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A One Hand Drive Wheelchair with New Manipulation Mechanism Constructed by a Triple Ring and with Assist Functions

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1. Introduction

The wheelchair is a useful tool providing an aid to mobility for the elderly and handicapped. There exist various researches concerned with wheelchairs (Bourhis, G. et al., 2001; Veeger, H. E. J. et al., 2002; Boninger, M. L. et al., 2002; Adachi, Y. et al., 2003; Miura, H. et al., 2004; Urbano, J. et al., 2005). In order to improve the mobility of persons who can use only one hand for the manipulation of a wheelchair, for example, due to the hemiplegia, various one hand drive wheelchair, such as a lever type and a double ring type, are marketed. These equipments are extremely useful and are utilized in various welfare facilities or homes, because these equipments are effective in moving a short distance on the flat ground with comparatively little rolling resistance. However, because of a heavy physical load on the rough surface and on the slope, many users of these one-hand drive wheelchairs have to transfer to electric wheelchairs at the outdoors. Hence, users of one hand drive wheelchair often give up moving a long distance alone in the outdoors. In order to enjoy life and to maintain the remained ability by rehabilitation effect, it is effective to use the remained ability for moving oneself. Therefore, we consider that various assist functions, such as power assist function and so on, are required to the one-hand drive wheelchair in order to use it in the outdoors. Our research group have been produced a one-hand drive wheelchair with newly proposed manipulation mechanism and some assist functions (Yasuda, T. et al. 2006). Figure 1 shows the developed one-hand drive wheelchair. Dimensions of the wheelchair are presented in Table 1.

In this investigation, we demonstrate a one-hand drive wheelchair with the power assist function, the maximum velocity limiting function on the downward slope, the reverse prevention function on the upward slope and the function for turning on the spot. In order to realize these assist functions, we first developed new manipulation mechanism with a triple ring on a side of the wheelchair. Secondely, we made an assist system, which is constructed by sensing device for human's intention and wheelchair's running speed, micro compter and power supply device. These manipuation mechanism and assist system are able to realize various assist functions.

Fig.1. Developed one hand drive wheelchair

Dimension	
Length	850[mm]
Height	760[mm]
Width	690[mm]
Rear Wheel (Diameter)	560[mm]
Left turn hand rim diameter	540[mm]
Center hand rim diameter	500[mm]
Right turn hand rim diameter	455[mm]
Total mass	33[kg]

Table 1. Dimensions of the developed one hand drive wheelchair

2. Manipulation and assist mechanism of a triple ring type one hand drive wheelchair

2.1 Manipulation mechanism

An outline of manipulation mechanism of one-hand drive wheelchair developed in our research group is shown in Fig. 2. This wheelchair is manipulated by using right hand. The characteristic of this wheelchair is that all three hand rims are mounted on a right side of the wheelchair. A right turn hand rim, depicted in Fig. 2, is connected directly with the left wheel by an axis, so rotating this hand rim, the left wheel rotates and the wheelchair turns right (See Fig. 3(a)). A left turn hand rim is mounted on the right wheel, so rotating this hand rim, the right wheel rotates and the wheelchair turns left (See Fig. 3(b)). Rotating a middle hand rim, at first, a mechanical clutch is operated and right and left wheels unite like a spinning wheel. Furthermore, rotating a middle hand rim, the manipulation torque is transmitted to the both wheels at the same time and the wheelchair goes straight (See Fig. 3(c)). If the middle hand rim is released, then the mechanical clutch returns to the original state by restoring force of a spring automatically and left and right wheels separate. Therefore, all operations, such that "turn right", "turn left" and "go straight", are possible in this state. This middle hand rim is called the hand rim for going straight from now. This manipulation mechanism has the following two features:

1) The middle hand rim creates a state, in which right and left wheels are combined and "sure going straight" and "sudden stop" are realized by simple operation such as "rotating or fixing the hand rim for going straight".
2) the manipulator's intention, namely, "turn right", "turn left" and "go straight", is easily obtained by installing the sensor for the manipulation torque to three hand rims.

These features yeild the ability for long distance running in the outdoor and the safety. This manipulation mechanism is most important feature of the developed one hand drive wheelchair.

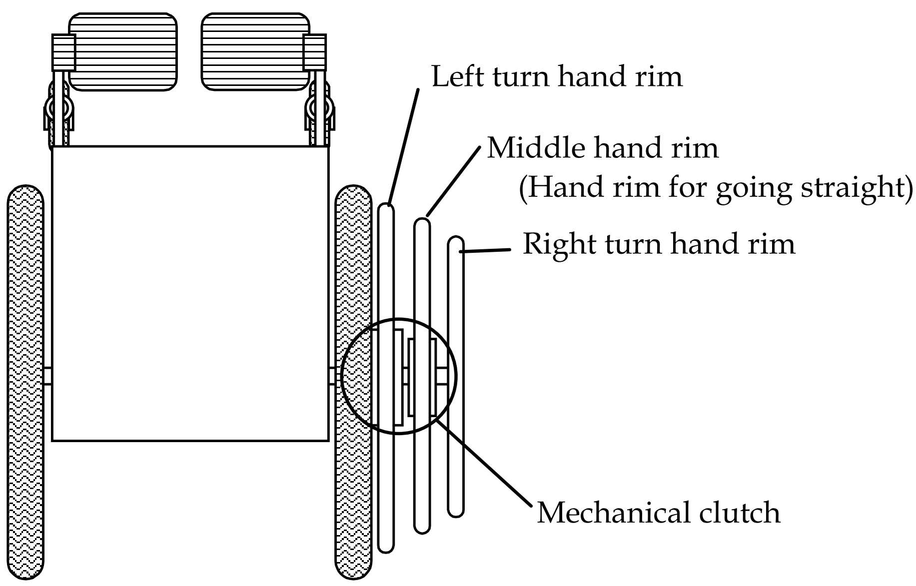


Fig.2. Manipulation mechanism (top view)

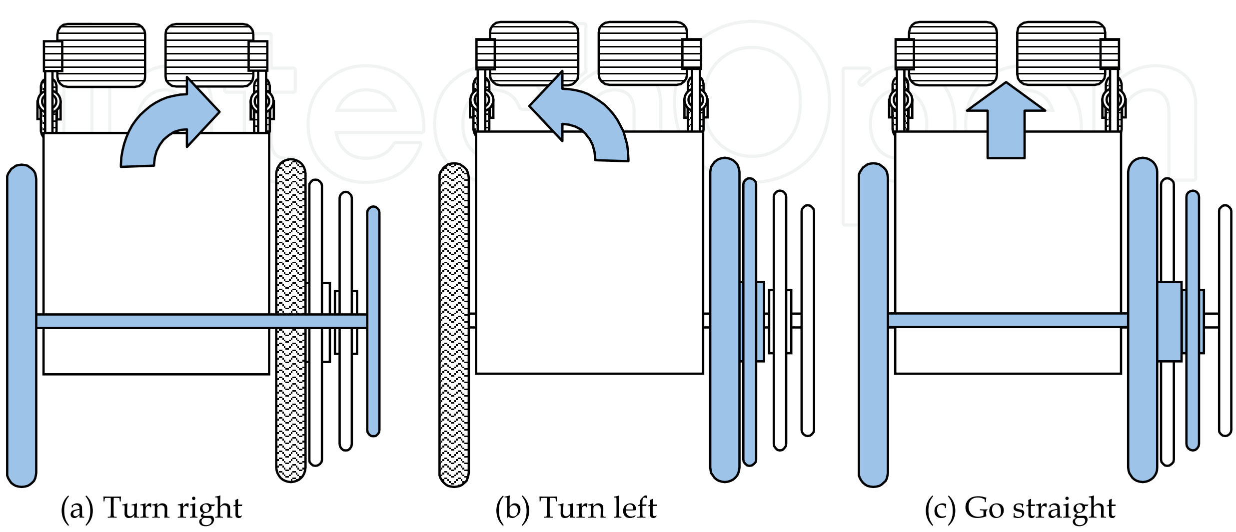


Fig.3. Manipulations for each direction

2.2. Assist unit

Figure 4 shows the assist unit, which realizes assist functions such as “power assist”, “maximum velocity limiting on the downward slop” and so on. This assist unit is composed of a DC motor (150W), an electromagnetic brake, a stepping motor and so on. Two rubber rollers, gripping wheels, transmit the assist torque from the DC motor to wheels. The assist unit has a link mechanism which is shown in Fig. 5. By using the link mechanism, which is drived by the stepping motor, when the wheelchair dose not need the assist torque by the DC motor or the brake torque by the electromagnetic brake, rubber rollers separate from the wheel, as shown in Fig. 6(a). Hence, the DC motor and rubber rollers don't yield the rolling resistance. On the other hand, while the wheelchair needs the assist torque by the motor, rubber rollers grip the wheel, as shown in Fig. 6(b). Hence, the DC motor can give the assist torque to the wheelchair. When the wheel is fixed, rubber rollers grip the wheel and the electromagnetic brake stops the rotation of the wheel. By using these three modes, we realize “the power assist function”, “the reverse prevention function” and so on. As shown in Fig. 7, this assist unit is independently equipped with both wheels.

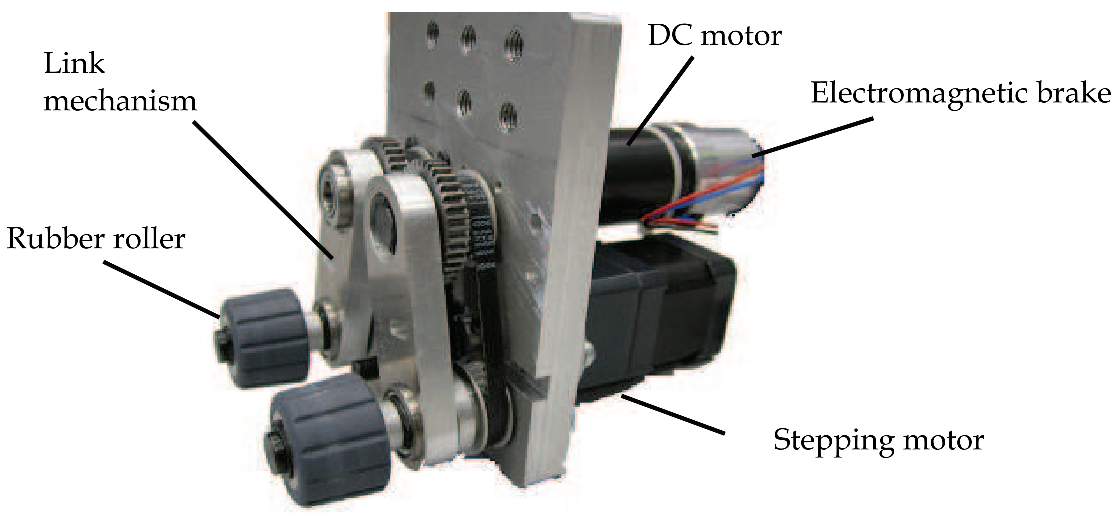


Fig.4. Assist unit

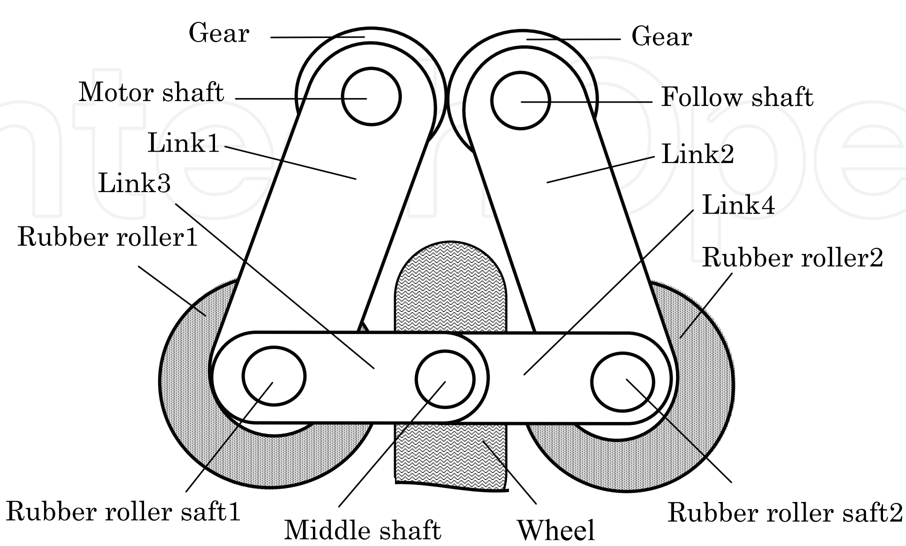
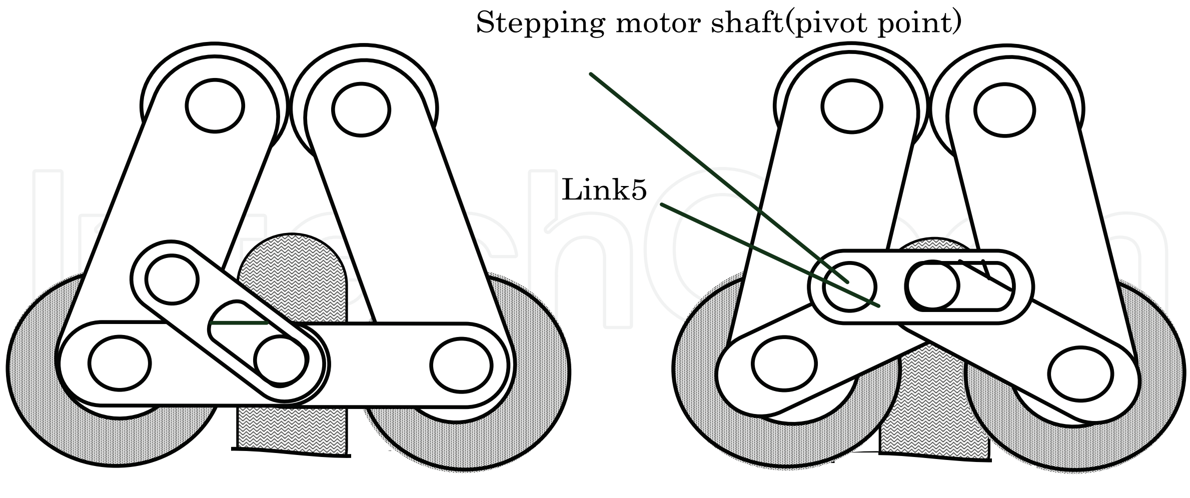


Fig.5. Link mechanism in assist unit



(a) Pull off state of rubber rollers (b) Put on state of rubber rollers

Fig.6. Manipulation of link mechanism

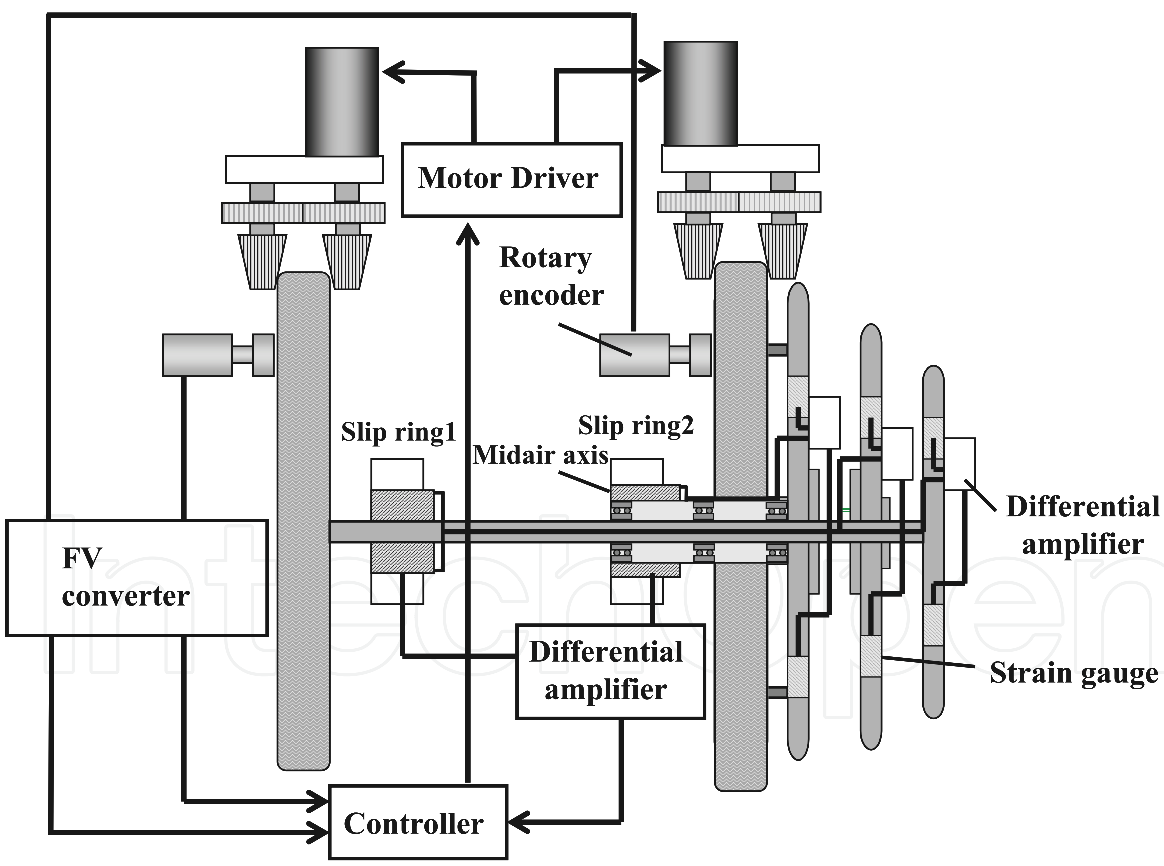


Fig.7. Structure of assist system

2.3. Assist system

Figure 7 shows the structure of the assist system, which includes a manipulation mechanism presented in section 2.1 and assist units presented in section 2.2 and, furthermore, includes some observation and control devices. “Manipulation torque inputted by using the hand rim” is acquired by the strain gauge mounted on hand rims. The detection range of the manipulation torque is from -60[Nm] (backward direction) to +60[Nm] (forward direction). This manipulation torque changes into the output voltage by using the bridge circuit of strain gauges, whose range is 0[V] (-60[Nm] backward direction) to 5[V] (60[Nm] forward direction). Slip rings are used to acquire the signal from the rotating part, namely, hand rims. The rotary encoder installed in right and left wheels acquires the rotation velocity of right and left wheels. The output of the rotary encoder is inputted to the FV converter. The output of FV converter for the forward velocity is 0[V] in the case where the forward velocity is 0[m/s] and the output of FV converter for forward velocity is 5[V] in the case where the forward velocity is 2.78[m/s]. The backward velocity is also observed by using the FV converter for backward velocity. The left and right wheels both have this velocity observation device. Based on these manipulation torques and rotation velocities of left and right wheels, various assist commands are automatically produced by the controller, built on a microcomputer H8/3048. The microcomputer controls the assist torque provided by the DC motor and ON-OFF of electromagnetic brake. Figure 8 presents the system flow of the assist system. The signal giving manipulation torques and rotation velocities are the analogue voltage, hence, these observation data are acquires through the A/D converter on the microcomputer. Motor drivers, electromagnetic brakes and stepping motors are controlled by commands, which are outputted from the D/A converter and the digital I/O ports.

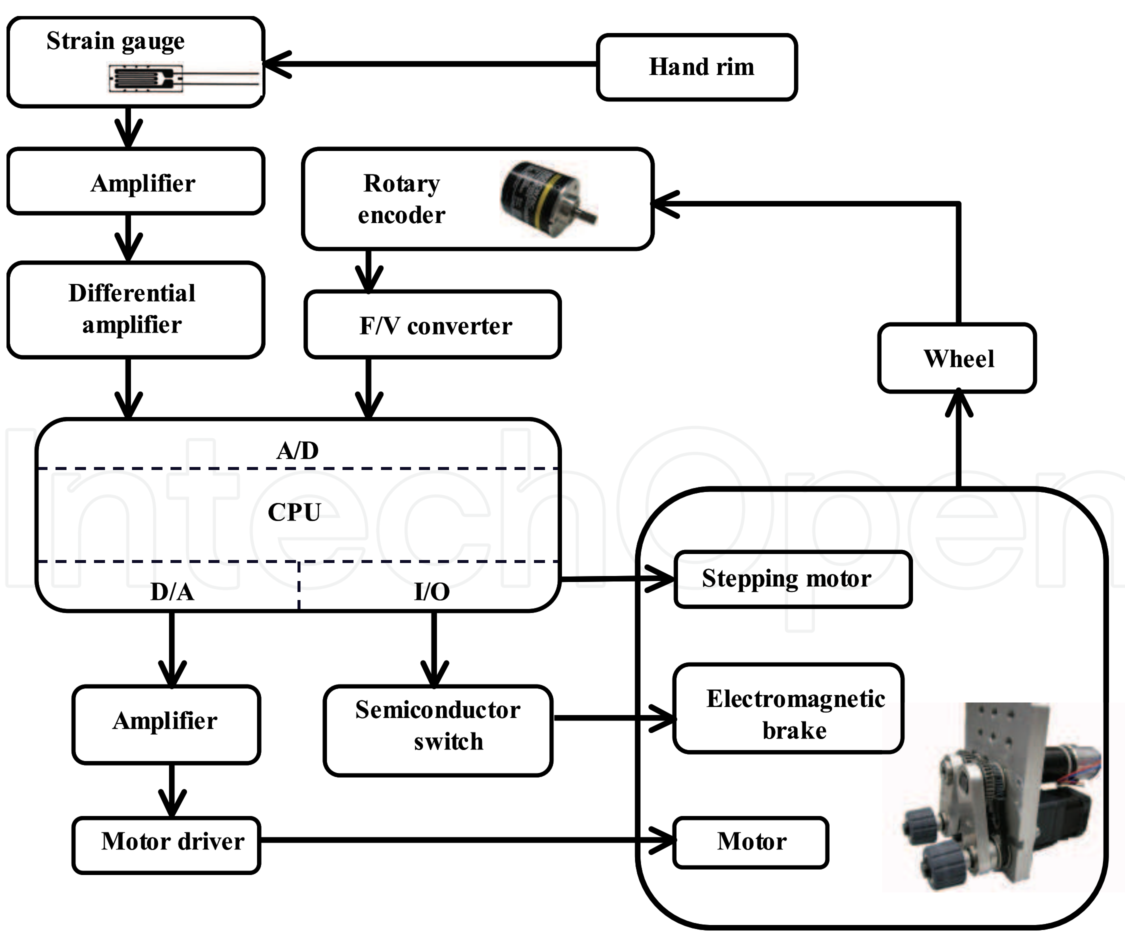


Fig.8. System flow of assist system

3. Assist functions and their evaluation

The manipulation mechanism and the assist unit, explained in Section 2, give the following four assist functions: the power assist function, the maximum velocity limiting function on the downward slope, the reverse prevention function on the upward slope and the function for turning on the spot. We consider that every four assist functions are required, in order to make the running ability of the one-hand drive wheelchair similar to the usual both hand drive wheelchair. The algorithm of each assist function is explained below and the effectiveness of assist functions is confirmed through experiments using a prototype, produced in our research group.

3.1 The power assist function

1) Aim of Assist

In order to realize the mobility similar to usual wheelchair manipulated by both hands, the manipulator's load of the one hand drive wheelchair for rotating handrim is heavy. For instance, the extremely heavy load is needed when the wheelchair goes straight on the upward slope. Therfore, in order to reduce the manipulator's load, the power assit function is indispensable to the one hand drive wheelchair.

2) Experimental Results of Long Distance Running

The purpose of the experiment is to evaluate the ability of the developed one hand drive wheelchair for the long distance running in the outdoor. The running route is on a flat ground in the outdoor and the distance of running is about 510[m] (from the entrance of school of engineering to the bus stop in our university). Table 2 shows experimental results, given by the one-hand drive wheelchair with the power assist function and a usual both hand drive wheelchair. Manipulators are five healthy men (from 22 to 24 years old). In this experiment, the assist torque is determined as

Assist Torque = Manipulation Torque.

Subject	Normal wheelchair [s] (a)	Developed one hand drive wheelchair [s] (b)	(b)/(a)
A	477	565	1.18
B	448	569	1.27
C	422	524	1.24
D	556	700	1.26
E	501	619	1.24
Average	480.8	595.4	1.238

Table 2. Experimental results of long distance running

The running time and the ratio are demonstrated in Table 2. Table 2 shows that, by using the normal wheelchair, subjects runs with the velocity about 4.04 [km/h] (average value) and, by using the developed one hand drive wheelchair, subjects runs with the velocity about 3.08 [km/h] (averaged value). Namely, about 75 percent of the velocity, that is obtained by using the normal wheechair, can be realized by the developed one hand drive wheelchair. Considering that human's average walking velocity is 4[km/h], this result shows the usability of the developed manipulation mechanism and power assist function. Furthermore, the running time of the one hand drive wheelchair doesn't take ten minutes. From these results, it is confirmed that we can use the developed one-hand drive wheelchair for a long distance running in the outdoor.

3.2 The maximum velocity limiting function on the downward slope

1) Aim and Assist Action

The running velocity of wheelchairs becomes excessive, when the wheelchair freely runs on the downward slope. Hence, manipulators keep on giving the manipulation torque in the opposite direction to the hand rim. Furthermore, the velocity and the direction of wheelchair must be adjusted with the suitable state by using both hands in usual wheelchairs. This manipulation increases the physical and the mental load of manipulators, especially, in the case where

– the distance of the downward slope is long.
– the downward slope is steep.

In the one hand drive wheelchair, the load becomes too heavy or it is impossibe to run the steep downward slope. Therefore, in order to reduce the manipulator’s physical load and to achieve a safe running on the downward slope, “the maximum velocity limiting function on the downward slope” is added to the one hand drive wheelchair. Figure 9 shows the relation between “the manipulation torque and the velocity of the wheelchair” and “the maximum velocity limiting function”. The limit of the wheelchair’s velocity on the downward slope is set as 0.56[m/s] ≅ 2.0[km/s]. If no manipulation torque is given and the velocity of wheelchair increases and exceeds this limit of velocity 0.56[m/s], then the DC motors are automatically used as a deceleration brake to decelerate the velocity of the wheelchair.

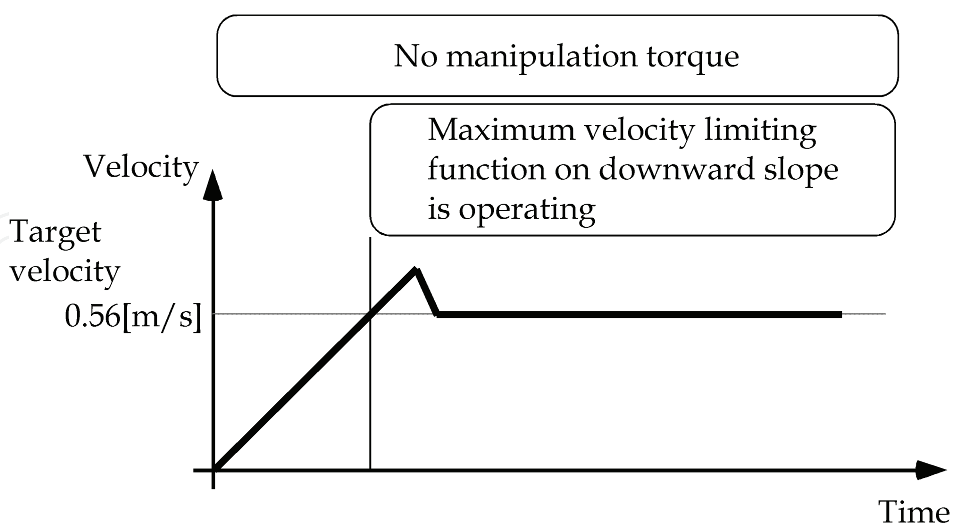


Fig.9. Assist action of the maximum velocity limiting function on the downward slope

In this investigation, we adopt PI controller for “the maximum velocity limiting function on the downward slope”. The block diagram of the control system is shown in Fig.10. The propotional gain K_P and the integral constant K_I of the controller in Fig.10 are determined as

$$K_P = 3, \quad K_I = 3$$

by using simulation studies and experimental results.

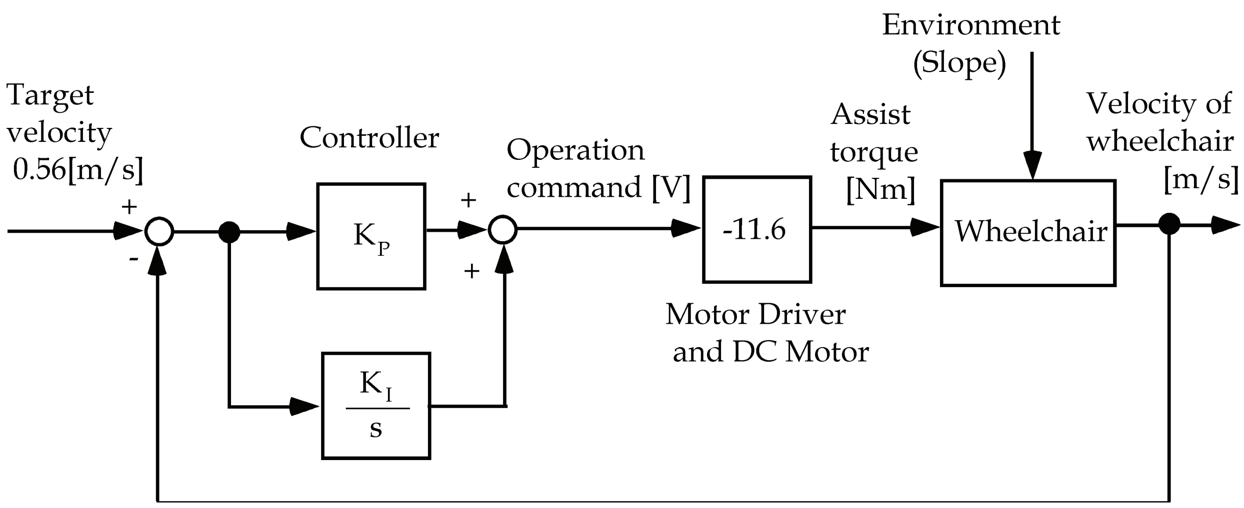


Fig.10. Block diagram of control system of the maximum velocity limiting function on the downward slope

2) Experimental Result of Maximum Velocity Limiting Function on Downward Slope

In order to confirm whether the running velocity in the downward slope can be maintained to 0.56[m/s] by using the maximum velocity limiting function, experiments using a prototype are carried out. The running velocity of wheelchair is measured, when the wheelchair runs from the top of the downward slope without and with "the maximum velocity limiting function". The length of the slope is about 5[m] and the average value of the slope angle is about 4.5[deg.] (See Fig.11 and Table 3). Subject is a healthy man (58[kg] in weight, 21 years old). Figure 12 shows the result of experiment.

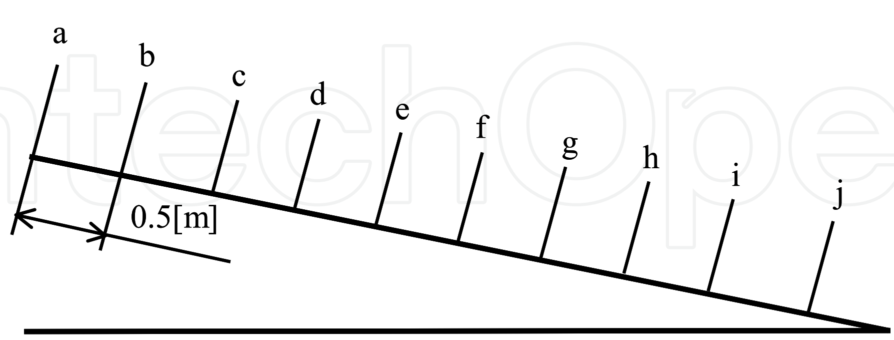
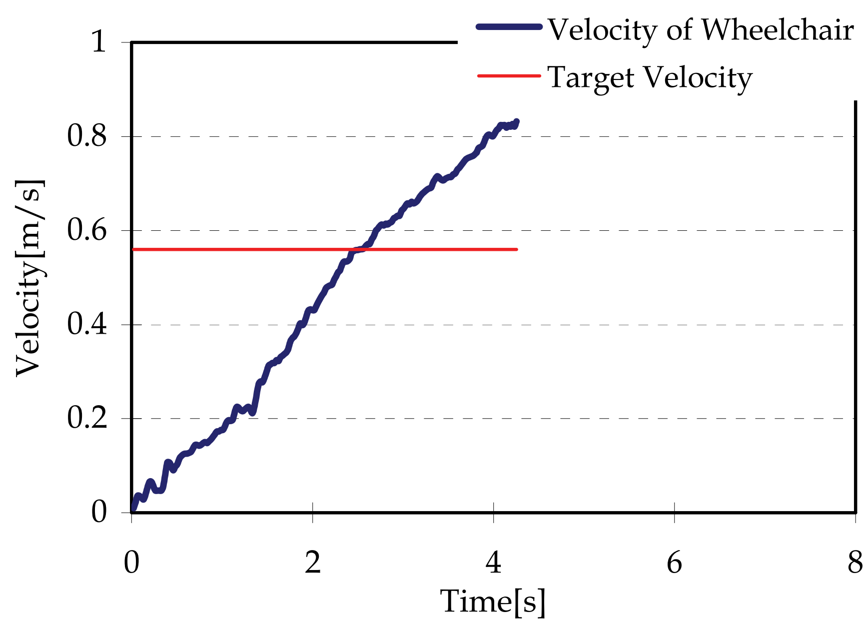


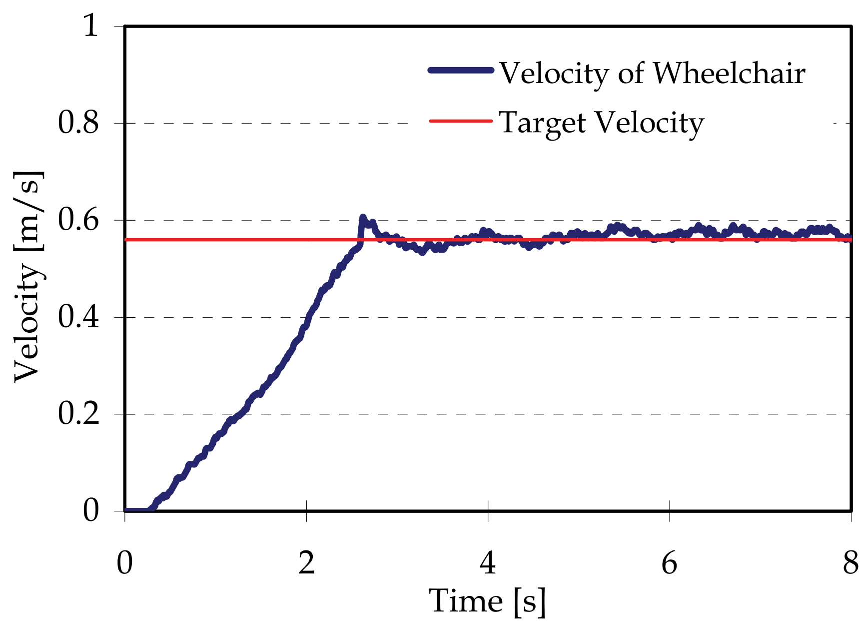
Fig.11. Experimental environment of the downward slope

	a	b	c	d	E	f	g	h	i	j	Average
Angle [deg.]	3.5	4	4.5	4.5	5	5.2	5	5	4.5	4	4.5

Table 3. Angle of each measuring point of the downward slope



(a) Without maximum velocity limiting function



(b) With maximum velocity limiting function

Fig.12. Experimental result (average slope angle 4.5[deg.])

When the maximum velocity limiting function does not act, from the result of experiment shown in Fig.12(a), the running velocity exceeds the target velocity 0.56[m/s] and accelerates to about 0.82[m/s] at the end of the downward slope. On the other hand, adding the maximum velocity limiting function, as shown in Fig.12(b), the velocity of wheelchair can be controlled at constant velocity almost 0.56[m/s]. The velocity 0.56[m/s] is half of the average person's walking velocity, namely, the manipulator can run safely on the downward slope. Moreover, because this maximum velocity limiting function permits to decelerate the wheel speed under 0.56[m/s], the manipulator can freely changes the direction of the wheelchair by decelerating the wheel in one side. Thus, the maximum velocity limiting function achieves a safe running on the downward slope and the manipulator's physical and mental load are reduced.

3.3 The reverse prevention function on the upward slope.

1) Aim and Assist Action

In the case where the wheelchair runs on the upward slope, if the manipulator doesn't keep giving the operation torque to the hand rim toward the upward direction, the reverse running occurs. Because the reverse running is dangerous for manipulators, the safe running on the upward slope is realized by using "the reverse prevention function". The relation between "the manipulation torque and the velocity of the wheelchair" and "the power assist function and the reverse prevention function" is shown in Fig.13. Namely, the power assist function and the reverse prevention function act according to rules depicted in Fig.13.

After the reverse prevention, new rules concerned with the power assist function of turn left or turn right is needed, because, according to the rules on the flat ground concerned with the power assist function of turn left or turn right, the wheel, that manipulator doesn't give the torque, becomes free and the wheelchair turns on the upward slope. Table 4 summarizes rules of the power assist and the reverse prevention after the reverse prevention starts. For example, consider the case where the manipulator gives the manipulation torque to the right wheel for turning left after the reverse prevention. In this case, the reverse prevention function keeps on locking the left wheel, and the right wheel rotates by the manipulation torque and the assist torque. This situation is continued while the manipulation torque for the right wheel is given. If this torque disappears, then a right wheel is locked again by the reverse prevention function. The change of direction after the reverse prevention at the upward slope is realized by such a series of assist actions and the operability on the upward slope is improved. By the "go straight" operation, the reverse prevention mode is finished.

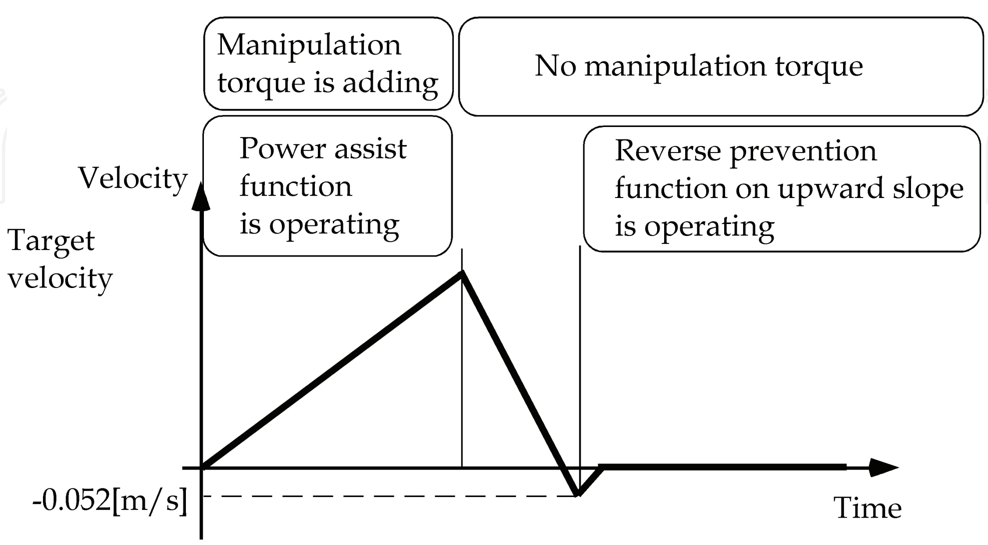


Fig.13. Assist action of the reverse prevention function on upward slope

Manipulation Torque	Left Wheel			Right Wheel		
	Brake	Roller	Motor	Brake	Roller	Motor
Nothing	ON	ON	Without Assist	ON	ON	Without Assist
Go Straight	OFF	ON	Assist	OFF	ON	Assist
Turn Right	OFF	ON	Assist	ON	ON	Without Assist
Turn Left	ON	ON	Without Assist	OFF	ON	Assist

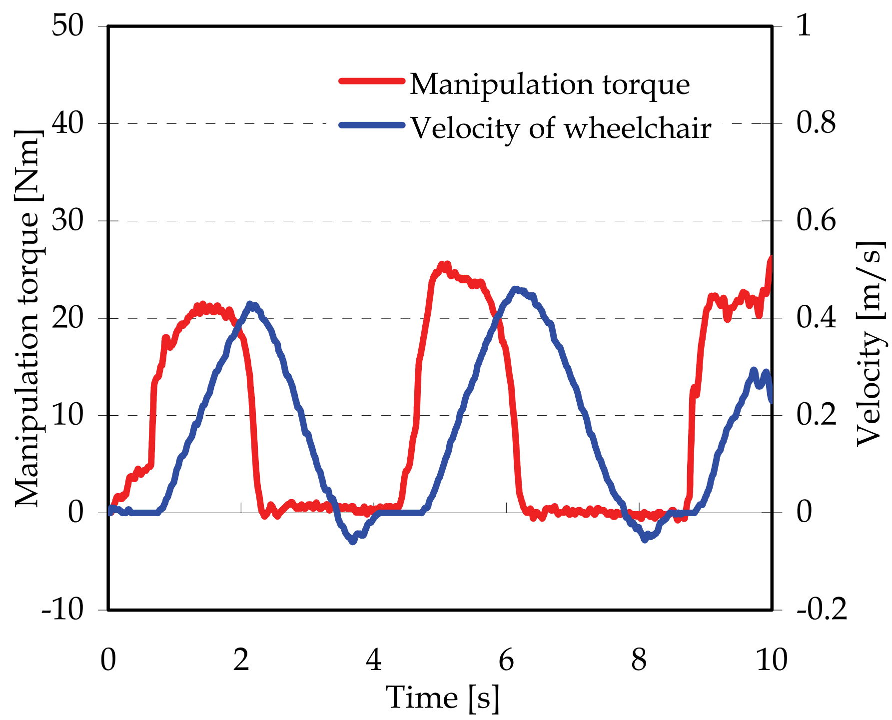
Table 4. Assist action after the reverse prevention

2) Experimental Result of Reverse Prevention Function on Upward Slope

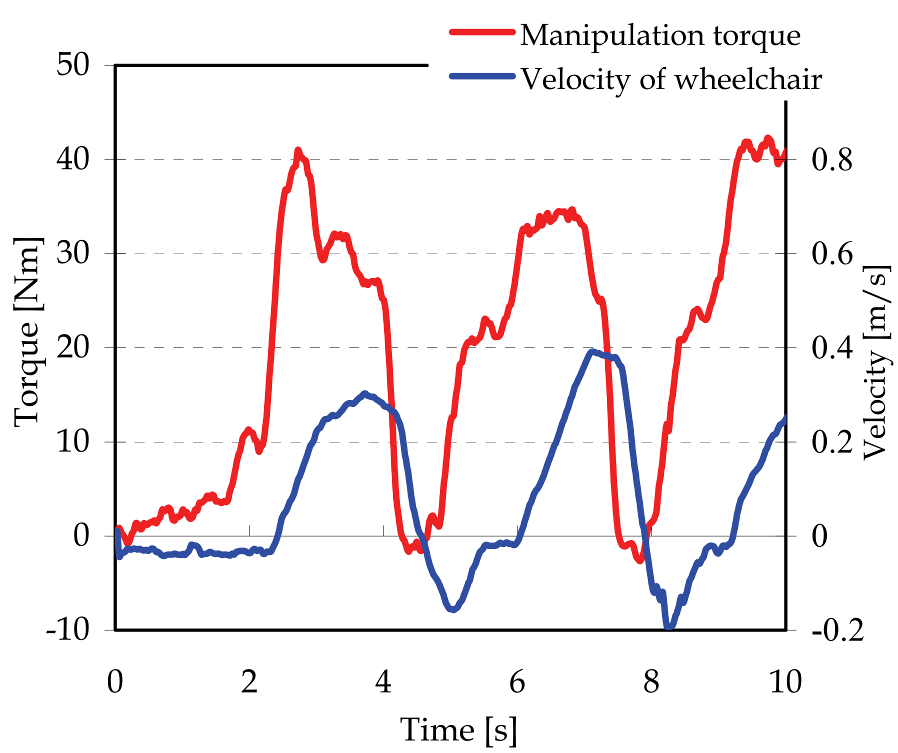
The effectiveness of the reverse prevention and the power assist function are confirmed by experiments. A manipulator gives the manipulation torque in forward direction to the hand rim for going straight and the wheelchair runs four upward slopes where the angle of the upward slope is from 3 to 6[deg.]. The running velocity and the manipulation torque are measured with and without "the power assist and the reverse prevention function". A manipulator is a healthy man (23 years old, 63[kg] in weight). Figure 14 shows the result of running in the case where the angle of upward slope is 5[deg.]. As shown in Fig.14, by adding the power assist function, the maximum manipulation torque, that manipulator gives to the hand rim for going straight, can be reduced to about 60 percent and the maximum running velocity increases about 1.2 times. The fact, that the maximum running velocity increases though the maximum manipulation torque decreases, indicates that manipulator's physical load on running upward slope is reduced.

In this investigation, a time from the beginning of the reverse running to the stopping of the wheelchair by the reverse prevention function is called "Stopping Time", and the maximum velocity in reverse running is called "Maximum Reverse Velocity". In Fig.15, the definition of "Stopping Time" and "Maximum Reverse Velocity" is illustrated. Experimantal results of "Stopping Time" and "Maximum Reverse Velocity" are demonstrated in Table 5, where subjects are three helthy men. In case of acting the reverse prevention function, the maximum value of the stopping time is 0.95[s] and the maximum value of reverse running velocity is 0.18[m/s] as shown in Table 5. The wheelchair stops surely on the upward slope by the aid of the reverse prevention function, as shown in Fig.14(a). On the other hand, without the reverse prevention function, even in the case where the slope angle is 5 [deg.], the maximun value of reverse running velocity is about 0.2[m/s] though the manipulation of the hand rim becomes extrimely quick, as shown in Fig.14 (b). From these facts, it is shown that the safe running on the upward slope is realized and the manipulator's mental load is reduced by the reverse prevention function. In addition, it is easy to freely change the direction of the wheelchair while the wheelchair stops.

As mentioned above, the manipulator's physical load can be reduced by the power assist function and the mental load can be reduced by the reverse prevention function. Thus, the comfortable drive on the upward slope is realized.



(a) With Assist Function



(b) Without Assist Function

Fig.14. Experimental Results of reverse prevention function (Slope Angle 5 [deg.])

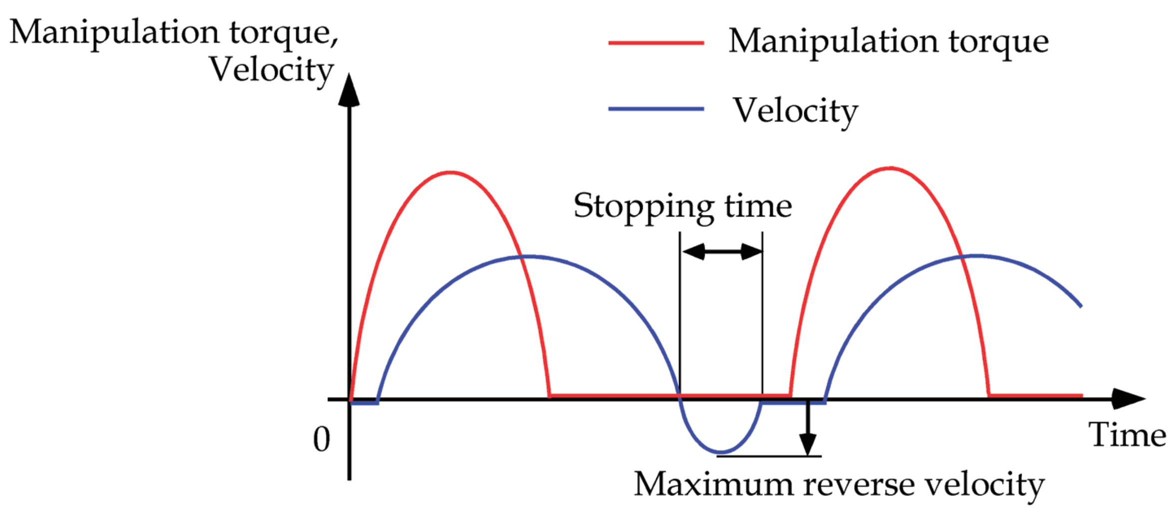


Fig.15. Definition of stopping time and maximum reverse velocity

		Slope angle [deg.]			
Subject Weight [kg]		3	4	5	6
A 61[kg]	Stopping time [s]	0.8	0.82	0.89	0.95
	Maximum reverse velocity [m/s]	0.06	0.09	0.11	0.18
B 61[kg]	Stopping time [s]	0.78	0.8	0.92	0.91
	Maximum reverse velocity [m/s]	0.07	0.09	0.10	0.15
C 85[kg]	Stopping time [s]	0.78	0.86	0.91	0.94
	Maximum reverse velocity [m/s]	0.06	0.09	0.14	0.15

Table 5. Stopping time and maximum reverse velocity until completing reverse prevention

3.4 The function for turning on the spot

1) Aim and Assist Action

In order to change the direction of wheelchair in narrow place and passage, the conventional both hand drive wheelchair usually turns on the spot. The manipulation for turning on the spot of normal wheelchairs is easy, because it is possible to rotate right and left wheels opposite direction at the same time by using both hands. However, for turning on the spot, the one hand drive wheelchair with a triple rings has to manipulate multi-step process like a car, which changes the direction in narrow place. Hence, we consider that it is effective to implement the assist function for turning on the spot to the one hand drive wheelchair.

A wheelchair turns on the spot, when right and left wheels rotate opposite direction at the same time, for example, the rotation direction of right wheel is forward and the rotation direction of left wheel is backward. Furthermore, it is desirable that right and left wheels rotate with same velocity. However, the motor driver in the assist unit of developed wheelchair does not act the velocity control mode, but acts the torque control mode. Namely, we cannot directly operate the velocity of wheels. Therefore, we obseve rotation angles of right and left wheels by using rotary encoders and we construct control system for the rotation angle of right or left wheel. The aim of the control system is to equalize the rotation angle of both wheels. The target value of the control system is the rotation angle of wheel, which rotates by manipulator and is called "input wheel". On the other hand, the opposite wheel is driven by the assist unit with reverse direction and is called "auto following wheel". Figure 16 shows the basic mechanism for turning on the spot. Figure 17 shows a block diagram of control system for turning on the spot. Suitable control scheme, implemented on controller, generates good performance of a function for turning on the spot.

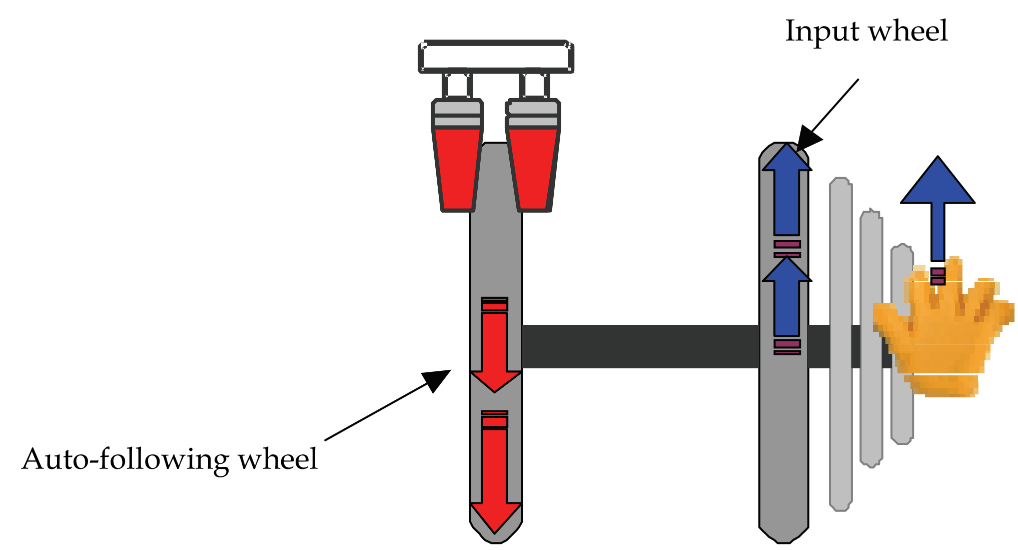


Fig.16. Method for turning on the spot

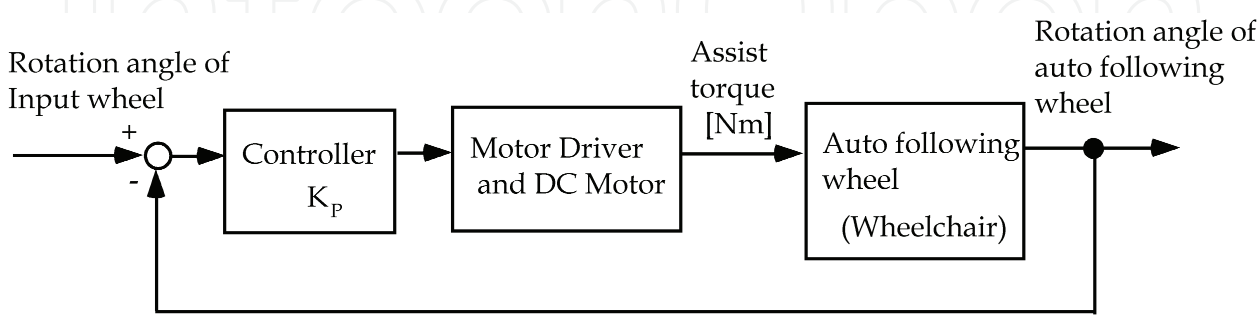


Fig.17. Block diagram of control system for turning on the spot

2) Experiments using Prototype

In order to realize the assist function for turning on the spot, we produced the simulator for one hand drive wheelchair with a triple ring, and simulated the motion of it in turning on

the spot. The proportional plus integral action of the controller was tried, but we could not observe any useful effect of integral action. Hence, in this work, we decide to adopt proportion control for turning on the spot from simulation studies.
In this subsection, experimental results using the prototype are demonstrated. Preliminarily experiments clarify the following problems:
In the case where the manipulator finishes the manipulation of hand rim and some deviation of rotation angle of two wheels remains, if the auto-following wheel keeps rotating, then it is difficult for the manipulator to stop the wheelchair at the target direction.
This phenomenon gives a manipulator unpleasantness. To solve the problems, we built the algorithm that the assist torque by the motor sets 0 when the manipulation of hand rim is over. As a result of this algorithm, manipulator can turn on the spot comfortably without feeling unpleasantness. This algorithm contradicts the purpose of controller, whose purpose is to decrease the deviation of rotation angle of two wheels. However, we think that comfortable feeling of the manipulator is more important.
From simulation results and experiments by using the prototype, we obtain that the suitable gain is $K_P = 5.0$ to 6.0. Subject is a healthy man (60.5[kg] in weight, 23 years old). Figure 18 shows the transition of the rotation angle of the input wheel and the auto-following wheel in the case where K_P =5.0. Figure 19 shows a movement of the wheelchair turning 180 degree. Rectangles with a line mark, which indicates the front of the wheelchair, show an outline of the wheelchair. Blue rectagle shows the start state and red rectagle shows the end state. The wheelchair turns inside area of a circle with radius 0.7[m]. The average displacement of middle point of both wheels is 135[mm]. For turning on the spot, we think that this performance is practical.

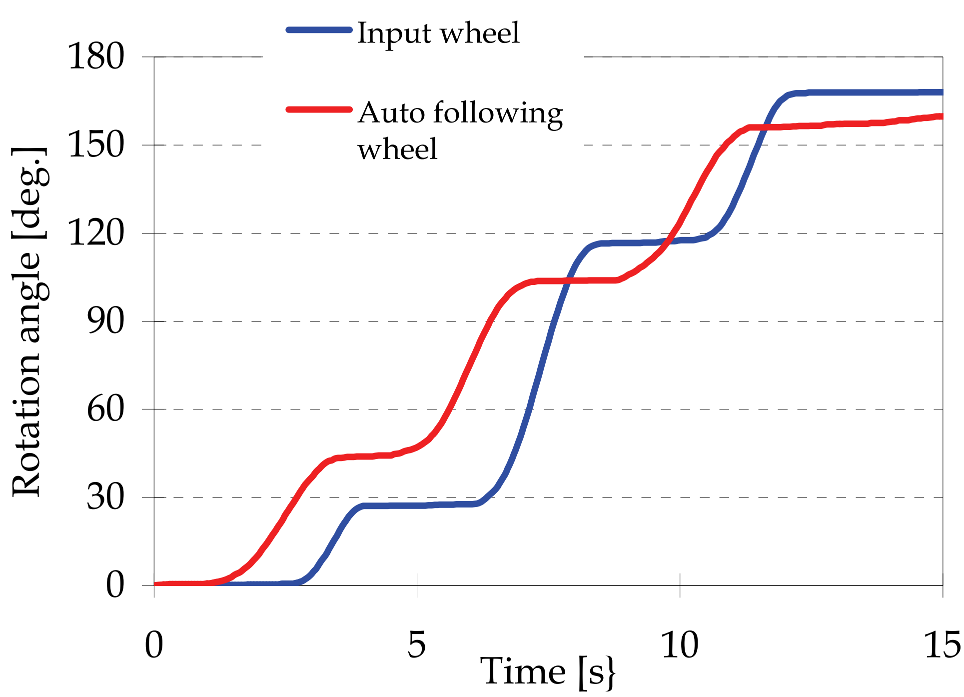


Fig.18. Rotation angle of input and auto following wheels

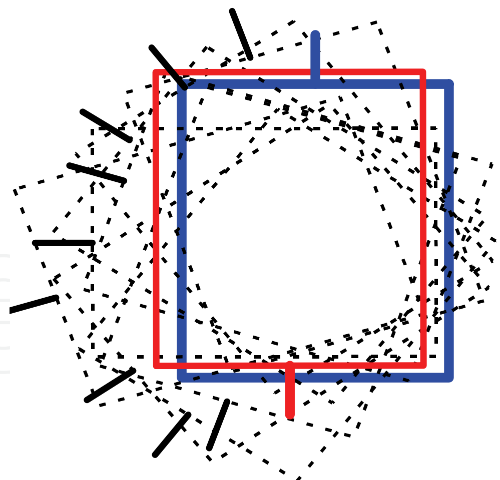


Fig.19. A movement of wheelchair in trun on the spot

4. Conclusion

In this investigation, a one-hand drive wheelchair has been proposed which has new manipulation mechanism with a triple ring and four assist functions such as “the power assist function”, “the maximum velocity limiting function on the downward slope”, “the reverse prevention function on the upward slope” and “the function for turning on the spot”. It was shown that these assist functions reduce the manipulator's physical and mental load and realize the safe drive in the outdoor.

If the manipulator's remained ability is efficiently used, then the welfare robot may be utilized as the effective rehabilitation tool. From such a point of view, as future problems, we consider that it is important to construct the power assist function, which adapts the ability of manipulators and the change of environments. Furthermore, now, we are trying to equip more excellent control for the turning on the spot, which yields more useful motion for our wheelchair users.

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The aim of this book is to provide new ideas, original results and practical experiences regarding service robotics. This book provides only a small example of this research activity, but it covers a great deal of what has been done in the field recently. Furthermore, it works as a valuable resource for researchers interested in this field.

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