ACTION CONTROL METHOD FOR POWERED WHEELCHAIRS CONSIDERING CONTROL INPUT AND ENVIRONMENTAL INFORMATION

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Abstract: Powered wheelchair is a mobility commonly used for people with disabilities. Recently, to improve the safety and efficiency of powered wheelchairs, various systems with control assistance are proposed. However most of the systems suppose joystick as input device and doesn't consider about people with difficulties using it. Not all devices alternative to joystick have enough operability compared to joystick. In this paper, considering corridor passing as verification environment, an action control method to drive through the corridor safely and efficiently for wheelchairs controlled by devices with low operability is presented. To achieve safe and efficient driving, proposed method considers the time series of passenger's input commands and combines the environmental information to select effective direction and speed for the wheelchair instead of passenger. Moreover for environment recognition, corridor detection algorithm is also proposed. To verify the effectiveness of proposed method, simulations and experiments were carried out.

1 INTRODUCTION

Recently, the number of wheelchair users is increasing at an average annual rate of 5.9 % a year and who have benefit from smart wheelchair, wheelchair with assist facility, is estimated as 61 to 91 % of all wheelchair users (Simpson, 2008). Hence assist facility is becoming one of the important features for users with disabilities that find difficulties in operating existing powered wheelchairs. In order to facilitate the operation, several wheelchairs were developed with obstacle avoidance methods and/or passenger's intention estimation so far and their effectiveness were verified (Levine, 1999); (Iturrate, 2009). Though most of the previous methods were focused on the wheelchair controlled by joystick and didn't consider people with difficulties using joystick: e.g. people with handicaps on upper limbs. Therefore wheelchairs enabled to control by devices alternative to joystick such as voice command (Simpson, 2002), face recognition (Saitoh, 2007) and brain machine interface (BMI) (Vanacker, 2007); (Iturrate, 2009) are recently proposed. However most of these devices don't have enough operability, low operating frequency, few input direction and uncertainty of information, compared to joysticks and needs further assist to establish safe and efficient control of wheelchair as shown in Figure 1.

Previously, two approaches are proposed to control the wheelchair with low operability devices (Vanaker, 2007); (Iturrate, 2009). One is automatic navigation and the other is implementation of existing approaches. Automatic navigation allows the passenger not to control directly the wheelchair. Though this approach limits the wheelchairs travel range of passenger as the navigation needs the map of environment preliminary. And implementation of existing methods enable to control the wheelchair safely but its efficiency is not same as that of joystick. For example, it is reported that the wheelchair controlled by BMI has difficulty in driving the wheelchair as shown in Figure 2 (Vanaker, 2007).

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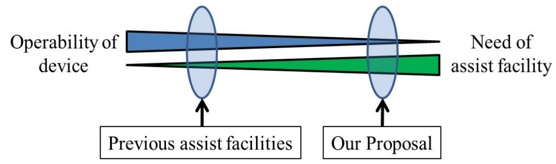


Figure 1: The relationship between the operability of device and necessity of assist facility.

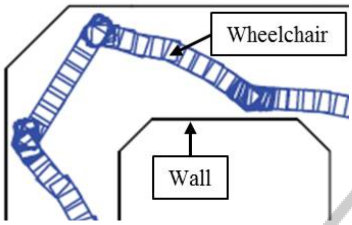


Figure 2: Inefficient driving of wheelchair by brain machine interface due to the low operability.

Therefore in order to control the wheelchair with devices alternative to joystick safely and efficiently, the assist facility has to take care of the features of the device and needs further assist of passenger's operation during the travel. More specifically, to achieve efficient and safe control of wheelchair without environmental constraint, reactive action control that comprises the devices' limitations is necessary.

In this paper, regarding corridor passing as a general task for wheelchair users, a new action control method to drive through the corridor safely and efficiently by devices with low operability is presented. For simplicity, we suppose that the input information doesn't have uncertainty. Particularly, we consider for the next two points:

(a) Deceleration before entering to the cross roads
(b) Smooth and efficient turns to change direction

(a) is to improve the safety of passenger from the undetectable moving objects shield by the walls like in Figure 3 and for the difficulty of keeping particular speed using low operability devices. (b) is to achieve efficient driving and to prevent from stopping at all times changing direction.

To achieve the points mentioned above, we propose a corridor detection algorithm and an action control method that simultaneously considers control input and environmental information. The wheelchair first considers the time series of passenger's inputs to deal with the low frequency and decides roughly the moving direction. Next, by combining the environmental information with decided direction, proposed method analyze the passenger's intention and selects effective direction and speed for the wheelchair instead of passenger. Finally combining the selected direction and speed with obstacle avoidance methods, proposed method realizes safe and efficient driving of wheelchair. To verify the effectiveness of the proposed method, several

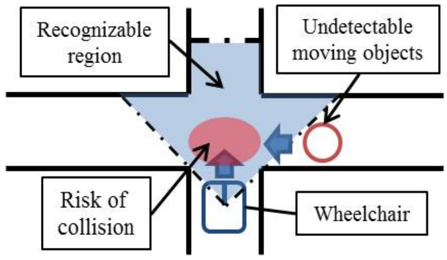


Figure 3: Example situation that deceleration is needed.

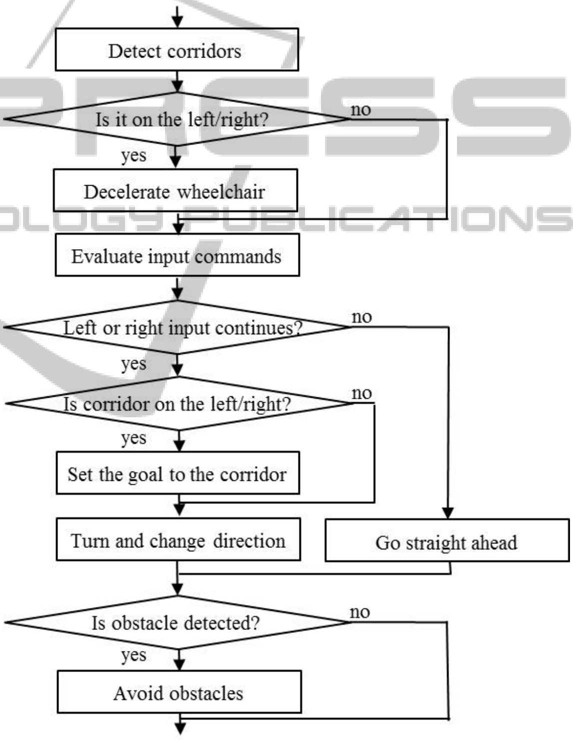


Figure 4: Flowchart of proposed algorithm.

simulations and experiments were carried out.

2 CONTROL SYSTEM OF WHEELCHAIR

The control system of wheelchair consists of three steps, corridor detection, evaluation of input commands and action control. The flowchart of our proposed method is shown in Figure 4. By considering the input commands of passenger and environmental information such as corridors and obstacles to decide the action, the system achieves safe and efficient driving of wheelchair. The design method of each step is described in following sections.

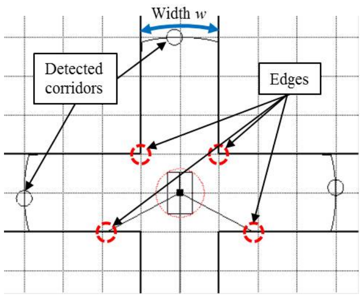


Figure 5: Corridor detection.

2.1 Corridor Detection

To achieve the two functions mentioned in section 1, the proposed method detects the corridors. We developed a corridor detection algorithm based on leg detection algorithm that uses laser range finder (LRF) (Belloto, 2009). First, it searches for the edges as shown in Figure 5 from the LRF data using next equation:

$$\left| l_i - l_{i-1} \right| > e_{th} \tag{1}$$

Where l_i is the i th data of LRF and e_{th} is the threshold. If the equation is satisfied, we assume the i th data corresponds to the edge. After edges are detected, proposed method calculates the width w between detected edges by following equation:

$$w = l_j \times r_{res} \times \left| i_{j+1} - i_j \right| \tag{2}$$

Where l_j is the distance between the wheelchair and j th detected edge, r_{res} is the angular resolution of LRF and $\left| i_{j+1} - i_j \right|$ is the number of scanned point between detected edges. Using the threshold w_{th}, if $w \geq w_{th}$, we assumed the space between detected edges corresponds to a corridor.

In this paper, thresholds e_{th} and w_{th} is set to 0.1 m and 0.3 m. These are set according to the parameter study to detect the corridors 2 m backward from it.

2.2 Evaluation of Input

To decide the moving direction roughly, the time series of input commands is considered. In this paper, we refer non-invasive BMIs as input device and assume that only three different directions (Forward, Left and Right) is fed to the wheelchair (Millan, 2004). The operating frequency of BMI is set to 2 Hz. The aim of this process is to select the passenger's intention, considering the inputting error, such as turn and change the direction or go straight ahead. To measure the intention we use the following index:

$$\begin{aligned} R_t^L &= \sum_{n=0}^{Memory} R(t_n) I_n^L \Big/ \sum_{n=0}^{Memory} R(t_n) \\ R_t^R &= \sum_{n=0}^{Memory} R(t_n) I_n^R \Big/ \sum_{n=0}^{Memory} R(t_n) \end{aligned} \tag{3}$$

This index is first proposed for mobile robots to measure the reliability of information and $R(t_n)$ is the forgetting function based on the experimental results on human short-term memory in psychology field (Fujii, 2005). As this function is based on the human's short-term memory, we expect to achieve intuitive driving of the wheelchair. Suffixes L and R indicates "Left" and "Right". The formulation of the forgetting function R is as follows:

$$\begin{aligned} &R(t) = A\exp(-Bt) \\ &A = 1.0 \quad B = 0.3595 \end{aligned} \tag{4}$$

The I_n^L and I_n^R in equation (3) represents the input from the device and is defined as follows:

$$\begin{aligned} I_n^L &= \begin{cases} 1 & \text{if input is left} \\ 0 & \text{otherwise} \end{cases} \\ I_n^R &= \begin{cases} 1 & \text{if input is right} \\ 0 & \text{otherwise} \end{cases} \end{aligned} \tag{5}$$

Therefore we can decide whether the passenger wants to go straight ahead or turn and change direction as the R_t^L or R_t^R becomes large when the left or right side input is fed to the wheelchair continually. In this paper, we set R_{th} as threshold and if the index became larger than the R_{th} we decide that the passenger wants to change direction.

2.3 Action Control

The action control of the wheelchair is achieved using fuzzy potential method (FPM) (Tsuzaki, 2003). In FPM, command velocity is generated by integrating the element actions represented as potential membership functions (PMFs). PMF is a function that its horizontal axis represents the traveling direction which is from -180 deg to 180

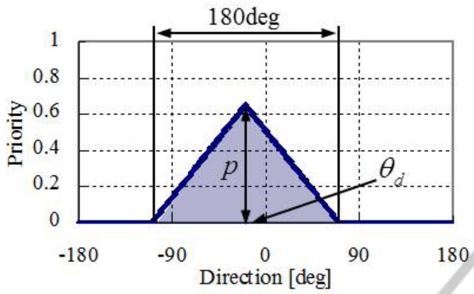


Figure 6: Example PMF for a desired direction.

Table 1: Key assignment.

Input	p_t
Forward	$p_t = \begin{cases} p_{t-1} + 0.1 & if\ p_{t-1} < 1.0 \\ 1.0 & otherwise \end{cases}$
Left	$p_t = p_{t-1}$
Right	$p_t = p_{t-1}$
No input	$p_t = \begin{cases} p_{t-1} - 0.1 & if\ p_{t-1} > 0.0 \\ 0.0 & otherwise \end{cases}$

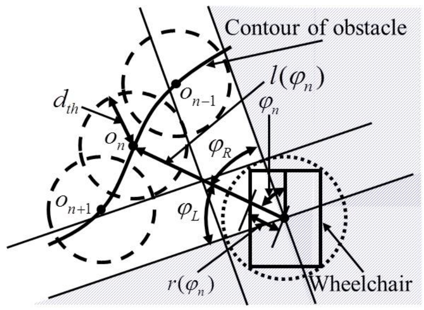


Figure 7: Relation between wheelchair and obstacle.

deg measured from the front of wheelchair and vertical axis represents the priority for each direction. In this paper, three PMFs, for going to the desired direction, to avoid obstacles and to consider passengers intention are designed. The design method of PMFs is described in following sections.

2.3.1 PMF for Going to the Desired Direction

To go to the desired direction, a triangular PMF μ_d is generated, as shown in Figure 6. μ_d is specified by the priority p_t at time t and θ_d. These parameters are determined by Table 1 and following equation:

$$\theta_d = \begin{cases} \theta_c & if\ R_t^L\ or\ R_t^R \geq R_{th} \\ 0.0 & otherwise \end{cases} \quad (6)$$

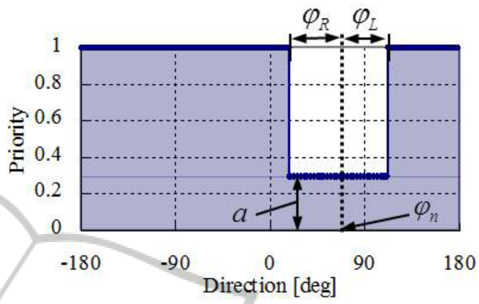


Figure 8: Example PMF for avoiding obstacles.

Where θ_c is the direction of detected corridors on the way which passenger wants to turn: i.e. if $R_t^L \geq R_t^R$ the leftward and if $R_t^R \geq R_t^L$ the rightward. In case corridor isn't detected and the equation is satisfied, θ_c is set to $\pm 45\,\text{deg}$.

2.3.2 PMF for Avoiding Obstacles

To avoid obstacle, PMF μ_o is generated. First, using the distance data from wheelchair to obstacles by LRF, the direction not to collide to obstacles, φ_R and φ_L in Figure 7, considering the margin d_{th} from the n th scanned point is calculated.

$$\varphi_R = \varphi_L = \arcsin\left((r_{wheel} + d_{th})/l(\varphi_n)\right) \quad (7)$$

Next, using the calculated directions, the PMF μ_o^n for n th scanned point is generated like in Figure 6. The priority a of PMF in Figure 8 is decided using following equation.

$$a = \begin{cases} \dfrac{(l(\varphi_n) - d_{th} - r(\varphi_n))}{(l_{th} - d_{th} - r(\varphi_n))} & if\ l(\varphi_n) < l_{th} \\ 1.0 & otherwise \end{cases} \quad (8)$$

Finally, the PMF μ_o is calculated as a logical sum of all PMF for each scanned point.

$$\mu_o = \mu_o^1 \wedge \cdots \wedge \mu_o^N \quad (9)$$

2.3.3 PMF to Consider Passenger's Intention

To consider passenger's intention, PMF μ_{OR} is generated as shown in Figure 9. The aim of this PMF is to restrict wheelchair from moving to the opposite direction of passenger's intention while

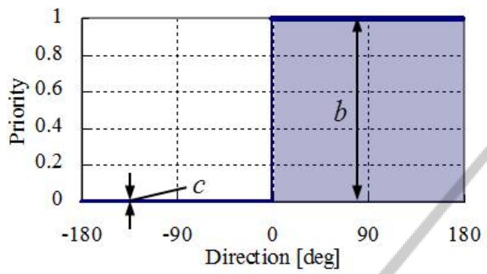


Figure 9: Example PMF to consider passenger's intention.

avoiding the obstacles. b and c shown in Figure 9 is calculated as follows:

$$b = \begin{cases} 0.0 & if\ R_t^L > R_t^R \geq 0 \\ 1.0 & otherwise \end{cases}$$
$$c = \begin{cases} 0.0 & if\ R_t^R > R_t^L \geq 0 \\ 1.0 & otherwise \end{cases} \quad (10)$$

2.3.4 Integration of PMFs and Calculation of Command Velocity

FPM integrates the PMFs to calculate the command velocity. The integrated PMF μ_{mix} is calculated by logical product of the PMFs designed in previous sections as follows:

$$\mu_{mix} = \mu_d \wedge \mu_o \wedge \mu_{OR} \quad (11)$$

Finally, by defuzzifier, the command velocity is calculated as a traveling direction φ_{out} and an absolute value of the reference speed of the wheelchair from the integrated PMF μ_{mix} . φ_{out} is decided as the direction that makes the PMF $\mu_{mix}(\varphi)$ maximum. Based on φ_{out} , the traveling speed v_{out} is calculated by following equation:

$$v_t = \mu_{mix}(\varphi_{out})(v_{\max} - v_{\min}) + v_{\max} \quad (12)$$

$$v_{out} = v_t \left(1 - \frac{1}{1 + \exp(-\beta(2|\varphi_{out}|/\pi - 0.5))} \right) \quad (13)$$

Where $v_{\max}$ and $v_{\min}$ are the upper and lower limits of the wheelchair speed. In this paper, we assume that the wheelchair's maximum acceleration is 0.5 m/s^2 and $v_{\max}$ is set to 0.75 m/s while the corridors are not detected on the left and right side of the

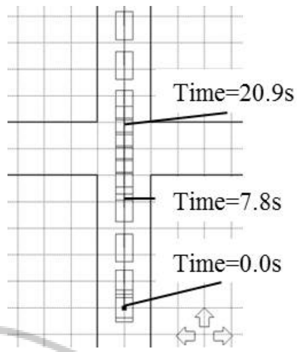


Figure 10: Simulation result of straight driving.

wheelchair and otherwise 0.25 m/s. 0.75 m/s is the speed that is able to decelerate to 0.25 m/s when the maximum acceleration of the wheelchair is 0.5 m/s^2 in 2 m of braking distance. $v_{\min}$ is set to 0.0 m/s. Moreover, to turn efficiently, proposed method limits the output according to the φ_{out} using the sigmoid function shown in equation (13). In this paper, the parameter β is set to $\beta = 25$.

3 SIMULATION

To verify the effectiveness of the proposed method, numerical simulations were carried out. The wheelchair size is set to L 1.05 × W 0.65 m. In order to recognize the environment, we assumed that a LRF is loaded on the center of wheelchair. The measuring range of LRF is 4.0 m from -120 deg to 120 deg. I_{th} is set to 0.25 and the margin from obstacles d_{th} is set to 0.3 m. In all simulations, the initial position of the wheelchair is set to (0 m, 0 m). Width of corridors is 2 m and the center of cross road is (0.0 m, 6.0 m). The interval of grids in the figures is 1 m. The commands of passenger are simulated by keyboard input with operating frequency of 2 Hz and the numbers 0 to 3 of the input command corresponds to "0: No signal", "1: Forward", "2: Left", and "3: Right".

3.1 Straight Driving

Figures 10 to 12 show the trajectory of wheelchair, input commands and speed of wheelchair in straight driving. From these results, it is verified that the proposed method accelerates and decelerates automatically while driving the wheelchair. Especially, while the corridor was detected,

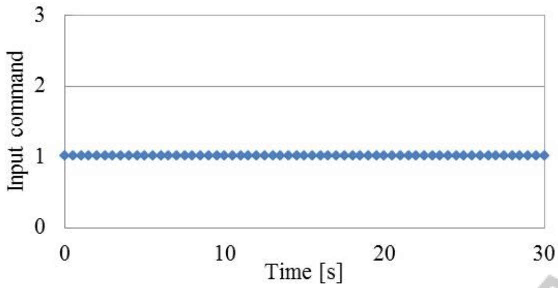


Figure 11: The input commands in straight driving.

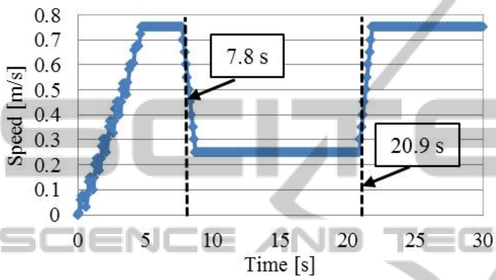
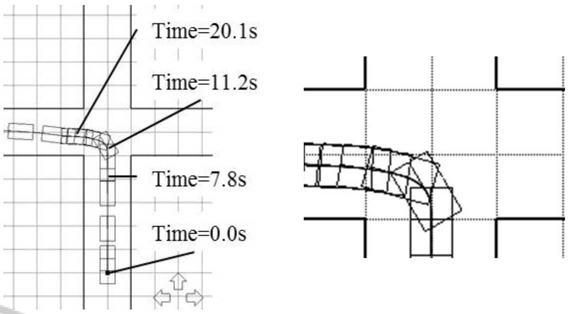


Figure 12: Speed of wheelchair in straight driving.

proposed method decelerates the wheelchair for safe driving considering the undetectable moving objects shield by the walls. By this simulation, it was confirmed that the proposed method realizes safe driving of wheelchair with simple input commands in straight driving.

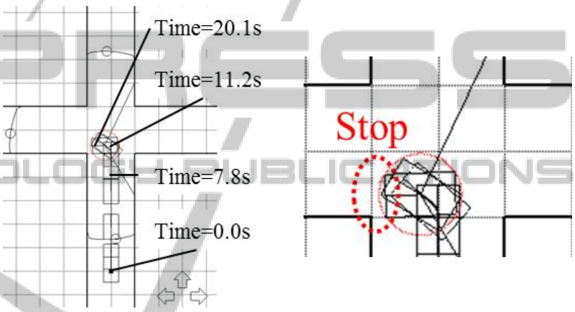
3.2 Direction Change

Figure 13 shows the trajectory of wheelchair with proposed method and Figure 14 shows the trajectory with conventional method in direction change. The input command that was given to the wheelchair in both methods is shown in Figure 15. Figure 16 shows the yaw angle of wheelchair in direction change with proposed method. From the results in Figures 13, 15 and 16, it was confirmed that proposed method enables the passenger to change the direction smoothly by detecting the corridors, analyzing the input commands and directing the wheelchair to the corridor. On the other hand, as shown in Figure 14, as the correspondence of input commands and the travelling direction was one-to-one which was not suitable for turning, the conventional method, without navigation to the corridors, failed to change the direction and stopped. Moreover, in case an unintended input is fed to the wheelchair, the wheelchair with conventional method swings as the time series of input is not



(a) Overview (b) Enlarged view

Figure 13: Simulation result in direction change with proposed method.



(a) Overview (b) Enlarged view

Figure 14: Simulation result in direction change with conventional method.

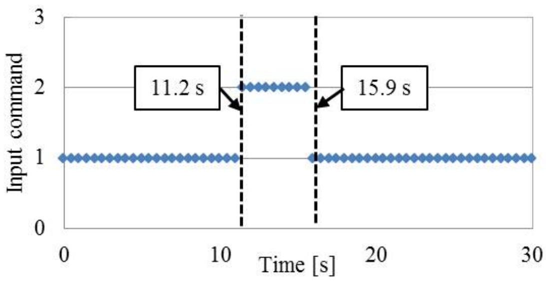


Figure 15: The input commands in direction change.

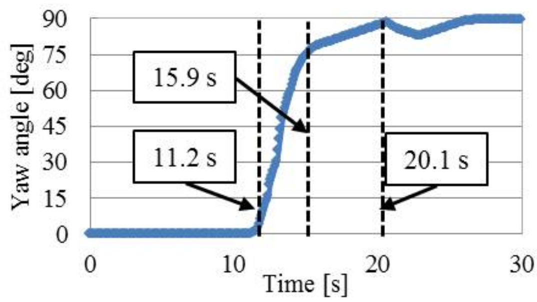


Figure 16: Yaw angle of wheelchair in direction change.

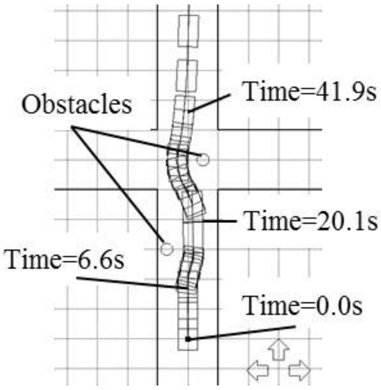


Figure 17: Simulation result of obstacle avoidance during straight driving.

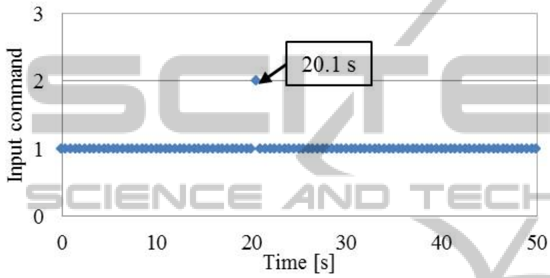


Figure 18: The input commands while avoiding obstacles during straight driving.

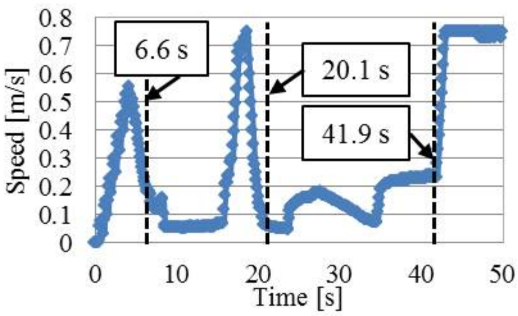


Figure 19: Speed of wheelchair while avoiding obstacles during straight driving.

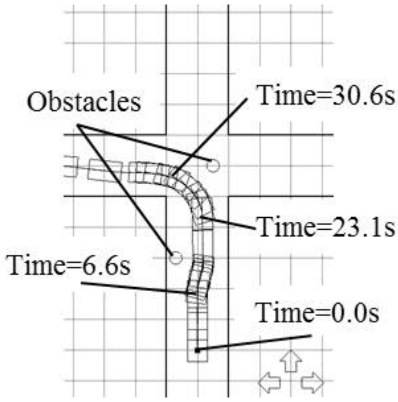


Figure 20: Simulation result of obstacle avoidance during direction change.

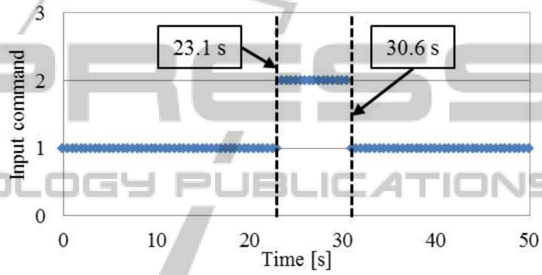


Figure 21: The input commands while avoiding obstacles during direction change.

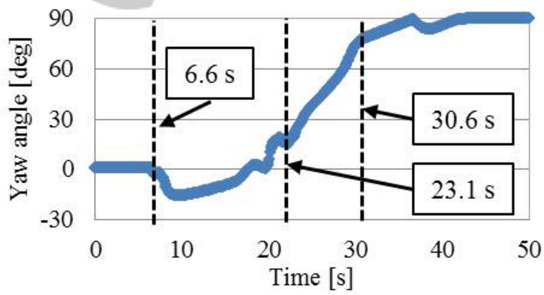


Figure 22: Yaw angle of wheelchair while avoiding obstacles during direction change.

considered. Therefore it is verified that the automatic navigation is effective for the wheelchairs controlled by low operability devices to change direction and it realizes smooth changing the direction without useless stopping inside the cross road.

3.3 Obstacle Avoidance

To verify the effectiveness of proposed method while avoiding the obstacles, two simulations were carried out. In the simulation two obstacles is placed in the corridor. One is placed in (-0.7 m, 3.0 m) and the other is placed in (0.5 m, 6.0 m). The radius of obstacle is set to 0.2 m. Figures 17 to 19 show the trajectory of wheelchair, input commands and speed of wheelchair in straight driving with obstacles in the corridor. From these results, it is verified that proposed method achieves safe driving of wheelchair maintaining the distance from obstacles and automatic control of velocity with simple input commands. Especially, at 6.6 s, though the obstacle is not placed in the travelling direction and the passenger commands to go straight ahead, the wheelchair automatically avoided the obstacle to maintain the safe distance.

Figure 23: Overview of wheelchair.

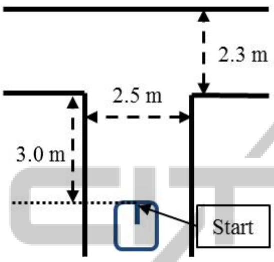


Figure 24: The experiment environment.

Moreover, the wheelchair analyzed the left-side input of 20.1 s as the input is not long enough for changing the direction. As a result, the wheelchair avoided the obstacle from its left side instead of changing the direction to the left.

Figures 20 to 22 show the trajectory of wheelchair, input commands and yaw angle of wheelchair in direction change with obstacles in the corridor. From this simulation, by analyzing the time series of input commands, instead of avoiding the obstacle and going forward, the wheelchair turned smoothly and changed its direction maintaining the distance from obstacles. From these results, it is verified that by analyzing the input commands and considering the environmental information, the proposed method achieves safe and efficient driving of wheelchair, controlled by low operability devices, in general corridor passing situations without complex commands.

4 EXPERIMENT

4.1 Experiment Environment

To verify the effectiveness of proposed method in real environment, experiment with real wheelchair was carried out. The wheelchair is YAMAHA JWX-1 with a HOKUYO URG04-LX LRF on the front of wheelchair to detect corridors and obstacles. Figure 23 shows the overview of wheelchair.

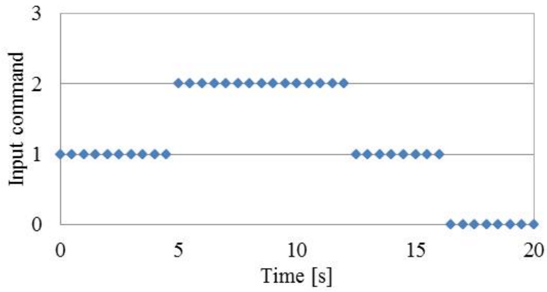


Figure 25: The input commands during the experiment.

Figure 26: Experiment result of direction change (back).

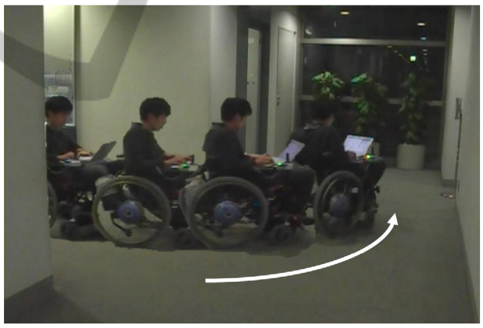


Figure 27: Experiment result of direction change (side).

LRF used in the experiment has 4 m of measurement range from 120 deg to -120 deg. The control of wheelchair is achieved with a laptop PC with Centrino-Duo CPU 2.0 GHz. The size of wheelchair is L 1.05×W 0.65 m. The maximum speed of wheelchair is set to 0.5 m/s. The input commands are given to the wheelchair by keyboard manually with operating frequency of 2 Hz. Figure 24 shows the experiment environment.

4.2 Experiment Result

Figure 25 shows the input command that was given to the wheelchair during the experiment and Figures 26 and 27 show the experiment result from different view angles. From these results, it was confirmed that proposed method automatically analyze the passenger's objective and changes the wheelchair's direction without complex commands. Moreover, it was verified that the proposed method achieves safe and smooth driving of wheelchair also in real environment by considering the passenger's control input and environmental information simultaneously while driving through the corridors.

5 CONCLUSIONS

In this paper, to control the wheelchair with devices alternative to joystick safely and efficiently, a novel action control method for powered wheelchairs controlled by low operability device, low operating frequency and few input direction, is proposed.

In order to achieve safe and efficient action while driving the corridors, the proposed method considers the time series of input commands and environmental information simultaneously. Moreover, to detect the corridors, a corridor detection algorithm is also proposed. Through the numerical simulation and experiment, efficient and safe driving of wheelchair, efficient turns to change the direction in cross roads and safe driving with automatic control of velocity was achieved by proposed method and its effectiveness was verified.

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