 &\fallingdotseq \frac{-x + 2L_2\theta}{y + (L_2 - L_1)}. \end{aligned} \tag{4}$$

When it is assumed that θ is sufficiently small, $\sin\theta \fallingdotseq \theta$, $\cos\theta \fallingdotseq 1$. After rearranging these relationships, we obtain

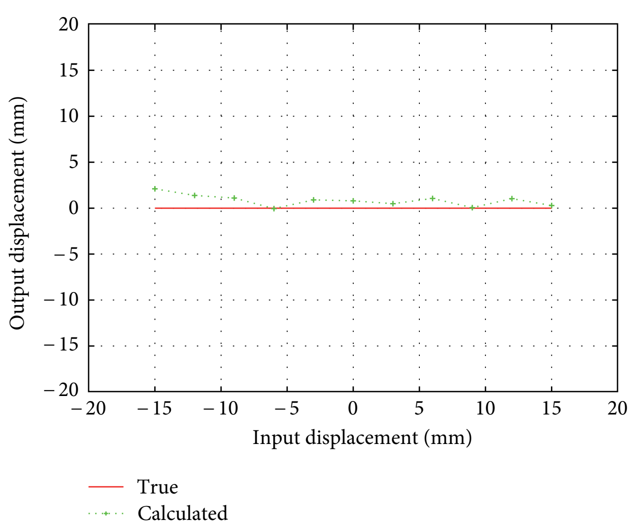
$$\mathbf{A}\mathbf{b} = \mathbf{c}, \tag{5}$$

where,

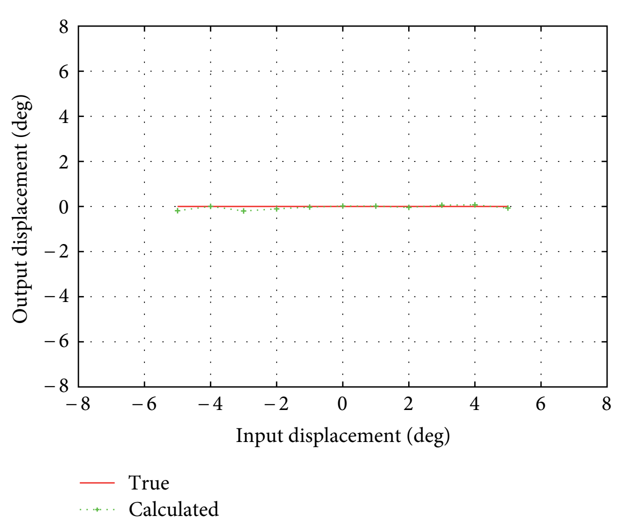
$$\begin{aligned} \mathbf{A} &= \begin{bmatrix} 1 + \sqrt{3}\tan\alpha_1 & \tan\alpha_2 - \sqrt{3} & 2L_2 \\ 1 - \sqrt{3}\tan\alpha_3 & \tan\alpha_3 + \sqrt{3} & 2L_2 \\ -2 & -2\tan\alpha_1 & 2L_2 \end{bmatrix} \\ \mathbf{b} &= \begin{bmatrix} x & y & \theta \end{bmatrix}^T \\ \mathbf{c} &= \begin{bmatrix} 2(L_2 - L_1)\tan\alpha_1 \\ 2(L_2 - L_1)\tan\alpha_2 \\ 2(L_2 - L_1)\tan\alpha_3 \end{bmatrix}. \end{aligned} \tag{6}$$



(a) x-axis displacement

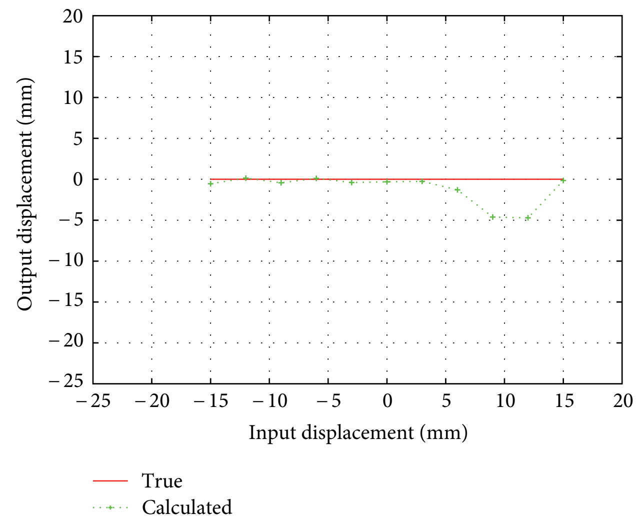


(b) y-axis displacement

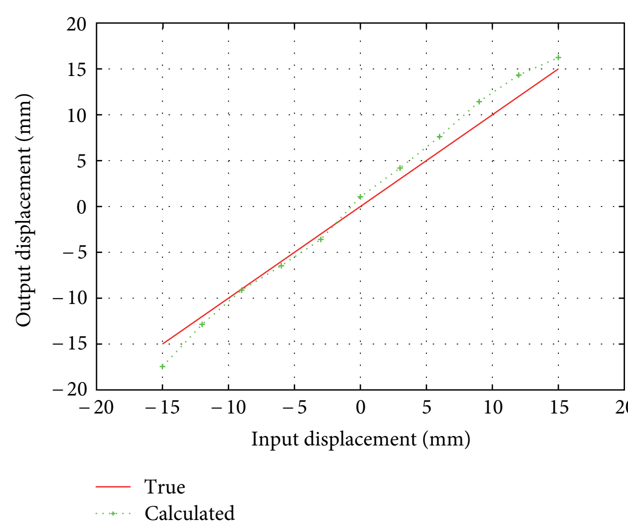


(c) θ-axis displacement

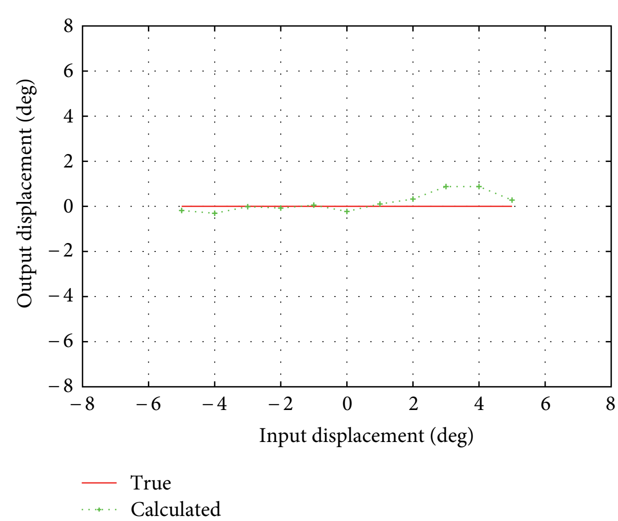
Figure 9: x-axis collision.



(a) x-axis displacement



(b) y-axis displacement



(c) θ-axis displacement

Figure 10: y-axis collision.

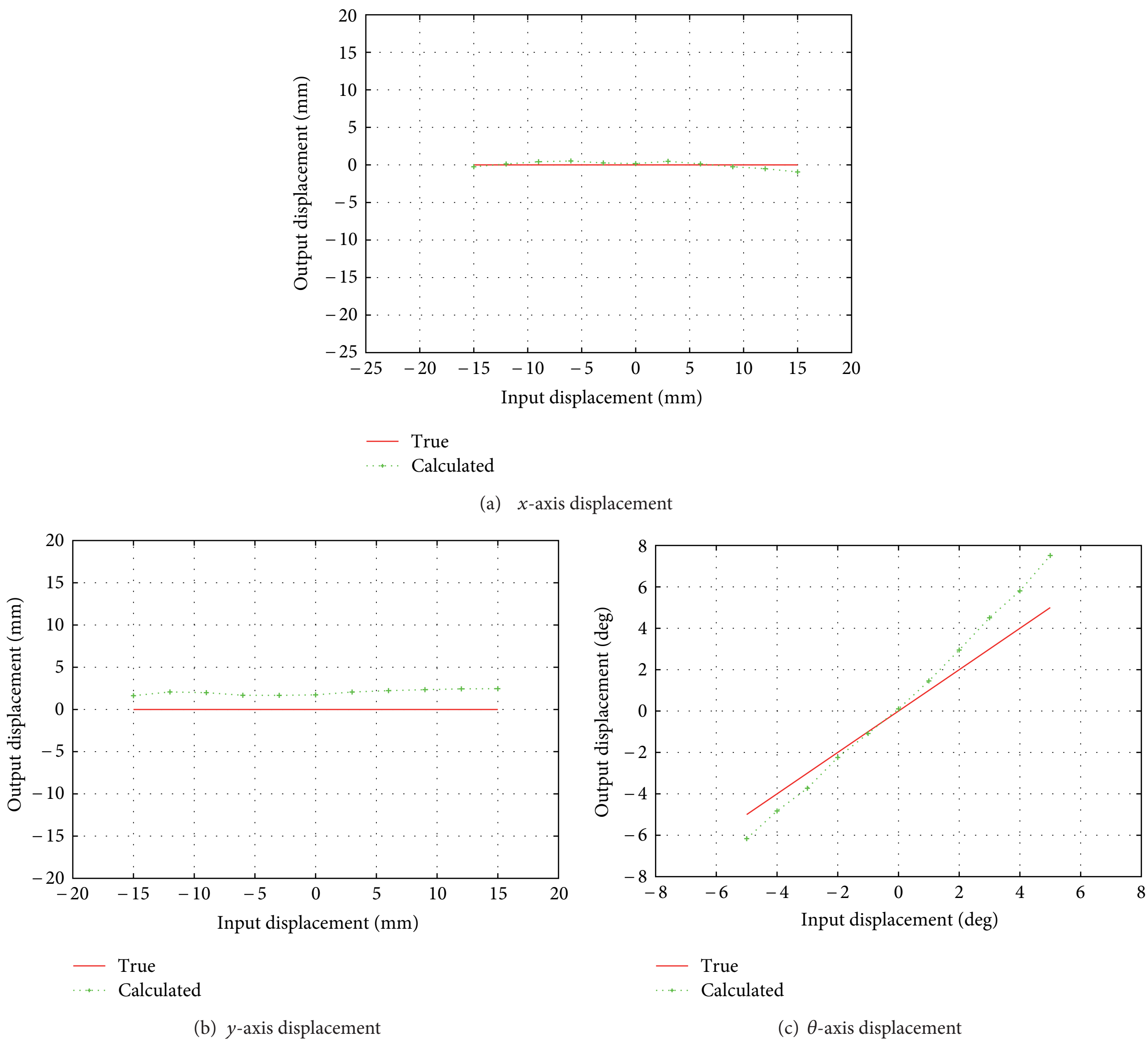


Figure 11: θ-axis collision.

We can calculate the bumper movement $\mathbf{b} = (x, y, \theta)^T$, which is in the direction of the collision, using

$$\mathbf{b} = \mathbf{A}^{-1}\mathbf{c}. \tag{7}$$

4.3. Accuracy of the Device. In this section, we describe a set of experiments conducted to confirm the accuracy of the collision-detecting device. We intentionally applied an external force to the bumper from the translational and rotational directions. We compared the true and calculated displacement of the bumper using (7) for three directions. Note that the maximum of movement range are ±18.5 mm in the front-back direction, ±20 mm in the horizontal direction, and ±7.5 deg in the rotational direction. Figure 8 shows the movement of the bumper when an external force is applied to the bumper in the following cases:

(i) motion in the front-back direction (−15 mm-15 mm at 3 mm intervals),

(ii) motion in the horizontal direction (−15 mm-mm at 3 mm intervals),

(iii) Turning (−5 deg-5 deg at 1 deg intervals).

The experimental results are shown in Figures 9–11. In these experiments, we applied an external force in particular direction. Ideally, the displacement in the other directions is zero. However, as the movement range increases, the displacement in other directions also increases. The desired directions, as shown in Figures 9(a), 10(b), and 11(c), exhibit satisfactory accuracy when the movement is small. The maximum errors are ±2.5 mm in the front-back direction, ±6.0 mm in the horizontal direction, and ±2.5 deg in the rotational direction. The problem is that the link is passively-deformed when the movement is big. To reduce the error, we should change the link material from MC nylon to a metal.

5. Conclusion

In this study, we developed a prototype with the aim of realizing high mobility and safety. The developed wheelchair is an omnidirectional vehicle with a high level of ability when negotiating a step, gap, or slope. Collision detection is realized by installing a bumper around the vehicle. When the bumper collides with an obstacle, the obstacle does not come in contact with the main body of the vehicle. The collision-detecting device can calculate the collision direction from the measured displacement (position and orientation) of the bumper from the initial position. The collision-detecting device is composed of low-cost sensors. In future work, we will implement the collision detecting device in an electric wheelchair and add an intelligent function to the wheelchair such as an operation assistance system.

Acknowledgments

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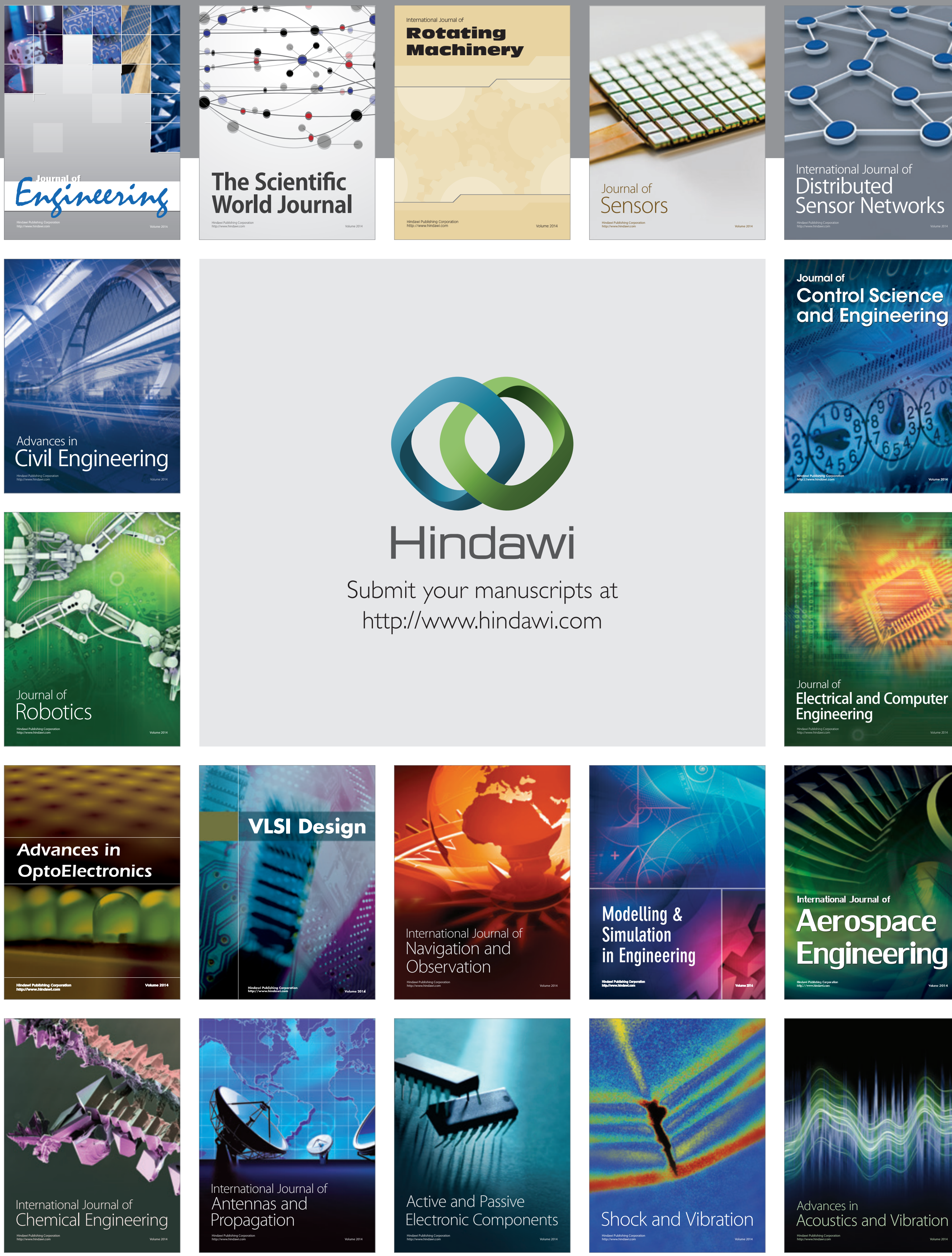
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