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Skill Assist Neuro-Fuzzy Control of Omni-directional Wheelchair for Attendants Considering Rotation Center of Vehicle

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Abstract: For improving the operability of an omni-directional wheelchair provided with a power assist system, the system must be able to adapt to the individual characteristics of the many different attendants that will use it. For achieving this purpose, an innovative human-interface using a touch panel that provides easy input and feedback information in real time of the operation of a power-assisted wheelchair was developed. The system was tested experimentally with many different attendants and the results show that in addition to providing a human friendly interface by using the touch panel system with a monitor, the system can successfully adapt to the particular habits of the attendants. Furthermore, control of the rotation center of the OMW is proposed by making use of the OMW's potential advantage and coordination transformation.

1. 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 (Wada and Asada, 1999)-(West and Asada,1992).

Many power assisted wheelchair have been developed for handicapped people or elderly people that can use their arms freely, such as, for example, those by Seki (Seki et al., 2005) and Frank Mobility Systems (Frank Mobility Systems, 2002), However, some elderly people or handicapped people cannot use their arms because they are damaged or weak, and require the help of an attendant. A power assist system that helps attendants move heavy loads was thus designed and developed in the author's laboratory (Kitagawa et al., 2004). The application of a power assist system to help attendants maneuver an omni-directional wheelchair is one of a novel research. To the author's knowledge, no other report on this topic yet appeared. There has been some research on a power system for omni-directional vehicles, but it is related to carts (Maeda et al., 2000), not 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 (Kitagawa et al., 2002) or semi-autonomous (Kitagawa et al., 2001) omni-directional wheelchair has been developed. Comfort has been a subject of study in the case with and without the joystick (Kitagawa et al., 2002), (Terashima et al., 2004).

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 ($\boldsymbol{CG}$) 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

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Fig. 1. Omni-directional wheelchair (OMW).

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 (Jang, 1993)-(Lin and Lee, 1991), being the basic difference the kind of NN that is used in combination with the fuzzy inference system.

Jang (Jang, 1993) 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 (Terashima et al., 2006).

In a previous paper (Terashima et al., 2006) by the authors, the forwards-bakwards velocity was not included in the ANFIS system of the OMW and then a Reduction Multiplicative Factor (RMF) was used for the improvement of the rotational motion of the OMW when there was some interference of the forwards-backwards velocity. By using the RMF, it was possible to achieve good operability in the forwards-backwards motion, lateral motion and rotational motion. However, the results were not satisfactory for slanting motion. By including the forwards-backwards velocity in the ANFIS system, as shown in Fig. 6, and with the use of the touch panel for providing teaching reference for the learning, it was possible to accomplish a general omni-directional motion. The simulation and experimental results in the case of diagonal motion are shown in Figs. 13 and Fig. 14.

In this paper, an innovative method for improving the operability of a power assist omni-directional wheelchair by using a touch panel with a neuro-fuzzy controller as a human interface is proposed. Furthermore, control of the rotation center for the OMW is presented to extend the freedom of rotation of the OMW. This motion can be achieved by using the OMW's advantage and coordination transformation. Then, the OMW can be rotated at the center of gravity of the OMW, or around the helper.

2. CONSTRUCTION OF OMW USING A TOUCH PANEL AS HUMAN INTERFACE

We built a holonomic omni-directional wheelchair (OMW) using omni-wheels, as was described previously (Kitagawa et al., 2002)-(Kitagawa et al., 2001). Figure 1 shows an overview of the OMW we developed.

The OMW is able to move in any arbitrary direction without changing the direction of the wheels. In this system, four omni-directional wheels are individually and simply driven by four motors. Each wheel has passively driven free rollers at their circumference. The wheel that rolls perpendicularly to the direction of movement does not stop its movement because of the passively driven free rollers. These wheels thus allow movement that is holonomic and omni-directional.

The OMW is also equipped with a handle and a six-axis force sensor, as shown in Fig. 1, which allows the OMW to be used in power-assist mode. The force that the attendant inputs to the grips of the handle is measured by this force sensor. Second, an order lag filter is used for the transformation from force to velocity (Terashima et al., 2006).

A touch panel is a display device that accepts user input by means of a touch sensitive screen. Because of their compact nature and ease-of-use, touch panels are typically deployed for user interfaces in automation systems, such as high-end residential and industrial control. Touch panels are also becoming common on portable computers such as Tablet PCs, Ultra-Mobile PCs and consumer devices such as VOIP phones. In this research, a touch panel as shown in Fig. 2 is used as an input device in which the attendant of the OMW draws the desired direction of motion. As is also shown in Fig. 2, the touch panel is mounted on the rear part of the OMW so the attendant

Fig. 2. Touch panel used for the OMW

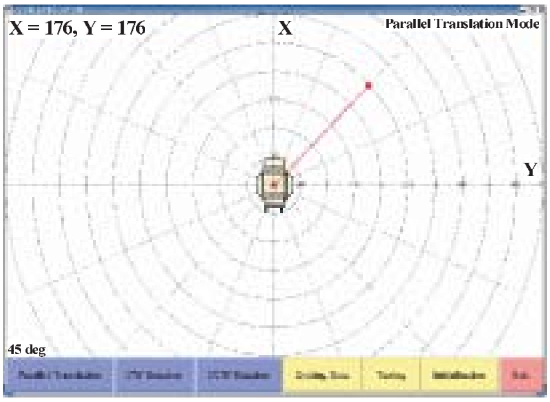
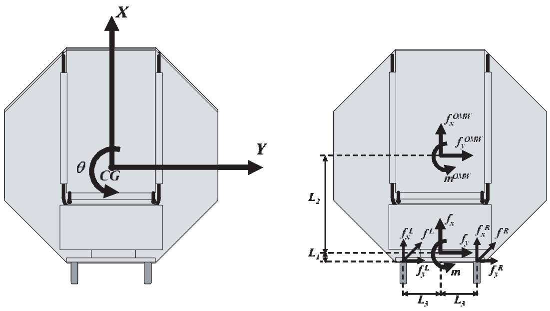


Fig. 3. GUI developed for the touch panel



(a) Coordinate system of the OMW. (b) Decomposition of the forces applied to the handles of the OMW.

Fig. 4. Working force.

can easily reach it. The touch panel used in this research is a TFT Touch Monitor HV-141T produced by ULTEC Corporation, Japan. A GUI (Graphical User Interface) was developed to make the interaction with the attendant easy, as shown in Fig. 3. In this GUI the attendant can draw any kind of motion, be in a slanting motion, or a rotational movement.

3. NEURO-FUZZY SYSTEM FOR IMPROVING OPERABILITY

When the user tries to rotate the OMW around its gravity center, the OMW begins to slide, the radius of rotation sometimes becomes very large, and rotation around the center is then very difficult (Kitagawa et al.,2004). A survey was conducted among various attendants to attempt to discover some relationships in the way they realized forwards backwards, lateral and rotational movements.

Table 1. Fuzzy reasoning rules for lateral motion and rotational motion

R	Antecedent	Consequent
1	If $Vy < 0$ and $\omega < 0$,	then $\omega < 0$
2	If $Vy \approx 0$ and $\omega < 0$,	then $\omega < 0$
3	If $Vy > 0$ and $\omega < 0$,	then $Vy > 0$
4	If $Vy < 0$ and $\omega \approx 0$,	then $Vy < 0$
5	If $Vy \approx 0$ and $\omega \approx 0$,	then 0
6	If $Vy > 0$ and $\omega \approx 0$,	then $Vy > 0$
7	If $Vy < 0$ and $\omega > 0$,	then $Vy < 0$
8	If $Vy \approx 0$ and $\omega > 0$,	then $\omega > 0$
9	If $Vy > 0$ and $\omega > 0$,	then $\omega > 0$

Table 2. Fuzzy rules for the change of Vx in order to improve operability

R	Antecedent	Consequent
1	If $Vx < 0$ and $Vy < 0$,	then $Vx < 0$
2	If $Vx \approx 0$ and $Vy < 0$,	then $Vx \approx 0$
3	If $Vx > 0$ and $Vy < 0$,	then $Vx > 0$
4	If $Vx < 0$ and $Vy \approx 0$,	then $Vx < 0$
5	If $Vx \approx 0$ and $Vy \approx 0$,	then 0
6	If $Vx > 0$ and $Vy \approx 0$,	then $Vx > 0$
7	If $Vx < 0$ and $Vy > 0$,	then $Vx < 0$
8	If $Vx \approx 0$ and $Vy > 0$,	then $Vx \approx 0$
9	If $Vx > 0$ and $Vy > 0$,	then $Vx > 0$

The goal of the survey was to find general rules that applied to there three types of motions. Even when it was impossible to find general rules that explained all cases, we found a relationship between lateral and rotational movements. These relationships were used as the basis for constructing a Fuzzy reasoning system (MathWorks, 2002)-(Harris et al., 1993) that helped to improve the operability of the OMW. In order to establish the rules of direction inference, first, the forces applied to the grips of the force sensor are changed to the center of the OMW, as shown in Fig. 4. It is easy to derive a basic equation to compensate for the difference between the sensor and the actuators allocation (Kitagawa et al., 2004). Furthermore, it is difficult to exactly give the force for the sensor to the target direction. In addition, how to give the force for the gripper sensor is slightly different depending on persons even for the same target motion of the OMW. The rules of direction inference, in which just lateral motion and rotational motion are considered, are shown in Table 1. In Table 1, Vy represents the lateral velocity of the OMW, and ω represents the angular velocity of the OMW. The forwards and backwards velocity of the OMW is given by Vx.

The system in which Fuzzy reasoning was applied just to the lateral and rotational velocity was tested, and it was found that even when the operability the lateral direction was improved, there were still some problems with the rotational movement because of a component Vx that did not allow achievement of a perfect rotation over the center of gravity of the OMW. A Reduction Multiplicative Factor (RMF) which decreases the value of Vx in the case of rotational motion, and keeps it unchanged in the case of forwards-backwards movement was the solution provided by the authors in previous research (Terashima et al., 2006). By using the RMF it was possible to improve the forwards-backwards motion, lateral motion and rotational motion over the gravity center of the OMW.

Fig. 5. Block diagram of the power assist system.

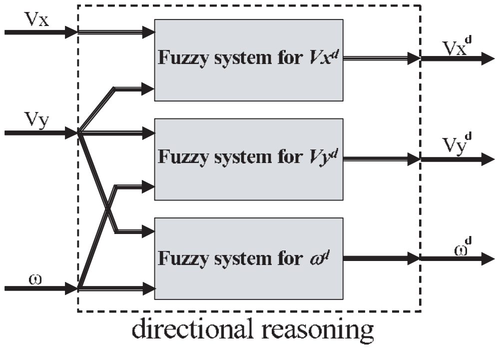


Fig. 6. Contents of the block "directional reasoning".

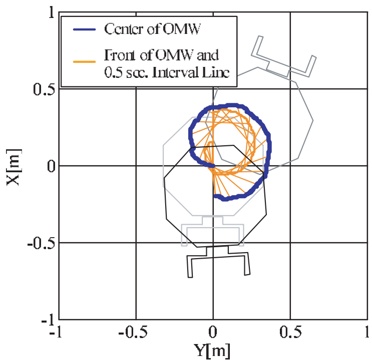


Fig. 7. Results when fuzzy reasoning is not applied for improving operability.

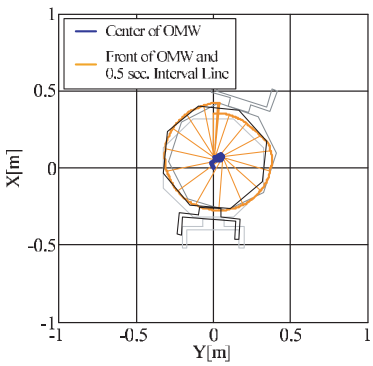


Fig. 8. Results when fuzzy reasoning is used by "**Attendant 1**".

However, as Vy was subjected to Fuzzy reasoning and Vx was not, it was not possible to achieve good operability for slanting motions, like diagonal motion. In the case of diagonal motion, for example, the attendant tries to move the OMW in such a way that the inputs of Vx and Vy are almost the same in the beginning. Nevertheless, as Vy is subjected to directional reasoning, its value changes. Vx is not subjected to directional reasoning, then its value always remains the same. As a consequence, it is not possible to achieve good operability in diagonal motion.

To solve this problem, Vx was subjected to directional reasoning also using the Fuzzy rules shown in Table 2.

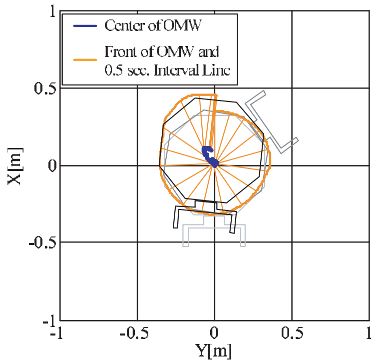


Fig. 9. Results when fuzzy reasoning is used by "**Attendant 2**".

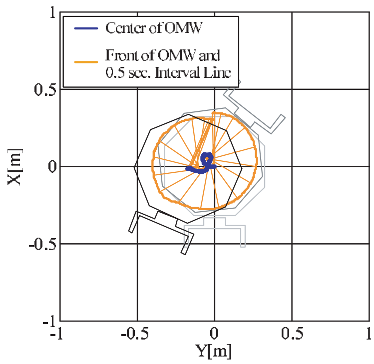


Fig. 10. Results when fuzzy reasoning is used by "**Attendant 3**".

These rules make it possible to include Vx in the Fuzzy reasoning system without disturbing the values of Vy or ω. The block diagram of the system that considers power assist and Fuzzy reasoning is shown in Fig. 5, and the contents of the block labeled as "directional reasoning" are shown in Fig. 6. By including Vx in the ANFIS system, it was possible to achieve a general omni-directional motion.

Fig. 7 shows the results in the case of a counter-clockwise rotation over the center of gravity of the OMW when no Fuzzy reasoning is used. It is possible to see that there is a deviation in the lateral direction as well as in the forwards-backwards direction. For solving this problem, the fuzzy system was used. It was tuned by trial and error, as explained in (Kitagawa et al., 2004), for an attendant that will be called "Attendant 1", and the results, presented in Fig. 8, show that the rotational movement was improved considerably. However, when the same system was tested with two other attendants, called "Attendant 2" and "Attendant 3", the results were not as good as with "Attendant 1", as shown in Figs. 9 and Fig. 10. This means that the system must be tuned in order to respond to the individual characteristics of the different attendants. However, condugting tuning by trial and error is time-consuming and boring for attendants. Because of this, automatic tuning of the system by using a neuro-fuzzy system, ANFIS (Adaptive-Neural Fuzzy Inference System), was proposed and developed as described in (Terashima et al., 2006). The ANFIS system of the OMW provided in this paper is shown in Fig. 11.

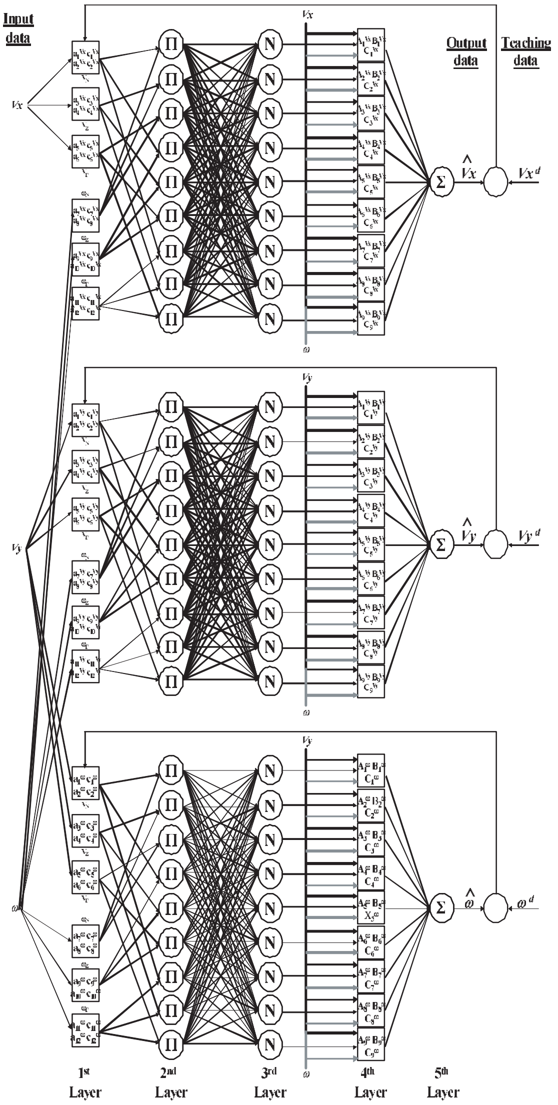


Fig. 11. ANFIS systems of the OMW

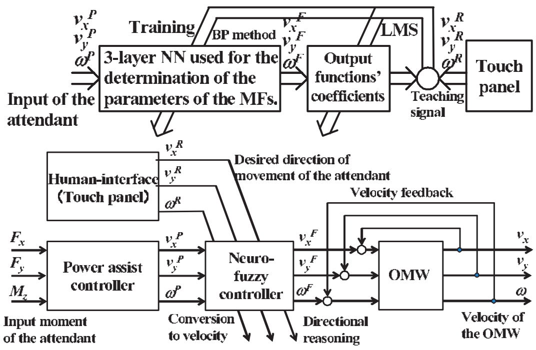


Fig. 12. Complete system when the touch panel is included.

4. ADAPTIVE CONTROL WITH HUMAN INTERFACE AND RESULTS

In previous research (Terashima et al., 2006), the desired direction of motion of the attendant was input by using the keyboard of the computer of the OMW. However, the attendant could not get a clear idea of the direction in which he wanted to move, nor could he verify if the real motion of the OMW actually corresponded to his desire. In

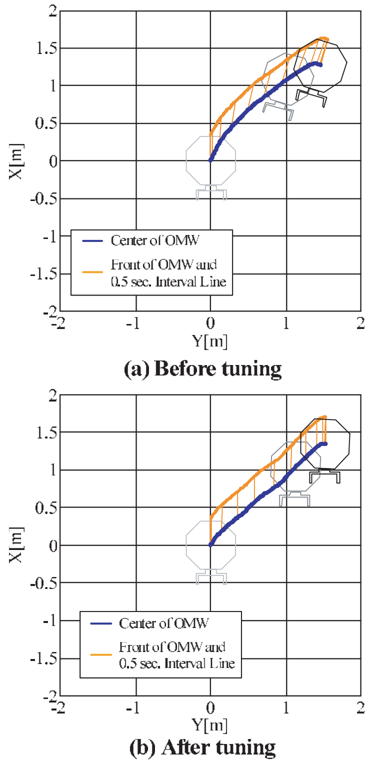


Fig. 13. Simulation results for one attendant in the case of diagonal movemement to the right.

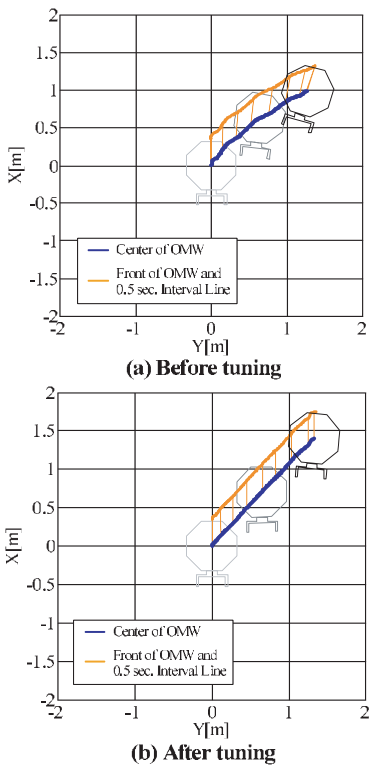


Fig. 14. Experimental results for one attendant in the case of diagonal movemement to the right.

order to provide the attendant with an easy way to input the desired direction of motion and to verify the direction of motion, a human interface consisting of a touch panel, as shown in Fig. 2, was used. A GUI (Graphical User Interface) was developed to enable ease of interaction with the attendant, as shown in Fig. 3. In this GUI the attendant can draw any kind of motion, like, for example, a slanting motion or a rotational movement. Moreover, it allows the attendant to follow the motion of the OMW in the screen of the touch panel, and compare the difference between the desired motion and real motion of the OMW. The complete system, when the touch panel is included, is shown in Fig. 12.

The procedure for applying the touch panel is as follows:

(1) First, the attendant draws the kind of movement that he desires to accomplish in the touch panel, as a teaching signal for the learning of the Neural Networks.
(2) Then, the attendant moves the OMW to try to accomplish the desired motion.
(3) However, in the general case, there is a difference between the desired motion and the real motion. This difference is used for the training of the ANFIS system of the OMW, as explained in (Terashima et al., 2006).

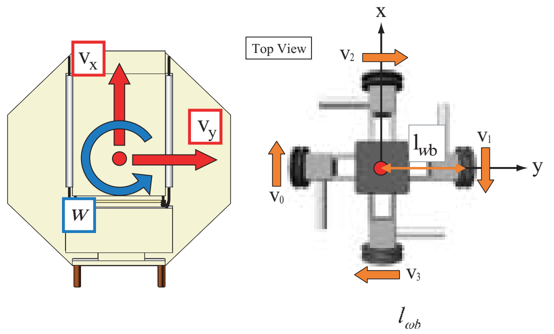
This system was used to support the operation of the attendant in many kinds of movements like, for example, forwards-backwards motion, lateral motion, rotational over the gravity center of the OMW in a clockwise and counter-clockwise direction, and many cases of slanting motion. In Fig. 13. it is possible to observe the simulation results of one attendant for the case of diagonal movement to the upper right corner of the XY system shown. Fig. 13 (a) shows the diagonal trajectory obtained before tuning is accomplished. It is possible to see that it is more an arc than a straight diagonal line. By using the same input data used in Fig. 13 (a), the system is tuned by using ANFIS, and the trajectory obtained after the tuning is shown in Fig. 13 (b). It can be observed that the trajectory has been improved, as expected. The number of data used for the training of the ANFIS was in the range of 3500 $\sim$ 4000 data, and the learning time was around 30 [s] $\sim$ 40 [s] in a Pentium III 1 [GHz] personal computer. The system was tested by an experiment, for the same attendant, with the results shown in Fig. 14 (a) for the case before tuning, and in Fig. 14 (b) for the case after tuning. As in the case of the simulation, the trajectory obtained in the experiments was not very good before tuning, but it was improved after the tuning of the ANFIS system of the OMW.

5. CONTROL OF ROTATION CENTER BY OMW OPERATION

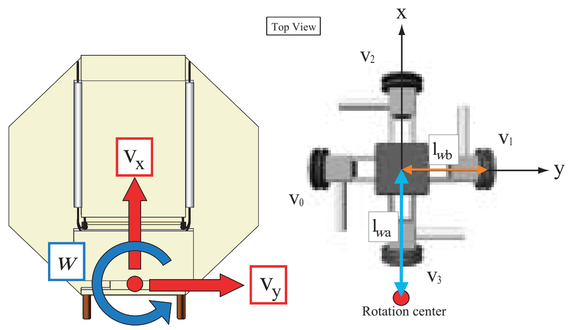
The OMW can revolve around any center point, since it has the characteristic of holonomic and omni-directional movement. In this section, the effectiveness of the ANFIS system is examined when the rotating center is moved from OMW's centroid point to the close point of the operator.

5.1 ALTERATION OF KINEMATICS MODEL

In the coordinate system of the OMW, the X-axis is defined by OMW's forward or backward direction, and



(a)Direction of OMW velocity (b)Direction of motors velocity
Fig.15 Direction of OMW and motors velocity



(a)Direction of OMW velocity (b)Direction of motors velocity
Fig.16 Direction of OMW and motors velocity

the Y-axis is defined by OMW's the right or left direction. Then v_x is the velocity of OMW in the X-axis, v_y is the velocity of OMW in the Y-axis, and ω is the angular velocity of OMW when it rotates around the Z-axis. The velocity of OMW can be expressed as $V_{OMW} = [\, v_x \; v_y \; \omega \,]^T$. The velocity of OMW is the vectorial sum of velocities of the four omni-wheels. The velocity vector for the the omni-wheels is written as $V_{wheel} = [\, v_0 \; v_1 \; v_2 \; v_3 \,]^T$. The velocity vectors corresponding to each omni-wheel are shown in Figure 15, where l_{wb} denotes the distance between the wheel and the OMW's centroid point, and l_{wb} is 0.30[m].

The conversion of V_{OMW} to V_{wheel} is described as follows.

$$\begin{bmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & -l_{wb} \\ -1 & 0 & -l_{wb} \\ 0 & 1 & -l_{wb} \\ 0 & -1 & -l_{wb} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \quad (1)$$

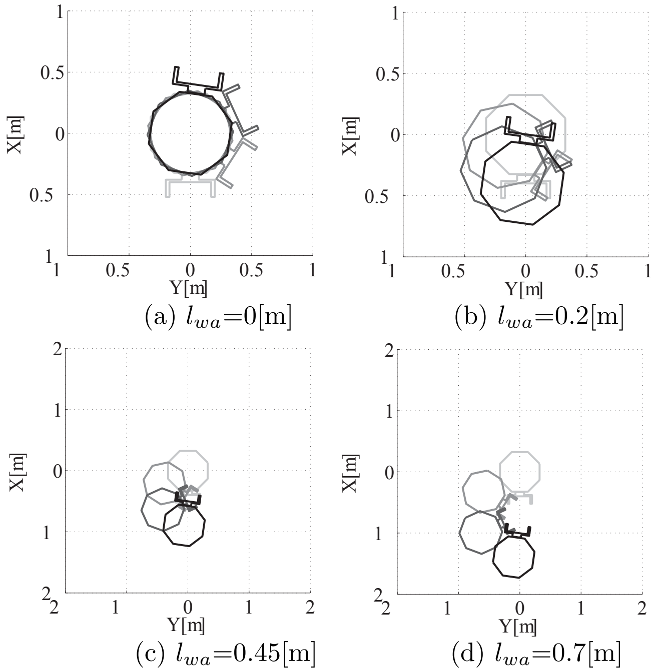
Next, l_{wa} is defined as the distance between OMW's centroid point and rotating center, when the rotating center is changed from OMW's centroid point to the close point of the operator, as shown in Fig.16.,

$$\begin{bmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & -l_{wb} \\ -1 & 0 & -l_{wb} \\ 0 & 1 & -(l_{wa}+l_{wb}) \\ 0 & -1 & (l_{wa}-l_{wb}) \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \quad (2)$$

which expresses that the kinematics model when the rotating center is moved from OMW's centroid point to the close point of operator.

5.2 SIMULATION RESULT OF KINEMATICS MODEL

The validity of Eq.(2) is confirmed by the simulation. The input to OMW was assumed as a constant of ω=0.3[rad/s], and also assumed to be rotation movement. A case such as l_{wa}=0[m], 0.20[m], 0.45[m], and 0.70[m], is analyzed and the simulation result is shown in Figure 17.



(a) l_{wa}=0[m] (b) l_{wa}=0.2[m]

(c) l_{wa}=0.45[m] (d) l_{wa}=0.7[m]

Fig.17 Movement of OMW

It can be confirmed that the case of Fig.17(a), l_{wa} =0[m], corresponds to the case of previous chapters, such that the rotation center is placed at the center of the OMW. Through Figs.17(a), (b), (c) and (d),the rotation center can be corrected according to the operator's intention by numerically changing the value of l_{wa} of Eq.(2).

5.3 EXPERIMENTAL RESULT

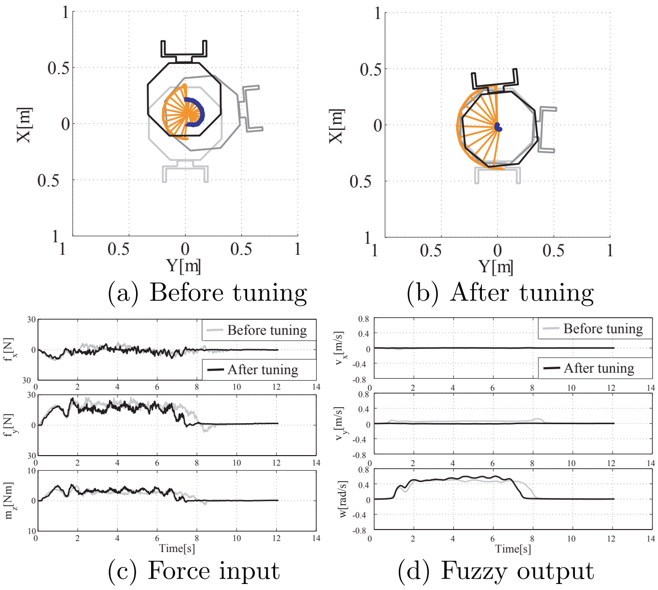
The effectiveness of ANFIS when l_{wa} is changed by the experiment was verified. First, it is half rotated counter-clockwise as l_{wa}=0[m] as well as the simulation of Fig.18(a) without Fuzzy parameter tuning. Next, through the tuning of a Fuzzy parameter by Neural network learning using the data of Fig.18(a), the operation succeeded succeeded well, as is shown in Fig.18(b).

The human input force added to the handle and fuzzy inference before and after tuning is respectively drawn in Fig.18(c) and Fig.18(d).

As seen from Fig.18, the operation's input force generates the large force of f_y and the small force of f_x which is not necessary for rotation. By power assist, this force especially derives v_y in the case without parameter tuning. However, after Fuzzy parameter tuning by the learning of Fig.18(c), v_y is not derived by Fuzzy parameter's adaptive tuning. Then, the rotation motion was completely achieved.

Next, the case of l_{wa}=0.20[m], 0.45[m] and 0.70[m] was studied, The result of (a) in Figs.19-Fig.21 shows the result when Fuzzy parameter was adapted the case of (b) in Fig.18. As seen from Fig.19-Fig.21, there was found to be little difference between before tuning and after tuning, in fact, a little improvement was found after tuning, but not much from the practical point of view. Once adaptive tuning by using ANFIS was done for the case of l_{wa}=0, the other case with respect to the rotation center realized the intended motion by using only Eq.(2). The property such that the rotation center can be freely shifted according to the operation's intention is a typical characteristic of OMW. Therefore, the property algorithm shows to have the good operability of OMW by using Fuzzy-Neural learning method and Eq.(2) such that rotation center can be freely changed.

It can be said that the automatic tuning system that used ANFIS when l_{wa} is changed is extremely effective.



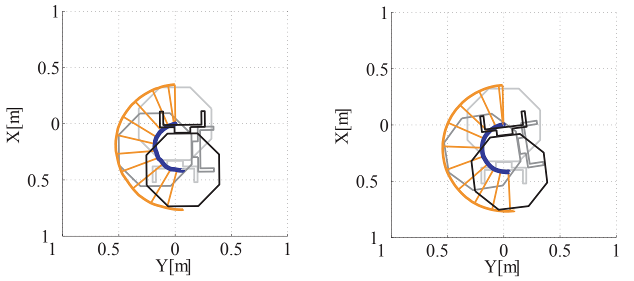
(a) Before tuning (b) After tuning

(c) Force input (d) Fuzzy output

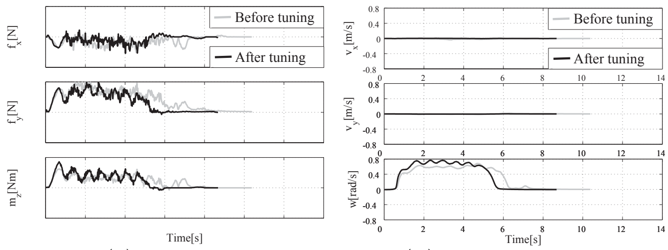
Fig.18 Movement of OMW at l_{wa}=0[m]

5.4 CONCLUSION

An innovative human-interface using a touch panel that provides easy input and feedback information of the operation of a power-assisted wheelchair in real time was developed. Furthermore, adaptive control using a Neuro-Fuzzy system was proposed in a human friendly fashion by means of a touch panel as a human-interface for improving the operability of the wheelchair. Furthermore, it was shown that the rotation center can be freely shifted by both the proposed coordination transformation algorithm and by using the touch panel. The system was tested by simulation and experiments, and its effectiveness was clearly demonstrated.

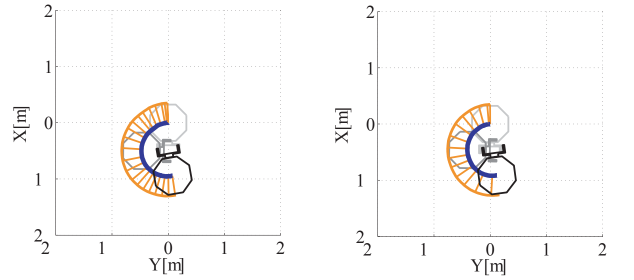


(a) Fuzzy control with Fig.18(b) (b) After tuning

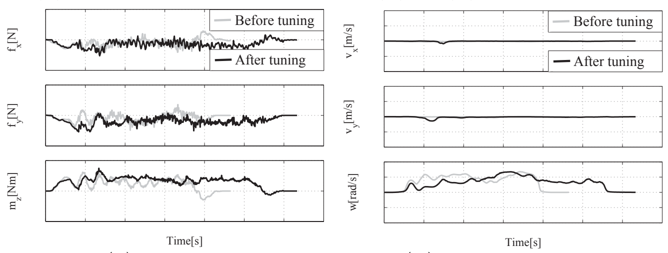


(c) Force input (d) Fuzzy output

Fig.19 Movement of OMW at l_{wa}=0.2[m]

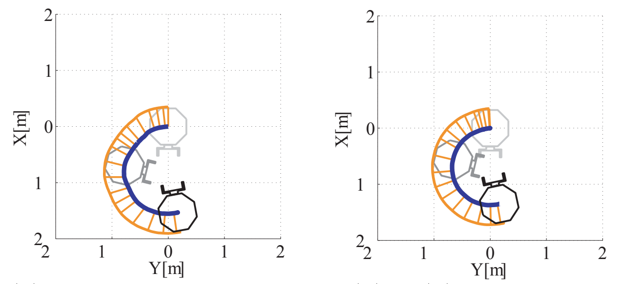


(a) Fuzzy control with Fig.18(b) (b) After tuning

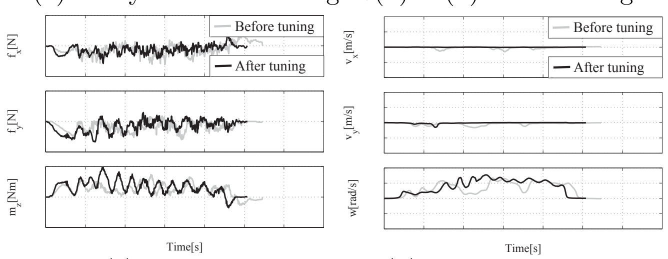


(c) Force input (d) Fuzzy output

Fig.20 Movement of OMW at l_{wa}=0.45[m]



(a) Fuzzy control with Fig.18(b) (b) After tuning



(c) Force input (d) Fuzzy output

Fig.21 Movement of OMW at l_{wa}=0.7[m]

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