Wheelchair Assistance with Servo Braking Control Considering Both the Gravitation-Negating and the User's Intention-based Assistance

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Abstract: This paper proposes a novel driving-assistance system for manual wheelchairs with consideration of both uphill and downhill conditions. On an inclined road, there is a high risk of a wheelchair moving in a direction that the user does not intend. In our previous works, the user has driven our assistive wheelchair in the usual manner. Our proposed system estimates its user's intentions and passively works to complement their intentional force by negating the wheel traction that is generated by the road's inclination using only the servo brakes on each wheel. Nevertheless, in some cases, our system fails to assist the driving motion of its user because the user drives the wheelchair in several ways that depend upon the environmental condition, for example, during uphill or downhill driving. The required assistance is not constant according to the situation, and it is difficult to assist with one wheel-control algorithm. Therefore, in this study, we first investigate the required assistance condition according to the driving situation by conducting a preliminary experiment with wheelchair users. Considering the results of this investigation, we then propose a novel user interface that intuitively shows the system information and a wheel-control algorithm that selects a suitable wheel controller according to the driving situation.

1 INTRODUCTION

Wheelchairs are widely used by mobility-impaired people in their daily activities. In recent years, many serious wheelchair-related accidents have been reported. In Japan, more than 80% of wheelchair accidents are caused by environmental hazards (National Consumer Affairs Center of Japan, 2002). The inclination of a sidewalk poses a potentially high risk for a wheelchair user. The Japanese government permits an incline in a sidewalk of up to 5°(Japan Institute of Construction Engineering, 2008). This inclination could potentially lead to a wheelchair deviating from the sidewalk into the roadway, which may result in collisions between wheelchairs and cars. Therefore, a wheelchair driving-assistance system is important for use on an inclined sidewalk.

In previous research, many assistive technologies for wheelchairs have been developed. Several disabled people traditionally use power wheelchairs (Yamaha Motor Co., Ltd., 2014) and previous researchers have attempted to develop assistance functions by adding wheels with actuators and controlling them using robotic technology such as motion control (Miller and Slack, 1995), sensing, and artificial intelligence (Katevas et al., 1997) (Murakami et al., 2001). These intelligent wheelchairs provide several functions such as suitable motion, obstacle avoidance, and navigation; thus, they provide a maneuverable system. However, many wheelchair users have the upper body strength and dexterity to operate a manual wheelchair. For these wheelchair users, such systems may be excessively expensive and unnecessary.

Therefore, we have developed a passive driving-assistance system for a manual wheelchair that uses servo brakes (Chugo et al., 2015) (Chugo et al., 2013). This system incorporates the concept of passive robotics (Hirata et al, 2007). Our proposed system passively operates on the basis of external forces imposed by its user. No actuators are required

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in our system; it uses servo brakes, which can control the brake torque, to produce the desired motion according to the applied force and reference track. In our previous research, we have developed two wheel-control algorithms. One estimates the intended direction of a manual wheelchair user by determining the characteristics of hand motion and maintains it as the reference track (Chugo et al., 2013). The other simply negates the effect of gravitational force on the wheelchair on an inclined road (Chugo et al., 2015).

However, in some cases, these wheel controls cannot assist in wheelchair driving, because users row in different ways according to the environmental situation, resulting in different required assistance conditions. In particular, when going uphill or downhill, a wheelchair driver uses completely different driving techniques to control their wheelchair. Under these conditions, our controller cannot use only one wheel-control algorithm. Therefore, in this study, we first investigate how users drive their wheelchairs according to the environmental situation and what conditions are required for assisting these techniques. Second, using the results of this investigation, we propose a novel human interface based on a hand brake and a wheel-control scheme that combines a gravitational negating control algorithm and a user's intention-based control algorithm. Using this idea, our proposed wheelchair can continuously assist users in driving on uphill or downhill roads.

This paper is organized as follows. We introduce our assistive wheelchair and its problem specification in section 2. In section 3, we propose a novel human interface for our system and in section 4, we propose an improved driving-assistance scheme based on the environmental situation. We show the results of experiments using our prototype in section 5. Section 6 presents our conclusions.

2 PROBLEM SPECIFICATION ON OUR SYSTEM

2.1 System Configuration

Figure 1(a) shows our prototype wheelchair, which utilizes a type of servo brake known as a powder brake. Powder brakes are widely used in industrial applications and their cost is low compared with other servo brakes. The powder brake (Fig. 1(b)) (ZKG-YN50, Mitsubishi Electric Corp.) generates enough brake torque to stop a wheelchair moving at 4 km/h, and containing a 100 kg user within 1 s. Our prototype is based on a normal manual wheelchair (BM22-42SB, Kawamura Cycle Co. Ltd.) and fulfills the ISO7193, 7176/5 standards. Furthermore, our prototype utilizes an encoder in each wheel to measure the wheel-rotation velocity and two tilt sensors in its body to measure roll and pitch angle (see Fig.3).

(a) Overview (b) Installed Servo Brake

Figure 1: Our Prototype.

2.2 Problem Specifications in Daily Usage with Our Assistive Wheelchair Prototype

2.2.1 Preliminary Experimental Setup

Eight subjects attempted to navigate the test course (Fig. 2) with our assistive wheelchair in order to investigate how users drive their wheelchairs according to different environmental situations. The length of this course is about 1.5 km. The experimental field is on the Kobe-Sanda Campus, Kwansei Gakuin University, Japan. Our campus is located atop a hill and this test course has uphill and downhill roads to easily investigate problems with our assistive system.

In this preliminary experiment, our system offers assistance using two wheel-control algorithms; one is a gravitation-negating control algorithm (Chugo et al., 2015) and the other is a user's intention-based control algorithm (Chugo et al., 2013). In both cases, our wheelchair system records all logs measured by the equipped sensors and outputs brake traction information. Furthermore, we record the subject's motion with a video camera during this experiment. This preliminary experiment includes eight subjects (Table 1), six wheelchair users and two able-bodied people including a nursing specialist and a student. Each subject tries one round using each algorithm.

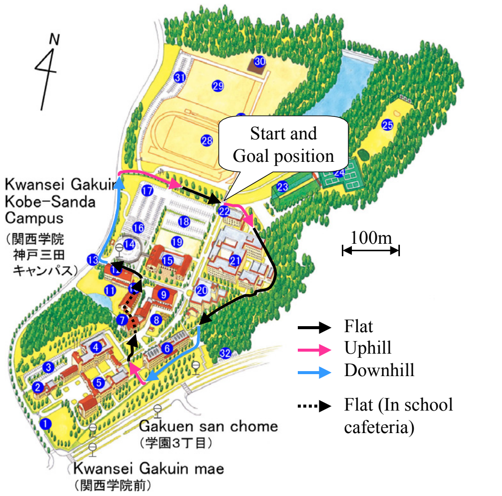


Figure 2: A test course for the preliminary experiment.

Table 1: Subjects.

Subject	Age	Sex	Weight (kg)	Dominant hand	Wheelchair User*
A	66	Male	54	Right	Yes
B	72	Male	62	Right	Yes
C	68	Male	73	Left	Yes
D	67	Female	51	Right	Yes
E	74	Female	49	Left	Yes
F	35	Male	81	Right	Yes
G	39	Male	75	Right	No
H	21	Male	59	Right	No

* A subject who uses a manual wheelchair in daily life.

2.2.2 Problems at the User Interface

Table 2 shows major problems in this preliminary experiment. Problem nos. 1, 2, and 3, which occur in both control algorithms, can be solved by an update of the user interface. For example, as problem no. 1, the subject pushes the start button of our assistive wheelchair system and tries to row its hand rim. However, as the subject moves their hand from the button to the rim, the wheelchair moves under gravitational force on an inclined road. Furthermore, as problem no. 2, our system stops the wheelchair for safety reasons and an LED alerts the user that the emergency brake is now working. However, on many occasions, users cannot recognize this alert and try to continue to drive the wheelchair. Questionnaire results show that many subjects feel that the system information is indistinct.

2.2.3 Problems with the Gravitation-Negating Control Algorithm

Problem no. 4 is caused by the gravitation-negating

Table 2: Results of the Preliminary Experiment.

No	Control*	Major Problems (Times)	A	B	C	D	E	F	G	H
1	I	The wheelchair moves by the gravitational force after the user pushes the start button.	1	2	1	1	2	1	1	0
2	I	The user tries to move the wheelchair when our system stops by emergency brakes.	3	4	3	2	6	2	2	0
	G		2	3	3	2	4	3	1	1
3	G	The wheelchair moves by the gravitational force after the user switch off our system.	1	1	1	1	1	1	1	1
	I		1	1	1	1	1	1	1	1
4	G	The user feels the wheelchair is too heavy on an uphill situation. (In some cases, the user cannot go by own physical strength.)	6	7	7	10	14	4	6	3
5	I	The user cannot go the intended direction on a downhill situation.	8	7	8	9	11	6	7	1
6a	I	Our system misjudges its user's intention.	9	5	8	8	11	8	8	4
6b	I	Our system misapplies emergency brakes.	3	3	2	3	3	2	2	0

* G is a gravitation-negating control algorithm and I is a user's intention-based control algorithm.

wheel-control algorithm. This wheel-control algorithm negates the effect of the gravitational force on the wheelchair on an inclined road. When the user goes uphill on a road as in Fig. 3, the wheelchair moves to a lower direction because of the gravitational force on the inclined road. In this condition, without an assistance system, a manual wheelchair user should row the left wheel hard as $f_l > f_r$ in Fig. 3(a) (where f_r is the row force at the right wheel, f_l is the row force at left wheel.)

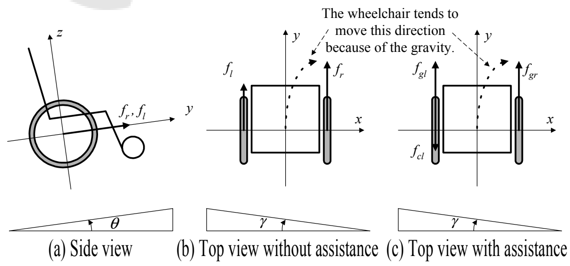


Figure 3: Brake tractions on an inclined road.

To negate this gravitational force, our wheelchair controls the servo brake according to (1) and (2), where (x_g, y_g) is the position of the center of gravity, m is mass of the wheelchair and T is the width between the wheels. Details regarding this calculation were given in our previous paper (Chugo et al., 2015).

$$f_{cr} = \frac{mg}{2}\sin\theta + \frac{y_g mg \sin\gamma}{\frac{T}{2} - x_g} \left(if\ |f_{cr}| > |f_{cl}|\right)$$
$$f_{cr} = 0\ (else) \tag{1}$$

$$f_{cl} = \frac{mg}{2}\sin\theta - \frac{y_g mg \sin\gamma}{\frac{T}{2} - x_g} \left(if\ |f_{cr}| < |f_{cl}|\right)$$
$$f_{cl} = 0\ (else) \tag{2}$$

In the case of Fig. 3(b), our system generates the brake traction, f_{cl}, on a left wheel to negate the gravitational force that leads the wheelchair to a lower direction (a right direction). In this case, our wheelchair user should row each wheel equally as $f_{gl} = f_{gr}$ (where f_{gr} is the row force at the right wheel with our assistance and f_{gl} is the row force at the left wheel with our assistance). This means that the user can row the wheelchair as if on a flat road; however, a passive system does not assist the force and the required row force increases with the brake force, f_{cl}, on the left wheel. Therefore, the users feel as if the wheelchair is too heavy in an uphill situation during this preliminary experiment.

2.2.4 Problems with the User's Intention-based Control Algorithm

Problem nos. 5, 6a, and 6b are caused by the user's intention-based algorithm. This algorithm uses knowledge of neurophysiology in the form of the minimum jerk trajectory model (Seki and Tadakura, 2004), which expresses the characteristics of hand motion. According to this model, hand motion is defined by equations (3) and (4), where x is the position of the wheelchair, x_0 is the initial position, and t_0 is the time when the user starts to row the hand rim.

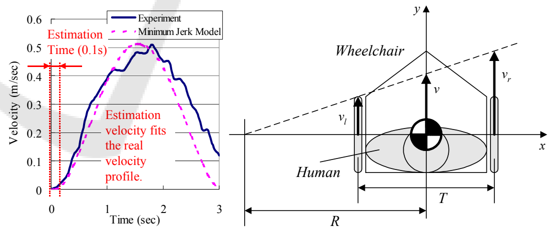
$$\begin{aligned} x(t) = {} & x_0 + (x_f - x_0)(6t_m^5 - 15t_m^4 + 10t_m^3) \\ & + \dot{x}_0 (t - t_0)(-3t_m^4 + 8t_m^3 - 6t_m^2 + 1) \\ & + \frac{\ddot{x}_0}{2}(t - t_0)^2(-t_m^3 + 3t_m^2 - 3t_m + 1) \end{aligned} \tag{3}$$

$$t_m = (t - t_0)/t_f \tag{4}$$

In this model, unknown values include the end position, x_f, and the final time, t_f. This algorithm estimates two values by determining the characteristics of hand motion when the user starts to row a hand rim (at 0.1 sec). Figure 4(a) shows the wheel velocity and the estimated movement using this model. According to this method, our system estimates the velocity of each wheel (v_r: velocity of the right wheel, v_l: velocity of the left wheel) and evaluates the intended direction of a manual wheelchair user as Fig. 4(b). After estimation, the system maintains the reference track that is estimated until its user rows the wheel again. Details regarding this algorithm were given in our previous paper (Chugo et al., 2013).

However, in problem no. 5, our system fails to assist when its user changes its movement direction on a downhill road. When a user goes down an inclined road, they turn by grasping a hand rim as a brake, rather than by rowing the hand rim. The control algorithm estimates the intended direction of the user only when they accelerate the wheelchair by their hand motion. When the user tries to change the running direction by grasping a hand rim, our assistive wheelchair controls the brake traction for maintaining the reference track when the user accelerates. Therefore, the assistance brake traction by this wheel controller interferes with its user's intention.

Problem nos. 6a and 6b are parameter-setting problems concerning how much error our system accepts at the estimation of a user's row motion. If our system does not accept a larger error, its wheel-control accuracy will increase; however, misjudgement will also increase because of a wheelchair vibration due to the unevenness of a road surface. Thus, this is a trade-off problem.



(a) Minimum jerk model (b) Kinematics of our wheelchair

Figure 4: A user's intention-based control algorithm.

3 PROPOSED USER INTERFACE

Based on the results of a questionnaire administered to the subjects and the opinions of the nursing specialist, the user interface of the assistive wheelchair should have the following conditions:

- The input device should be equipped around a hand rim, because the user activates the assistive device and then rows a hand rim.

Therefore, the distance between the input device and the hand rim should be small.

- Subjects require very little information, namely (1) whether a driving-assistive system works or does not work, and (2) whether an emergency brake works. Thus, its user interface should clearly show this information.

Therefore, we propose a novel user interface based on a hand brake as shown in Fig. 5.

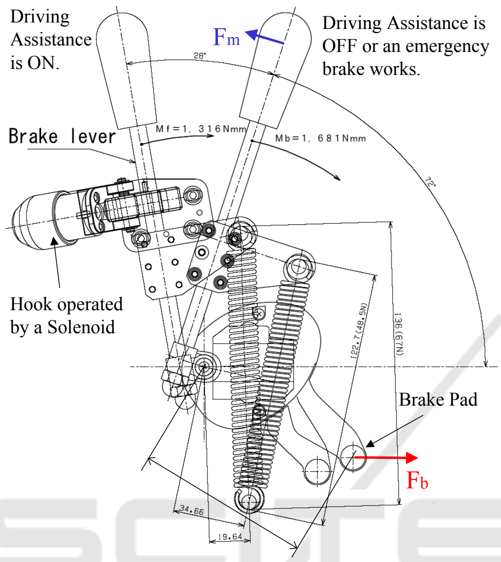


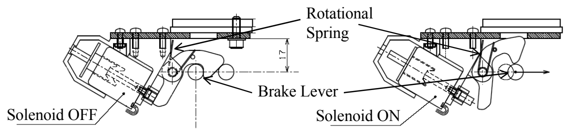
Figure 5: A proposed user interface based on a hand brake.

Usually, a wheelchair user takes off a hand brake when they drive, and then puts it back on when they stop. Therefore, our system can determine the intention of its user by the position of the hand brake. The proposed user interface is quite simple; when the user takes off a proposed hand brake interface, our system starts offering driving assistance, and when they put on a hand brake, our system stops offering assistance. Furthermore, when our system uses an emergency brake, this hand brake interface moves to the off position automatically so that its user can know easily that the emergency brake is working.

The proposed hand brake uses a spring as in Fig. 5. A spring connected to a hand brake pulls it into the off position. When a hand brake is in this position, it pushes the brake pad to the wheel with $F_b(\approx 14N)$, and this force is the same as that of a typical hand brake on a general manual wheelchair. When the user switches our system on, they turn the hand brake interface to the on position. There is a hook with a rotational spring (Fig. 6) at this position that holds this hand brake in place. The force required to turn our system off is $F_m(< 0.8N)$, which is a light load for a manual wheelchair user.

When our system uses an emergency brake, a solenoid equipped on a hook works as shown in Fig. 6(b) and releases the hand brake. The hand brake is backed to the off position by the spring. Figure 7 shows our prototype hand brake interface, which moves to the switch off position automatically.

The proposed hand brake interface works as a normal hand brake, meaning the user can simply replace an original hand brake on a general wheelchair with the proposed hand brake interface. This mechanism fulfills the ISO7193, 7176/5 standards and can be installed on a general wheelchair without any special reconstruction.



(a) The solenoid is off. (b) The solenoid is on.

Figure 6: A hook operated by a solenoid.

(a) The hand brake is off. (b) The hand brake is on.

Figure 7: A prototype of a proposed hand brake interface.

4 PROPOSED WHEEL CONTROL ALGORITHMS

4.1 Combination of the Gravitation-Negating Control Algorithm and the User's Intention-based Control Algorithm

From the results of a preliminary experiment, the major driving techniques and required assistance conditions for the wheelchair user are as follows.

- The wheelchair driving technique consists of two phases—a rowing phase and an inertial running phase.
- In the rowing phase, the load should be small, especially in an uphill situation. Based on the opinions of the wheelchair users in the preliminary experiment, no brake traction is felt to be better than gravitational cancellation.

The nursing specialist thinks that when the wheelchair goes in an uphill direction, its user concentrates on rowing its hand rim and cancels the gravitational force unconsciously due to inclination. The gravitational cancellation makes users spend their physical strength on the brake traction.

- In the rowing phase on a downhill situation, the gravitational force should be removed for safe driving. Based on the opinions of wheelchair users, on a downhill road, the required force to row is small and the wheelchair tends to deviate from the intended direction of its user due to gravitational force, and users report fearing this motion.
- In the inertial running phase, the wheelchair deviates from the intended track due to the gravitational force; therefore, driving assistance is necessary. However, in many cases, wheelchair users grasp the hand rim and change the running direction.

Therefore, we propose a novel wheel-control scheme that combines the gravitation-negating control algorithm and the user's intention-based control algorithm as follows.

- For reducing the required physical strength in an uphill situation, our system uses the user's intention-based control algorithm during the rowing phase.
- For the same reason, on a flat floor situation, our system uses the user's intention-based control algorithm during the rowing phase.
- To increase the driving ability in other situations, our system uses a gravitation-negating control algorithm during the rowing and inertial phases on a downhill road and the inertial phases on uphill and flat roads.
- For safety reasons, when the wheelchair accelerates in all situations, our system judges whether this acceleration is done by human rowing motion. If not, our system turns on an emergency brake.
- When our system switches to a different control algorithm, it controls the brake traction, τ_{ref} , according to (5) to prevent sudden change:

$$\tau_{ref} = \begin{cases} \dfrac{\tau_g(t_s - t)}{t_s} + \dfrac{\tau_i t}{t_s} & (if\ G \to I) \\ \dfrac{\tau_i(t_s - t)}{t_s} + \dfrac{\tau_g t}{t_s} & (if\ I \to G) \end{cases} \tag{5}$$

where τ_g is the brake-traction reference derived by a gravitation-negating control algorithm (Chugo et al., 2015) and τ_i is a reference by the user's intention-based control algorithm (Chugo et al., 2013). t_s is the switching time between the two control algorithms, which we set to 0.1 s in this study. $G \to I$ means that our system switches from a gravitation-negating control algorithm to a user's intention-based control algorithm.

Figure 8 shows the details of the proposed algorithm. Our system measures the road inclination, θ, using a tilt sensor and evaluates the uphill or a downhill condition.

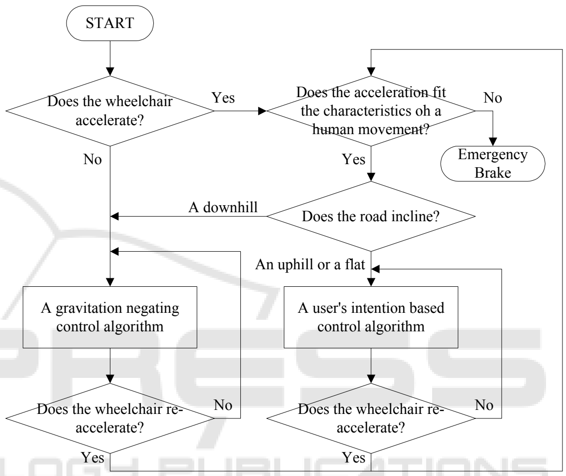
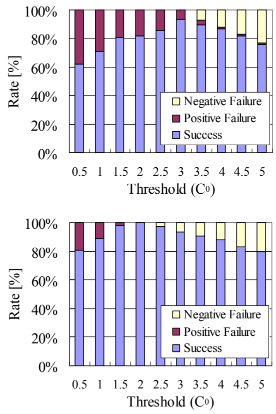


Figure 8: Flow chart of our proposed control scheme.

4.2 Parameter Setting for Estimation of a User's Rowing Motion

Our system judges that wheelchair acceleration is caused by human rowing motion if the difference between the real velocity and human movement profiles is less than the pattern-matching parameter, c_0 , in the user's intention-based control algorithm (Chugo et al., 2013). However, the parameter should change according to the road condition.

In the preliminary experiment, the wheelchair accelerates 3,700 times; 3,043 of these are caused by the user's rowing motion. Our system evaluates these accelerations with various parameters and the evaluation results are presented in Fig. 9. The false positive error is the misjudgement of human motion as acceleration by some other source and the false negative error is the misjudgement of the acceleration by other sources as being due to human motion. From the results, our system can distinguish between being indoors or indoors based on unevenness in a road surface, and uses $c_0 = 3.0$ in an outdoor environment and $c_0 = 2.0$ in an indoor environment.



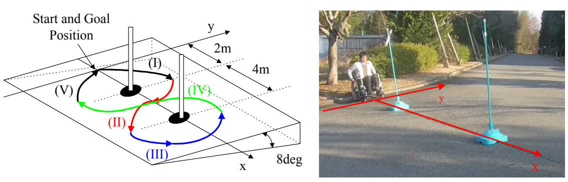
(a) Asphalt surface (outdoor) (b) Linoleum floor (indoor)

Figure 9: Success rate with each pattern-matching parameter.

5 EXPERIMENTS

5.1 Experimental Setup

We tested our system's performance in two experiments. In the first experiment, the subjects move from side to side in a figure of eight on a test road with an 8° incline using our prototype wheelchair with the proposed controller (Case P) as in Fig. 10. In this course, (I), (III), and (V) in Fig. 10(a) are uphill and (II) and (IV) are downhill. To verify the controller's effectiveness, the subjects repeated this activity in wheelchairs without the system (Case N), with only a gravitation-negating control (Case G) and with only the user's intention-based control (Case I). The subjects are the same as those of the preliminary experiment as shown in Table 1. In the second experiment, subjects try the test course shown in Fig. 2 with our proposed system. All experimental conditions are the same as in the preliminary experiment.

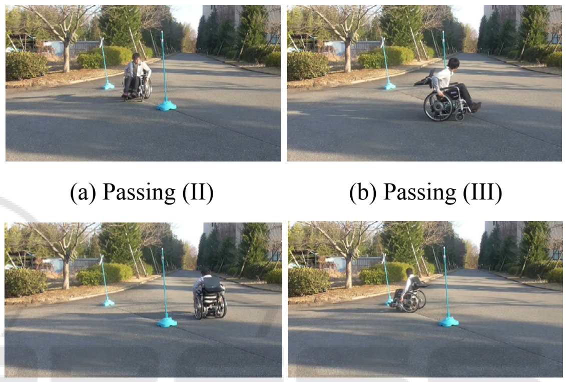


(a) Test course (b) Real environment.

Figure 10: Test course on an inclined road.

5.2 Experimental Results

The results show that the subjects could drive in an intended direction when using our system (Fig. 11). Figure 12 shows the running tracks of the wheelchair. With the proposed assistance system, the subject can drive the wheelchair smoothly. On the other hand, in case I, it is difficult to change the forward direction on a downhill situation and in case G, the brake traction that negates the gravitational force increases the load in uphill situations and it is difficult for the subject to climb in the vertical direction. As a result, in case G, the subject makes a detour.



(a) Passing (II) (b) Passing (III)

(c) Passing (III) to (IV) (d) Passing (IV)

Figure 11: Test run with our proposed controller by subject H.

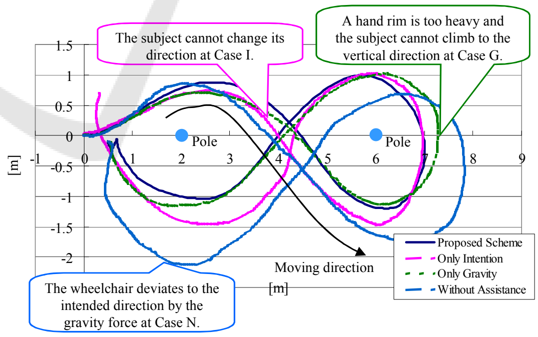


Figure 12: Running tracks by subject H.

Figure 13 shows the brake traction differences between the right and left wheels. A positive value means that a brake traction on the right wheel is generated and our system negates a gravitational force to the left direction. A negative value implies the opposite. In Fig. 13, for example, when a wheelchair passes (I), our system negates a gravitational force to the right direction; thus, the traction value is negative. On the other hand, the traction value is zero when the subject rows a hand rim because at this time, our system uses the user's intention-based control algorithm. Furthermore, Table 3 shows the workload that a subject outputs during one trial. Our proposed scheme requires only the workload of the user's intention-based control algorithm. From these results, our proposed control scheme realizes a gravitation-negating function with a smaller workload.

Table 4 shows the experimental results with our proposed user interface and the proposed controller on the test course shown in Fig. 2. The proposed user interface works effectively and settles major problem nos. 1, 2, and 3. The subjects can use the proposed interface without difficulties. The proposed control scheme settles major problem nos. 4 and 5. Subjects D and E are women with

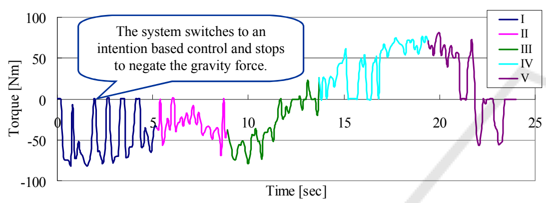


Figure 13: Brake traction differences in case P by subject H.

Table 3: Workload for one trial (J).

	Subject						
	A	B	C	D	E	G	H
Proposed Scheme	457.1	445.6	498.4	403.2	418.5	453.7	447.0
Only Intention	442.6	428.6	471.1	389.2	398.2	424.6	426.1
Only Gravity	523.4	493.5	552.1	427.5	466.2	479.1	501.4

Table 4: Results on a test course with the proposed system.

No	Major Problem (Times)	Subjects							
		A	B	C	D	E	F	G	H
1	The wheelchair moves by the gravitational force after the user pushes the start button.	0	0	0	0	0	0	0	0
2	The user tries to move the wheelchair when our system stops by emergency brakes.	0	0	0	0	0	0	0	0
3	The wheelchair moves by the gravitational force after the user switch off our system.	0	0	0	0	0	0	0	0
4	The user feels the wheelchair is too heavy on an uphill situation.	0	0	0	3	2	0	0	0
5	The user cannot go the intended direction on a downhill situation.	0	0	0	0	0	0	0	0
6a	Our system misjudges its user's intention.	1	0	0	1	0	0	0	0
6b	Our system misapplies emergency brakes.	2	1	1	2	2	0	1	1

somewhat less physical strength in their hands who feel that an uphill road is a heavy load using a normal manual wheelchair. Although the accuracy of rowing motion-estimation increases, there are some errors due to small steps.

From these results, we can verify that our proposed system is effective for assisting a manual wheelchair.

6 CONCLUSIONS

This paper presents an investigation into the way wheelchair drivers operate in various environmental conditions. We explore several assistance strategies that are appropriate to the various operating modes that the wheelchair driver presents with in these conditions. By this investigation, we propose a novel human interface based on a hand brake and a wheel-control scheme that combines a gravitational negating control algorithm and a user's intention-based control algorithm. Using this idea, our proposed wheelchair can continuously assist users in driving on uphill or downhill roads. Its effectiveness in daily usage is verified by experimental results with our prototype.

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