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Auto-tuning Control of Power Assist System Based on the Estimation of Operator's Skill Level for Forward and Backward Driving of Omni-directional Wheelchair

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Abstract— **This paper presents intelligent control of power assist system considering skill level of operators for wheelchair. In this paper, operability and anti-fluctuation running against the fluctuation of human force added to the handle by operator are progressed by the proposed auto-tuning system of power-assist controller. A method to estimate the operator's skill level and appropriately adjust the parameters of power-assist controller is presented by applying Fuzzy reasoning method. The effectiveness of the proposed method is demonstrated through experiments of OMW wheelchair.**

I. INTRODUCTION

In order to satisfy the demand for higher mobility, designers have created new driving concepts such as omni-directional movement which allows any combination of forward, sideways, and rotational movement, thus ensuring users much more freedom and safety in wide or narrow spaces. A variety of wheelchairs with different options and special add-on features have been developed to meet a wide range of needs [1], [2].

A power assist system that helps attendants move heavy loads was thus designed and developed in the author's laboratory [3]. The application of a power assist system to help attendants maneuver an omni-directional wheelchair is one of a novel research. There has been some research on a power assist system for omni-directional vehicles, but it is related to carts [4], few to wheelchairs. Moreover, that system still has some problems in rotation and in occupant's comfort since this system was developed for a food tray carry vehicle in a hospital.

In the author's laboratory, a holonomic omni-directional wheel-chair (OMW) which can act as an autonomous or semi-autonomous omni-directional wheelchair has been developed. Comfort has been a subject of study in the case with and without the joystick [5].

However, there is a problem related to the operability of the OMW. Due to the application of the power assist system, operability of the OMW degrades, especially when the attendant tries to rotate the wheelchair in a clockwise (CW), or counter-clockwise (CCW) direction around the center of gravity (CG) of the OMW. This problem is generated from the fact that it is difficult to apply human force exactly towards the target direction by means of the handle attached to the wheelchair, hence the movement of the OMW using conventional power assist does not provide to the target exactly. Furthermore, the sensor position to measure the force added by human for power assist is different from the position of the gravity center of the OMW, and therefore the force generated by its difference must be compensated.

It was impossible to find general rules to solve both problems stated above, but relationships between lateral and rotational movements were found by the authors. These relationships were used as the basis for constructing a Fuzzy reasoning system that helped to improve the operability of the OMW. Nevertheless, when the system was tested by different attendants, it was found that a complete satisfactory result was not obtained by every attendant. It is because each person has its own tendencies and the fuzzy inference system must be tuned to respond to them. We thus attempted to tune the Fuzzy inference system by trial and error. However, this proved, time consuming, requiring the attendants to perform many trials, which was both boring and fatiguing for them.

Thus, a better tuning method, a method that allows tuning of the Fuzzy inference system, is needed. It can be obtained by adding Neural Networks (NN) to the Fuzzy inference system, obtaining what is known as a Neuro-Fuzzy system. There has been, a lot of research on this topic [6], being the basic difference the kind of NN that is used in combination with the fuzzy inference system. Jang [6] developed ANFIS: Adaptive-Network-based Fuzzy Inference Systems, a Neuro-Fuzzy system in which the Fuzzy inference system is tuned by using the input data of the system. The desired direction of motion of the attendant as the teaching reference for the learning could be input by just using the keyboard of the computer. However, the keyboard input is not user-friendly. Furthermore, this method does not provide feedback information to the attendant that would let him or her know how well he or she is accomplishing the desired motion. Therefore, a human interface that provides information to the attendant is needed. This can be achieved by using a touch panel system with a monitor, which is a device that can be used as an input and at the same time can show the resultant motion of the OMW. The desired motion and real motion of the OMW are compared in order to obtain the difference, or error, that will be used for the training of ANFIS, as explained in a previous paper [7].

Though these research experience, we discovered that our developed system showed nice performance from the both viewpoints of power assist to support the operator's force,

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and also good mobility because of omni-directional function. However, it is found that the running of OMW is sometimes fluctuated due to the fluctuation of the force added to the handle of OMW by operator. On the other hand, if the fluctuation is suppressed by making the time-constant of power assist controller adjust larger value, however operability then became worse due to the response delay. Therefore, the system such as good operability and comfort driving with anti-fluctuation should be developed.

In order to satisfy the both stated above, development of skill-assist system will be demanded. On the skill assist research, there are a lot of studies. Among them, Yamada, et al presents interesting results on automobile assembly line. In the linear positioning work, Phase-dependent impedance control method has been proposed such that a mechanical impedance is adjusted every work phase such as (P1) Start phase, (P2) Transfer phase, and (P3) Positioning phase. While transiting from (P2) to (P3), mechanical impedance is changed from inertial dominaut to viscosity dominant for exact positioning. On the other hand, there is an interesting report that the skill level can be judged by the fluctuation of hand's force in the grinding work. These two reports is considered to be very useful for the present purpose, and we will use its concept to develop skill-assist system of OMW.

In this paper, an auto-tuning method for improving both the operability and anti-fluctuation of a power assist omni-directional wheelchair by using a fuzzy controller is proposed. For the brevity of concept explanation, in this paper, the discussion on the proposed method is restricted on the forward and backward driving.

II. POWER ASSIST SYSTEM CONSIDERING RUNNING STATE

A. Construction of OMW Power Assist System

Omni-direction mobile wheelchair (OMW) developed in author's laboratory is shown in Fig. 1, and the details is omitted because it is written in the previous paper [7]. Analysis and experiments is done in this paper.

Block diagram of the proposed skill assist system is shown in Fig.2. The force added to the handle by operator is detected by 6-axis force sensor, and the force is transformed into the velocity reference by the first-order lag controller for the purpose of power assist as follows.

Fig. 1. Omni-directional mobile wheelchair

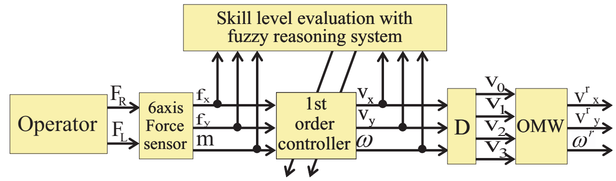
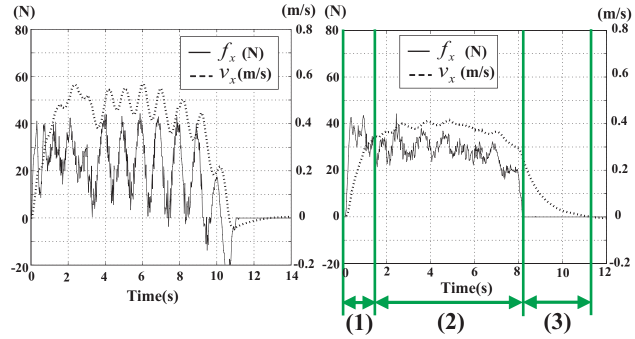


Fig. 2. Block diagram of skill assist system



(a) example of beginner (b) example of expert

Fig. 3. Example of f_x and v_x

$$\begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{K_{vx}}{T_{vx}s+1} & 0 & 0 \\ 0 & \frac{K_{vy}}{T_{vy}s+1} & 0 \\ 0 & 0 & \frac{K_{\omega}}{T_{\omega}s+1} \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ m \end{bmatrix} \quad (1)$$

, where $V(s) = [v_x, v_y, \omega]^T$ is the reference velocity of OMW, $F(s) = [f_x, f_y, m]^T$ is the force added to the handle by operator, $K = [K_{vx}, K_{vy}, K_{\omega}]^T$ is a gain of power assist controller to transform the added force into the reference velocity, and $T = [T_{vx}, T_{vy}, T_{\omega}]^T$ is characteristics of skilled or unskilled operator time-constant of this controller.

B. Operation Characteristics

Fig. 3 (a) shows an example of the operator's force f_x added to a handle and then the velocity v_x of OMW, where OMW is moved forward in X-direction by unskilled operator with unfamiliar for the operation. Fig. 3 (b) shows an example of f_x and v_x by skilled operation with respect to the operation of OMW. In the both cases, Gain and Time-constant of power-assist controller with first-order lag filter is respectively K_v = 0.02 and T_{vx} = 0.8.

In the case of Fig. 3 (a), operator's force f_x added to the handle of OMW is fluctuated by unskilled operator, and then v_x of OMW is fluctuated due to the vibration of OMW. Thus, velocity v_x of OMW becomes unstable. On the other hand, in the case of Fig.3 (b), velocity of OMW becomes stable, because skilled operator can stably give the force f_x without fluctuation.

Here, we defined the running state of the wheelchair of Fig. 3 (b). The running interval (1) of Fig. 3 (b) is defined as the *acceleration driving period*, the interval (2) is as the *steady driving period*, and the interval (3) as *deceleration driving period*. In the period of (1) and (3), the delay between human operation and OMW's movements is generated due to the power assist controller with first-order lag filter. Especially, in the case of (3) in Fig. 3 (b), OMW still moves for about 2 seconds, ever after operator's hand release the handle of OMW. Thus, operability is bad.

TABLE I

FUZZY RULES OF T AND K

RN	Antecedent	Consequent
1	if($f_x > 0$ and $v_x \approx 0$),	then Tv_x : small
2	if($f_x > 0$ and $v_x > 0$),	then Tv_x : large
3	if($f_x \approx 0$ and $v_x > 0$),	then Tv_x : small
4	if($f_x < 0$ and $v_x > 0$),	then Tv_x:Kv_x:small
5	if($f_x < 0$ and $v_x \approx 0$),	then Tv_x : small
6	if($f_x < 0$ and $v_x < 0$),	then Tv_x : large
7	if($f_x \approx 0$ and $v_x < 0$),	then Tv_x : small
8	if($f_x > 0$ and $v_x < 0$),	then Tv_x:Kv_x:small

However, if time constant T of the power assist controller is reduced to solve the problem of operability, the running state of OMW during steady period (2) is largely fluctuated, because filtering ability in the range of higher frequency will be lost. Thus, comfort in the rider will become worse in this period. Generally, unskilled operators hand such the tendency that they add the force to the handle of wheelchair with fluctuation of higher frequency. Therefore, it is suggested that the time constant's value T_x of power assist controller should be changed corresponding to the each driving period of (1), (2) and (3).

C. Auto-tuning of power assist controller by Fuzzy-reasoning

Auto-tuning method to suitably adjust time constant and gain of power assist controller according to the running periods (1), (2) and (3), is proposed by means of Fuzzy reasoning.

First, in Table I, Fuzzy rule is described between operator's force f_x and the velocity v_x of OMW. Here, Rule 1 - 4 is the case of forward running, while Rule 5 - 8 is the case of backward running. Focussing on Rule 1, 3, 5, and 7, time constant T is favorable to give the small value, because movements of OMW in the acceleration and deceleration period should be quickly responded corresponding to the operator's operation. On the other hand, in the steady driving period of Rule 2, time constant T should be large to reduce the fluctuation of OMW's velocity against the fluctuation of operator's force added to the handle of OMW. Further, Rule 4 shows the state of f_x >0 and v_x <0, where this operation is often used to suddenly stop OMW. In this state, wheel of OMW suddenly rotates in reverse direction, and then slip is produced between wheel and ground. Then, it induces the dangerous state. Thus, in Rule 4, both value of T and K are given as smaller value to stop OMW safely. In order to satisfy these requirements, membership function for forward parts of each Fuzzy Rule is given as follows:

Rule 1

$$\mu_{fxt1} = \frac{\tan^{-1}\{a_{fxt1}(Kf_x - b_{fxt1})\}}{\pi} + 0.5 \quad (2)$$

$$\mu_{vxt1} = \exp\left(-c_{vxt1} \cdot v_x^2\right) \quad (3)$$

Rule 2

$$\mu_{fxt2} = \frac{\tan^{-1}\{a_{fxt2}(Kf_x - b_{fxt2})\}}{\pi} + 0.5 \quad (4)$$

$$\mu_{vxt2} = \frac{\tan^{-1}\{a_{vxt2}(v_x - b_{vxt2})\}}{\pi} + 0.5 \quad (5)$$

Rule 3

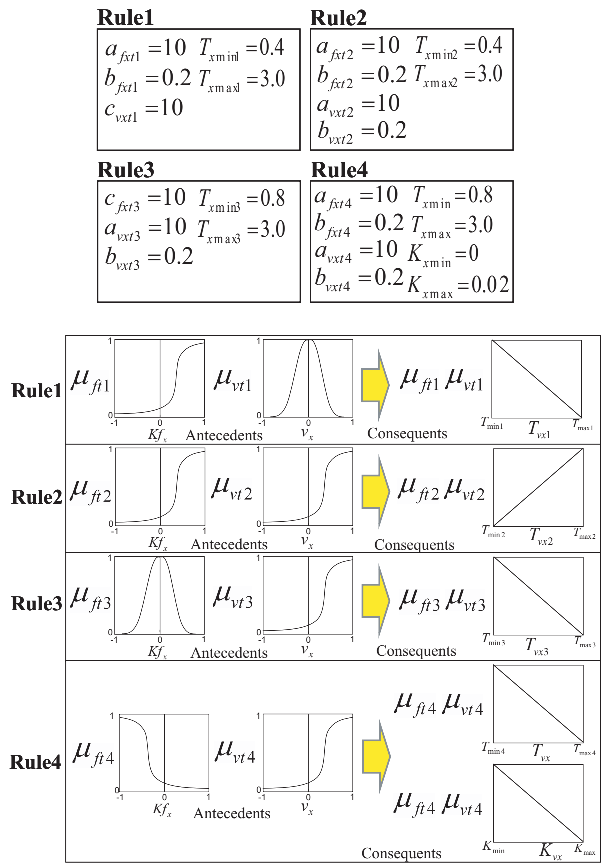


Fig. 4. Membership function

$$\mu_{fxt3} = \exp\left(-c_{vxt3} \cdot (Kv_x)^2\right) \quad (6)$$

$$\mu_{vxt3} = \frac{\tan^{-1}\{a_{vxt3}(v_x - b_{vxt3})\}}{\pi} + 0.5 \quad (7)$$

Rule 4

$$\mu_{fxt4} = \frac{\tan^{-1}\{a_{fxt4}(Kf_x - b_{fxt4})\}}{\pi} + 0.5 \quad (8)$$

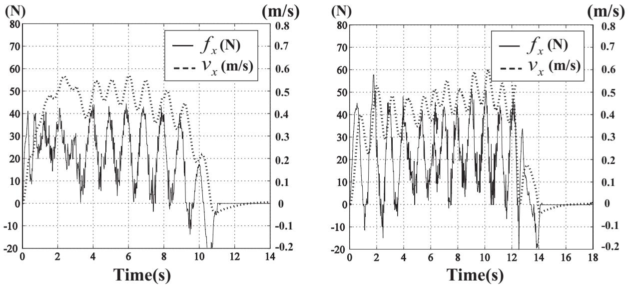
$$\mu_{vxt4} = \frac{\tan^{-1}\{a_{vxt4}(v_x - b_{vxt4})\}}{\pi} + 0.5 \quad (9)$$

Each parameter is determined considering both of anti-fluctuation and operability for OMW by experiments as follows. Time constant T_{vx} is calculated by (10) of a *weighted average method* considering adaptation degree for each rule. Gain K_{vx} is not the case, but linear output because of single Rule with respect to K_{vx}.

$$T_{vx} = \frac{\sum_{i=1}^{4}(\mu_{fti}\mu_{vti}T_{vxi})}{\sum_{i=1}^{4}(\mu_{fti}\mu_{vti})} \quad (10)$$

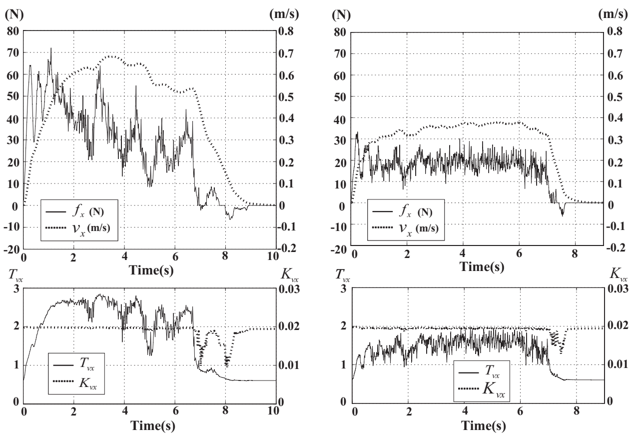
D. Experimental Results

Comparative experiments have been done for two people. Running distance of 5 m, and the moving direction is forward, and we ordered each person (subject 1 $\sim$ 4) to walk in natural way. Fig. 5 shows the experimental results by the conventional power assist where K_{vx} = 0.02, and T_{vx} = 0.08. Fig. 6 shows the result by the proposed novel power assist system. In Fig. 5, the running velocity v_x of OMW is largely fluctuated due to the high frequency fluctuation



(a) Subject 1 (b) Subject 2

Fig. 5. Conventional power assist system



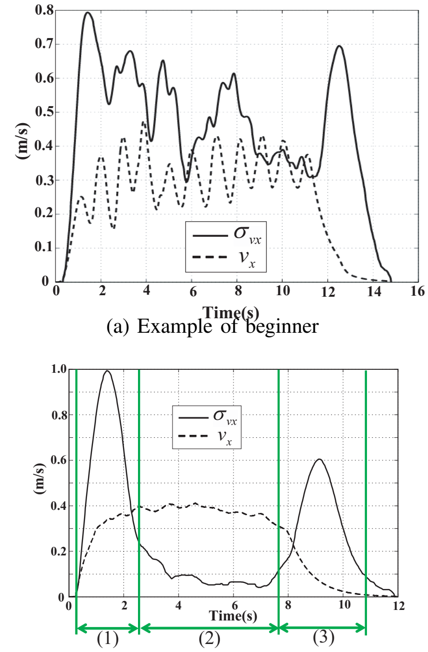
(a) Subject 1 (b) Subject 2

Fig. 6. Proposed skill assist system (1)

force f_x. Especially, in the case of subject 2, wheel motion repeats forward and reverse rotation, and shows dangerous states. On the other hand, by the proposed system, the fluctuation of velocity v_x in steady running period is well suppressed against fluctuation of operator's force f_x. Also, in the stopping period, OMW is smoothly stopped by reducing both value of T_{vx} and K_{vx}. Further, the reverse movements is not generated until OMW is stopped, even if operator suddenly gives the reverse force against the moving direction of OMW. Thus, the dangerous phenomena is avoided such as slipping between wheel and ground. By auto-tuning method according to the running state of OMW, both operability in acceleration and deceleration period which enable OMW to respond quickly for the operator's maneuver, and to aboid anti-fluctuation of OMW running velocity in steady period against human force fluctuation are achieved.

III. PROPOSED POWER ASSIST SYSTEM CONSIDERING SKILL LEVEL OF OPERATOR

In the previous section, a skill assist system is constructed such as unskilled operator can operate OMW as well as the skilled operator. However, in the steady period, time constant T_x becomes larger, and then responsibility of OMW for the operator's force f_x becomes slower. Thus, this slow response makes skilled operator feels such that operability of this system is bad. Therefore, in this section, it is argued that, according to skill degree of operator, the upper limit of time-constant T_x of time-varying system proposed in the previous section is newly assigned, and its value is appropriately adjusted, and then the response rate to enhance operability is improved.



(a) Example of beginner

(b)Example of expert

Fig. 7. Example of v_x and σ_{vx}

A. Evaluation of Skill Level

In the experiments addressed in former section, it is found that big difference between skill and unskill operation is the amplitude of the fluctuation of OMW velocity v_x in the steady period. Thus, performance index evaluating operator's skill degree is defined as follows:

$$\sigma_{vx} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(v_{xi} - \bar{v_x})^2} \tag{11}$$

Here, sampling time of controller is 0.02 second, and also n=50 is adopted.

Fig. 7 (a) shows the experimental result of unskilled operator, while Fig. 7 (b) the case of skilled operator. In Fig. 7 (a), because v_x is fluctuated, σ_{vx} shows the higher value persistently. This means that this operator is unfamiliar with operation. On the other hand, in Fig. 7 (b), σ_{vx} is smaller value, because the fluctuation of v_x is small in steady period. This means that operator is familiar with operation. Then, based on this facts, we consider that the maximum (upper) limit of time-constant T_{vx} in power assist controller should be adjusted adequately in Fuzzy membership function, according to the operator's skill level. Then, an auto-tuning system is proposed according to the skill level of operator.

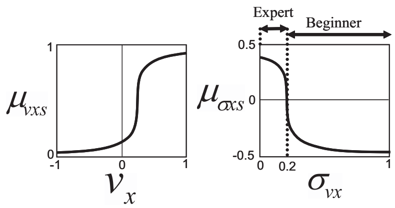
B. Auto-tuning System of Power Assist Controller by Fuzzy Reasoning

In the steady running period, skilled operator shows smaller value of standard deviation σ_{vx} with respect to the fluctuation of OMW velocity, while unskilled operator shows higher value of σ_{vx}. Through results of Fig. 7 (a) and Fig. 7 (b), we set the threshold σ_{vx0} on σ_{vx}. Then, we assume that operator's skill is high if $\sigma_{vx} < \sigma_{vx0}$, and low if $\sigma_{vx} > \sigma_{vx0}$. Based on this relation, Fuzzy rule is built in Table II.

TABLE II

FUZZY RULES OF v_x AND σ_{vx}

RN	Antecedent	Consequent
1	if ($v_x > 0$ and $\sigma_{vx} < \sigma_{vx0}$),	then skill : high
2	if ($v_x > 0$ and $\sigma_{vx} > \sigma_{vx0}$),	then skill : low



(a) (b)

Fig. 8. Antecedents of v_x and σ_{vx}

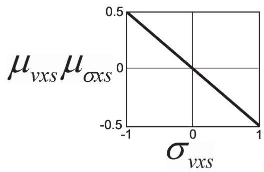


Fig. 9. Consequent of v_x and σ_{vx}

Membership function is written in (12) and (13), where this membership function works mainly in the steady running period.

$$\mu_{vxs} = \frac{\tan^{-1}\{a_{vxs}(v_x - b_{vxs})\}}{\pi} + 0.5 \quad (12)$$

$$\mu_{\sigma xs} = -\frac{\tan^{-1}\{a_{\sigma xs}(v_x - \sigma_{vx0})\}}{\pi} \quad (13)$$

Here, parameter a_{vxs}, b_{vxs}, $a_{\sigma xs}$ and $b_{\sigma xs}$ of membership function are determined by experiments as follows:

$$a_{vxs} = 10,\ b_{vxs} = 0.2,\ a_{\sigma xs} = 10,\ b_{\sigma xs} = 0.2$$

Fig. 8 and Fig. 9 shows the membership function of Autecedents, and Consequent of v_x and σ_{vx}, respectively. However, σ_{vxs} is largely varied every sampling, and then it is not favorable to straightforwardly use this value owing to noise. Then, the novel following skill level index S_{vx} is proposed.

Skill level index:

$$S_{vx(t)} = S_{vx(t-1)} + \frac{\sigma_{vxs}}{T_s} \quad (14)$$

Here, S_{vx} is a skill level index, where lower limit is named to be 0, and upper limit is 1. In this paper, T_s is named as *forgettable time* to average the variable value of S_{vx}. If the value of T_s is large, the change of S_{vx} becomes smoothly, where the change of S_{vx} becomes quickly if T_s is small. Then, T_s = 250 is adopted by analysis of simulation and experiments. Then, S_{vx} is varied between $0 \sim 1$. Skilled person shows higher value of S_{vx}, and unskilled person shows lower value. Maximum (Upper) limit T_{vxmax} of time-constant T_{vx} is given as follows:

$$T_{vxmax} = T_{max5} - (T_{max5} - T_{min5}) \cdot S_{vx} \quad (15)$$

, where $T_{vx} \leq T_{vxmax}$, and T_{vx} is restricted under this value. In (15), T_{max5} and T_{min5} can be suitable assigned. Here, T_{max5} is adapted as T_{min5} = 0.4, because skilled person can operate without fluctuation even if T is reduced until 0.4, and OMW becomes unstable if less than 0.4. On the other hand, T_{max5} = 3.0 is adopted, because operator feels that operational response is too bad for even unskilled operator. These values are determined by experiments. By this algorithm, T_{vxmax} will be approached to T_{vxmax} = 3.0 being upper limit of T_{vx} if S_{vx} is decreased, while T_{vxmax} approaches to T_{vxmax} = 0.4 if $S_{vx}$is increased.

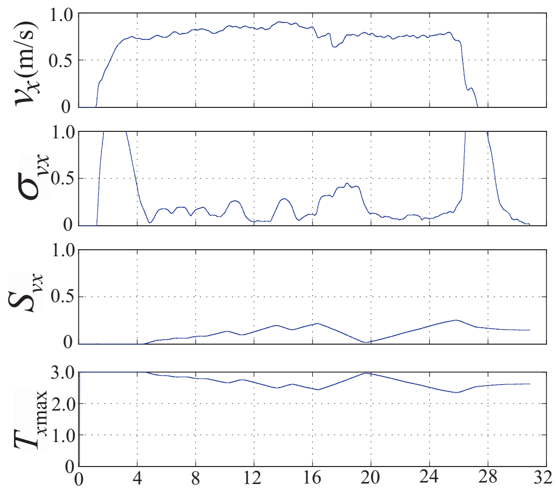


Fig. 10. Experimental result by proposed method (subject 1)

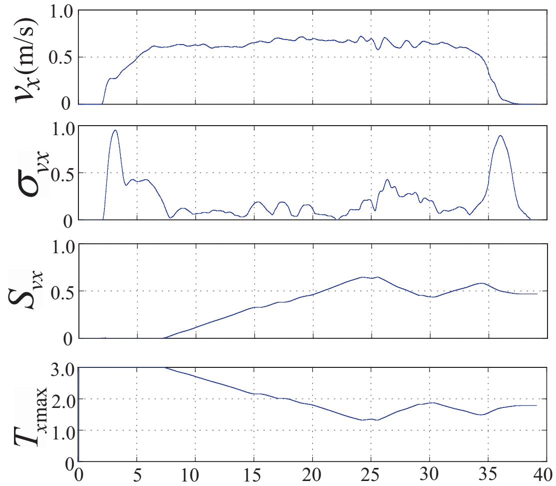


Fig. 11. Experimental result by proposed method (subject 2)

C. Experimental Results

Driving tests have been conducted by using four people. As experimental conditions, we ordered four operators for experiments to run 20 m in X-direction with almost constant velocity in usual way. Figs. 10 - 13 is the results of subject 1 - 4, respectively.

In Fig. 10, skill level is evaluated to be low. Namely, skill level index S_{vx} is transited under the small values, because the stranded deviation σ_{vx} of the velocity v_x shows the higher value. However, because T_{xmax}, is transited around the higher value of 2.5, the fluctuation of velocity v_x is suppressed well. In Fig. 11, skill level is considered to be middle, because S_{vx} is transited around S_{vx} = 0.5. In Fig. 12, skill level is considered to be high, because S_{vx} is high,

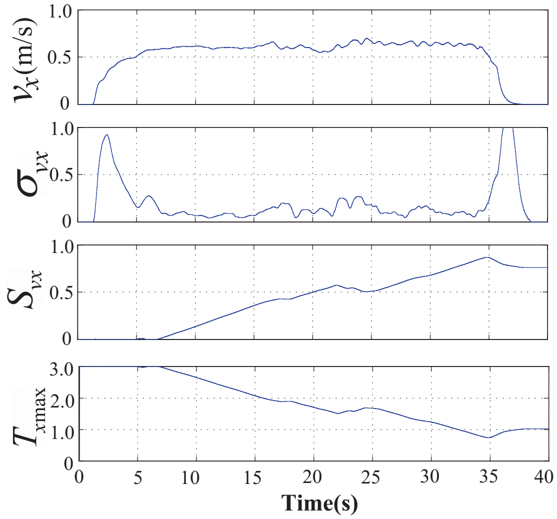


Fig. 12. Experimental result by proposed method (subject 3)

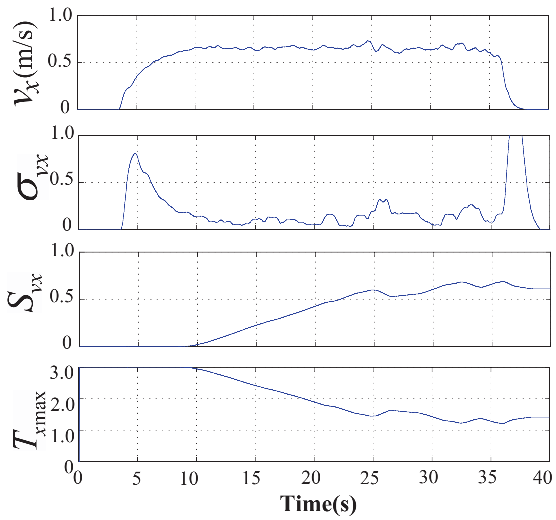


Fig. 13. Experimental result by proposed method (subject 4)

and T_{xmax} = 1.0. Although T_{xmax} is smaller compared with other cases, the fluctuation of velocity v_x is well reduced, and therefore operability is good for expert operator because of small time delay. In Fig. 13, skill level is considered to be middle, became S_{vx} and T_{xmax} is transited around S_{vx} = 0.7 and T_{xmax} = 1.4, respectively. In any cases, the fluctuation on velocity v_x of OMW is well reduced according to the skill level of operator, and the response of operator on the velocity of OMW becomes faster in case of skilled operator of subject 3 as seen from the stopping period in Fig.12. So, skilled operator can accept the proposed power assist system because this system does not degrade the operation of skilled operator. Through Figs.10 - 13, it has been shown that optimum time-constant was automatically derived corresponding to skill level. Hence, Taylor made skill assist system has been built.

We are now extending a skill assist system proposed in the paper to the case of lateral, slant and rotation movements in OMW. In the lateral movements case, the result will be the same with forward and backward case presented in this paper. Reader will be understood intuitively. But, in the case of slant and rotational case, the problem will be further difficult, because X- and Y-direction movement will be combined, and becomes complex behavior. These results will be roughly reported in conference, and also the details in near future.

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper, an auto-tuning system of power assist controller for forward and backward movements of omni-directional wheelchair (OMW) has been proposed to realize the Taylor made skill-assist system. The results obtained in this paper is summarized as follows:

1) Evaluation index representing skill level has been proposed.
2) Even helper operating OMW with low skill level can drive OMW stably without velocity fluctuation of wheelchair against hand's fluctuation, and helper with high skill level can drive OMW without degrading the operability of skilled person by proposed power assist system.
3) Time constant of skill assist can automatically tuned according to individual person by the proposed Fuzzy-reasoning, and Taylor made skill assist system has been realized.

B. Future Works

We checked only forward and backward straight direction movements of OMW concerning with the proposed skill assist system. In future, we will check the effectiveness of the proposed method on the lateral direction, the rotational direction and slant direction movements of OMW with the real users.

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