The Conception of an Autonomous Traveling Manual Wheelchair and a Study on its Localization

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Abstract

In a care facility, it is one of the factors that the burden of a caregiver is increasing by guiding many cared persons in a wheelchair before and after a meal. Although many autonomous electric wheelchairs have been researched and developed, it is not reasonable to introduce them for the entire care receivers in a nursing home from the viewpoint of cost, time and trouble of maintenance. We are developing a detachable robot that makes a manual wheelchair run autonomously. This paper describes the basic concept, target specifications and design conditions of the experimental machines and feasibility study about the localization by using the optical flow sensor. In the future, we will proceed with the implementation of the autonomous driving function.

1. Introduction

In a nursing home, it is one of the factors that the burden of a caregiver is increasing by guiding many cared persons in a wheelchair before and after a meal. Besides, even in the rehabilitation center, when a patient moves to a training facility with a wheelchair, a trainee must accompany him and the burden on the trainee's work increases. It is thought that these can be eliminated by autonomously moving the wheelchair. A lot of research has been done on the autonomous movement of electric wheelchairs. An electric wheelchair that travels in a hallway using visual servo \cite{1}, a map creation using 3D SLAM, and an electric wheelchair that estimates its position \cite{2}. In addition, Whill and Panasonic are carrying out demonstration experiments of autonomous movement with an electric wheelchair at the airport \cite{3}.

They are highly feasible for continuous use by individuals and in applications where operation with a high utilization rate is expected. However, the opportunity to use the autonomous function in a nursing home is limited only before and after events such as meals, and the operation rate is low. Also, it is not reasonable to introduce them for the entire care receivers in a nursing home from the viewpoint of cost, time and trouble of maintenance.

On the other hand, there are products such as SmartDrive \cite{4}, which is a drive unit to add motorization to a manual wheelchair, research examples in which the robot climbs the step in cooperation with the user \cite{5}, and cases of burden reduction for assistants by the addition of electrically assisted function \cite{6}. However, no one adds an autonomous movement and guidance function to a manual wheelchair.
In this research, we propose a robot that drives and guides wheelchairs one by one by attaching an easily detachable autonomous drive unit to an already installed or inexpensive manual attendant-controlled wheelchair. This paper describes the basic concept of driving manual wheelchairs with a robot, the target specifications and design conditions of the experimental machines and feasibility study about the localization by using the optical flow sensor.

2. Basic concept and the design criteria

2.1 Operating environment and user
The use environment is indoor barrier-free. Corridor width of a nursing home is defined as more than 1,800mm in Japan [7]. The structure of the wheelchair should be able to be turned into a super soft turn so that direction changes can be made even if people are passing by in the 1,800 mm wide corridor. The users are an operator (caregiver) and a passenger (care receiver). There is no restriction on the caregiver but is a weight restriction on the care receiver. According to the age-specific physique data of the Ministry of Education, Culture, Sports, Science and Technology, the average weight of the elderly over 65 years old is less than 65 kg [8]. Therefore, the weight of the care receiver was set to a maximum of 70 kg with a margin. Besides, there is a possibility that a dangerous event may occur, such as the cared person lowering their feet below the foot support and coming into contact with the ground while traveling in a wheelchair.

2.2 Basic function
We plan to incorporate the following as basic functions:
(a) Simple coupler function
(b) Autonomous mobile function (self-position estimation, route generation)
(c) Obstacle detection, avoidance function
A simple connection device is incorporated so that the caregiver can easily attach and detach from the wheelchair.

The self-position estimation function recognizes its position on the map, generates a route to the destination, and incorporates an autonomous movement function that follows the route. At the time of connection, since many wheels come in contact with the ground, self-position estimation that is more robust to wheel slippage is required than in the case of an independent wheeled robot.

When there are obstacles such as persons and things on the way, the sensor detects this and incorporates the function to avoid it. It is necessary to detect the situation where the passenger's foot is likely to get to the ground and stop it.

2.3 Method of connecting a robot to a wheelchair
Methods for driving a manual wheelchair from the outside are roughly classified into two categories whether the robot pulls from the front of the wheelchair or pushes it out from the rear of the wheelchair. The pulling type is advantageous in that the sensor measurement range is wide because it does not obstruct the front of the robot, but it has the following disadvantages. When the wheelchair is turned on the spot, the turning radius increases and the movement increases, so the battery consumption is fast. The rigidity of the tip part, which is the connecting part with the wheelchair, is low. When reaching the dining room table, the robot needs to be removed from the wheelchair under the table and there is a risk that the caregiver's head may collide with the table.

On the other hand, the pushing type adopted in this study has the following advantages, although the detection range of the sensor is partially blocked and limited by the wheelchair itself and the passenger. Both the turning radius and the traveling distance can be reduced. It can be connected with a highly rigid tipping lever. Tipping levers are usually made rigid because they are used when an assistant steps on one foot and crosses a step. Desorption can be performed in a space where the caretaker does not have a head collision with the table.

2.4 Driving force
The autonomous mobile robot needs to be placed between the left and right rear wheels. Besides, the size of the robot is made as compact as possible to make it easy to secure the storage space in a nursing home. In order to drive the wheelchair on which the care receiver rides, it is necessary to take into consideration the mass of the wheelchair, the mass of the care receiver (weight), the mass of the robot, and the friction coefficient of the floor. The prototype is designed for MIKI BAL-01 (its weight is 13 kg). As described above, the weight of the care recipient is 70 kg; the mass of the robot itself is set to 25 kg by calculating the torque required for the motor, and the coefficient of friction of the floor is set to 0.4 assuming the floor of the nursing care facility as flooring. Regarding speed, there is a document that 3.7 km/h is suitable for wheelchair transfer by assistants [9]. However, the maximum speed was set at 2 km/h to reduce the anxiety of the cared person because of the machine as the driving source instead of the person.

3. Prototyped experimental machine

Figure 1 shows the appearance of the autonomous mobile robot prototyped based on the target specifications and design study, Figure 2 shows the appearance of the wheelchair when it is connected to a wheelchair and Table 1 shows the basic specifications. Although it became large from the standard of the target size, there is no trouble in connecting with the tipping lever. In order to give priority to the realization of the concept, this prototype does not incorporate a simple removal mechanism without tools.

### Table 1. Specification of autonomous robot

| Dimension         | W458.0 × D718.7 × H284.5 [mm] |
|-------------------|-------------------------------|
| Motor             | DC Brushless Motor: 180W     |
|                   | Gear head: 1:26               |
|                   | Encoder: 1,024 pulse          |
| Velocity          | 2 km/h Max                   |
| Controller        | Raspberry Pi 3B              |
| Battery           | 24V 6Ah×4 (Li-ion)           |

As the drive system, Maxon EC-i52 brushless motor was adopted in terms of the size, required torque and required rotation speed. By using Maxon's GP52C planetary gearhead (speed reduction ratio 1:26) and pulleys (speed reduction ratio 44:60), the required torque of the drive wheel is generated. The motor driver should be able to control the position, voltage, and rotational speed and be equipped with a heat sink. Likewise, ESCON 70/10 from Maxon was selected. The microcomputer used the Raspberry Pi 3 Model B, which has a USB port that can receive information from a two-dimensional range sensor and has Wi-Fi and Bluetooth communication functions. Two sets of two 14.4-V Li-ion batteries connected in series are used in parallel as the drive source. The microcomputer power supply supplies/ provides 5 V, which is stepped down by the DC-DC converter.
Figure 3 shows a system-block diagram of the autonomous traveling robot. In order to detect obstacles, two-dimensional laser range sensor URG-04LX-UG01 (measurement range 240 deg, maximum measurement distance 5.6m) made by Hokuyo Electric Co., Ltd. is installed parallel to the floor surface at the lower front of the robot. The reason for installing it in the lower part is to detect as a dangerous state the above-mentioned cared person lowered his/her foot beneath the foot support. Because the robot is connected to the wheelchair and driven, many wheels touch the ground, and slippage of the drive wheels is expected. Therefore, the amount of movement is measured by an optical flow sensor directed to the ground without relying on odometry based on the rotational speed of the drive wheel. The optical flow sensor can measure the translation direction but cannot detect it in the turning direction, so it is fixed at a position away from the robot's turning center. If there is only one optical flow sensor, there are not enough degrees of freedom, so two sensors are attached to the front and back of the robot. The following equation is derived to perform relative self-position estimation.

\[
\begin{bmatrix}
x(k) \\
y(k) \\
\theta(k)
\end{bmatrix} = \begin{bmatrix}
x(k-1) \\
y(k-1) \\
\theta(k-1)
\end{bmatrix} + \begin{bmatrix}
\Delta O_{F,lo}(k)^2 + \Delta O_{F,la}(k)^2 \cos \theta(k) \\
\Delta O_{F,lo}(k)^2 + \Delta O_{F,la}(k)^2 \sin \theta(k) \\
\Delta O_{R,lo}(k) - \Delta O_{F,la}(k) / L
\end{bmatrix}
\]

\(x(k):\) x position at time step k  
\(y(k):\) y position at time step k  
\(\theta(k):\) Orientation at time step k  
\(\Delta O_{F,lo}(k):\) Relative longitudinal position by a front optical flow sensor  
\(\Delta O_{F,la}(k):\) Relative lateral position by a front optical flow sensor  
\(\Delta O_{R,lo}(k):\) Relative longitudinal position by a rear optical flow sensor  
\(\Delta O_{R,la}(k):\) Relative lateral position by a rear optical flow sensor  
\(L: \) Interval between front optical flow sensor and rear optical flow sensor

In addition, the position and orientation are corrected based on the wall information measured by Laser Range Finder. A control system that follows the generated path is combined with the low-accuracy absolute self-location using a wireless ID tag. In this paper, self-position estimation is limited to verification of its feasibility with two optical flow sensors.
4. Basic Experiment

4.1. Detecting the environment with the Laser Range Finder

With the robot connected to the wheelchair on which a person is riding, the obstacle measurement situation by a two-dimensional range-finding sensor was investigated. In an indoor corridor with a width of 1,850 mm, which is about the same as a nursing home, sensor measurements were obtained when an obstacle was placed 1 m, 2 m, and 3 m ahead.

Figure 4 shows the results. Figure 6 (a) shows the measurement results when the obstacle was placed 1 m ahead, (b) 2 m ahead and (c) 3 m ahead. In each case, the vertical axis is the X coordinate of the moving direction, and the horizontal axis is the Y coordinate perpendicular to the traveling direction.

In any case, obstacles installed in the riding direction are detected, and it is considered that there is no problem in obstacle detection during traveling. However, it can be seen that a part of the wall (about 1 m to 3 m away) is blocked by the front wheel of the wheelchair and cannot be detected. We confirmed that it is necessary to apply an algorithm that excludes this range for self-location estimation using wall information.

![Figure 4. Examples of measuring distance](image)

4.2. Localization with the Optical flow sensor

Figure 5 shows two examples of the trajectory when the robot was traveling straight 1m. The X-axis is the direction of travel, and the Y-axis is the direction perpendicular to the direction of travel. The red dashed line means the trajectory drawn with a pen attached to the robot on graph paper laid on the ground, and the blue solid line means the trajectory calculated by Equation (1) from the values of the front and rear optical flow sensors. The tendency of the wobbling of the trajectory was similar between the two, but there was a difference in the accumulated error. Therefore, the value was calculated on the assumption that the error of the initial angle between the direction of the graph paper and the straight direction of the robot affected. In (a), the initial angle error was assumed to be 2 deg, and in (b) the calculation result when 0.5 deg was assumed is shown by the black dotted lines in the figure. The results showed that the error of the trajectory due to the error of the initial angle affected.

In this experiment, since two optical flow sensors were connected to different microcomputers, the two sensors were not synchronized, and it is considered that the timing difference affected them. Besides, since the current calculation algorithm was based on the front sensor, the error tended to increase if the front sensor missed the reading. However, the initial angle error and the error due to
reading error can be solved by considering the correction by wall information detected by the Laser range finder.

![Graph showing trajectory comparison]

**Figure 5.** Examples of the trajectory of the robot when forwarding 1 m.

### 5. Conclusion

In this report, to automate the mobility assistance of a wheelchair in a nursing home, we designed a removable autonomous traveling robot, set its concept, set target specifications, and made a trial design. Furthermore, the basic experiment of the prototyped robot was performed, the results and the consideration were reported, and the following was clarified.

- The concept of driving a manual wheelchair for people was shown to the board.
- It is necessary to estimate the position of the vehicle taking into account the effect of the partially-blocked area by the front wheel of the wheelchair.
- It was shown that a trajectory with both translational motion and swivel motion can be calculated using an optical flow sensor attached to the front and rear.

In the future, in addition to mounting linear tracking control, obstacle avoidance function using ranging sensors, navigation function, and so forth, a mechanism that can be connected easily is incorporated to promote demonstration experiments.

### Acknowledgements

This research was funded by the NSK Mechatronics Technology Foundation grants. I would like to thank the NSK Mechatronics Technology Foundation, NSK Ltd. and its related companies.
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