Wheelchair control based on a polynomial function approximating a user's gaze curve

著者	Furuya Sawako, Alexopoulos Alexander, Badreddin Essameddin, Watanabe Tetsuyou
journal or publication title	Proceedings of the IEEE/SICE International Symposium on System Integration (SII)
number	13-15 Dec. 2016
page range	16656226
year	2016-12-13
URL	http://hdl.handle.net/2297/46896

doi: 10.1109/SII.2016.7843984

Wheelchair Control Based on a Polynomial Function Approximating a User's Gaze Curve

Sawako. Furuya, Alexander. Alexopoulos, Essameddin. Badreddin, and Tetsuyou. Watanabe, *Member, IEEE*

***Abstract*— We propose a new wheelchair control system based on a polynomial function approximating a user's gaze curve. Conventional studies utilizing gaze data recognized three wheelchair movements: "go straight," "turn right," and "turn left." However, it was difficult for the system to assess when it should switch wheelchair motions because the user's gaze was always changing. To solve this problem, we divided "turn right" and "turn left" wheelchair movements into three groups each in order to control the wheelchair easily. Consequently, the system has to recognize seven wheelchair movements: straight, and three groups each for turning right and left. It is not sufficiency for a system to assess seven wheelchair movements by only the user's gaze. Thus, we developed a wheelchair system considering not only the user's gaze but also the angular velocity and acceleration to control wheelchair motions. We approximated the user's gaze using a polynomial function, and calculated the fine gaze angle, angular velocity and acceleration. The effectiveness of the proposed method was shown by experimental results.**

I. Introduction

Recently, many studies have examined moving a wheelchair without using hands or arms for older and disabled persons [1]-[13]. Our study also aims at developing a wheelchair control system by using the user's gaze. The key design requirements for our control system are

- only the horizontal gaze curve is used, and
- recognizing seven different wheelchair motions.

Preliminary experiments show that a user's vertical gaze angle is almost constant even if the wheelchair motion changes. For stable control, we will construct a control system utilizing only the horizontal gaze curve.

Conventional systems recognize the three wheelchair movements of "go straight,", "turn left," and "turn right" [4][5]. Many wheelchair studies control the velocity of a wheelchair according to the user's gaze angle. However, controlling velocity according to a user's gaze is difficult because it is not always in a constant direction and sometimes changes because of physiological factors. Thus, the system needs to control the velocity of a wheelchair based on a user's gaze for each of the wheelchair's motions. However, different trajectories exist in a wheelchair's movement of "turn right (left)." For example, the trajectories of turning right at a corner and just turning to the right from going straight are different. These motions are both "turn right," but are different situations. If these motions are both characterized as "turn right," controlling the wheelchair by the user's gaze becomes difficult. To overcome this, our study divided the wheelchair movements of "turning right (left)" into three groups (Fig.1).

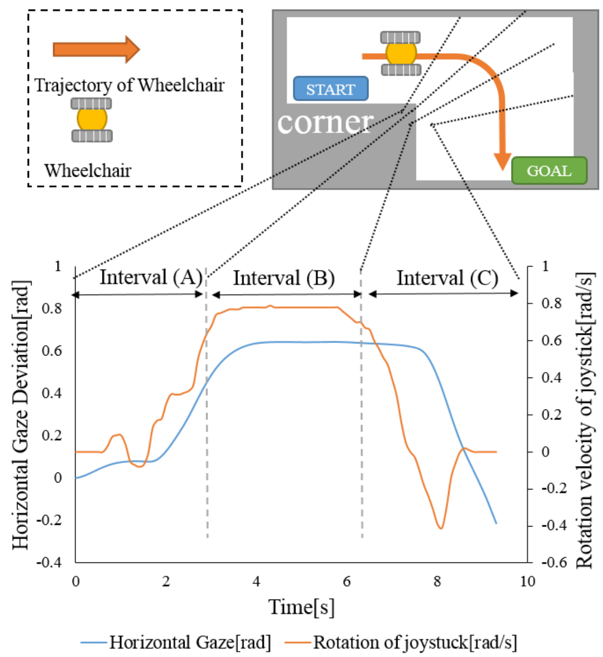


Figure 1. Deviation of gaze angle during wheelchair movement

Fig. 1 describes the deviation of the horizontal gaze angle and rotational velocity of a joystick while a wheelchair is turning right. By subdividing the wheelchair's motion when turning right, the system can easily control the velocity of the wheelchair. In our study, the system recognizes seven wheelchair movements. However, recognizing seven wheelchair movements by using only the horizontal gaze is not sufficient in our study. Thus, our approach is that the system considers not only the gaze angle but also the angular velocity and acceleration when it controls wheelchair movement. In this paper, to compute the gaze angle, angular velocity and acceleration, we propose a method of utilizing a polynomial

*Research supported by Kanazawa University and Heidelberg University.

Sawako. Furuya is with Division of Mechanical Science and Engineering, Kanazawa University, Natural Science Building 3, Nu 7, Kakuma, Kanazawa, Ishikawa, Japan (corresponding Sawako. Furuya to provide phone: 076-234-4684; fax: 076-234-4684; e-mail: s-furuya@stu.kanazawa-u.ac.jp).

Alexander. Alexpoulos is with Heidelberg University, B6 26, Mannheim, Germany. (e-mail: alexander.alexopoulos@ziti.uni-heidelberg.de).

Essameddin. Badreddin is with Heidelberg University, B6 26, Mannheim, Germany. (e-mail: essameddin.badreddin@ ziti.uni-heidelberg.de).

Tetsuyou. Watanabe is with Kanazawa University, Natural Science Building 3, Nu 7, Kakuma, Kanazawa, Ishikawa, Japan. (e-mail: te-watanabe@ieee.org).

function to approximate the gaze curve. The merits of this method are

- Simplicity
- Expandability
- Noise rejection

Modelling the gaze with a polynomial function is clearly easy. Moreover, using a polynomial function approximating the gaze curve, we can construct a local model, which makes further extension of the method easy (for example, a model based on observers can be applied). When the system computes the angular velocity and acceleration, normally, these values are computing by a differentiated gaze angle. However, these values also include considerable noise. To solve this problem, our approach is to compute these values using a polynomial function approximating the user's gaze. This is tested through experiment to compare our approach with that of using just the differentiated gaze.

A. *Related Work*

Tomari et al. [4] [5] developed a system for severely motor impaired individuals to operate a wheelchair by using head motions and gaze directions in a narrow space. This system was composed of multi-input devices: Kinect and a webcam. The system is controlled by three wheelchair motions: straight, right, and left, with large gaze deviation changes corresponding to each of the wheelchair's motions. Moreover, Arai et al. [6] presented a system that detects a user's horizontal and vertical gaze directions. After capturing the image of the user's pupil, the system analyzes the image to determine the direction in which the user is looking. Utilizing both the horizontal and vertical gaze directions, the system is able to affect various wheelchair motions, stop, and pause, by gaze behaviors. These results were applied to the thresholds of gaze deviation for each of the wheelchair's motions. Thus, the system can recognize wheelchair movements. Purwanto et al. [7] developed a system to control the velocity of a wheelchair using the gaze direction. These directions are converted by an original equation using facial images. Differentiated gaze angles are used to set the velocity, acceleration, and rotation of the wheelchair. Pai et al. [8] conducted research to control wheelchair motions by means of pupil images. By analyzing where a user's pupil is in an image, the system can control wheelchair motions. Considering the calibration of the wheelchair is important. Lin et al. [9] noted the way in which calibration can be conducted for the wheelchair to be moved using gaze direction; they developed an interface using image processing. The system calculates the position of the pupil in an image in real time. Applying these results to control wheelchair motions, the system enhanced usability. Until now, our work has been developed for a wheelchair system using a Hidden Markov Model (HMM) [11]. We collected much of the data on a subject's gaze direction while the wheelchair moves, and the data is applied to the HMM. System outputs of suitable wheelchair motions were based on sample data. However, correcting sample data requires significant time and work effort. Our approach does not need to use as much sample data as our previous study. Our proposed system should reduce the time and work required to correct the sample data considerably.

II. WHEELCHAIR SYSTEM

In this section, the utilized wheelchair system is introduced.

A. *Devices*

Our study uses the following devices. Fig. 2 left is an electronic wheelchair made by *Otto Bock Healthcare GmbH* that is used as the basis for the gaze-based assistance system. This electric wheelchair was also utilized in our previous study [10]-[13]; it can estimate the user's intentions and targeted goals progressively. Fig. 2 right shows the equipment of *Senso Motoric Instruments GmbH* used to capture gaze angles. These glasses detect the user's pupil image and convert it to the gaze angle. More detailed information about the wheelchair system is given in Batrolein et al. [10]-[12].

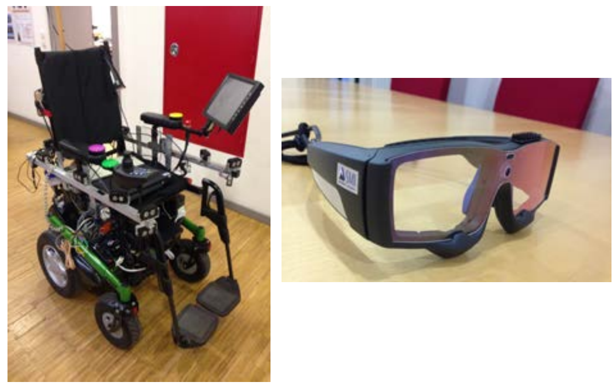


Figure 2. Electronic wheelchair and pupil glasses

B. *Overview of Control System and Problem Definition*

An electronic wheelchair has various functions. Fig.3 shows the detail of the wheelchair structure. In order to have multiple functions, this system is applied with Recursive Nested Behavior-based Control (RNBC) [10]-[13] (Fig.3). Fig. 3 shows the control systems using RNBC [12]. By using the hierarchical structure of RNBC, it enables the system to estimate user intention, output wheelchair motions, and perform more functions. These functions are related with each level of the hierarchical structure. Bartolein et al. state, "Mission related global goals need to be decomposed into spatial sub goals by path planning functionality. To reach the estimated or mission related spatial goal positions, suitable trajectories must be generated by local navigation, knowing about the wheelchair's current position via position update. To ensure safe drive through the environment, the reference velocities generated by the motion estimation or the local navigation can be modified by the underlying collision avoidance behavior." (Bartolein et al. 2007). Our study targeted the white square area in Fig. 3. We developed the system of Gaze-based Motion Estimation, Position Update and Gaze-based Goal Estimation in Fig. 3. Using data of the gaze angle from sensor input, the system controls wheelchair motions and outputs wheelchair velocity corresponding to the wheelchair motions.

The Flowchart of our approach is shown in Fig. 4. Let the user's horizontal gaze angle from sensor be $E_h(t) \in R$, gaze angle be $E(t) \in R$,angular velocity be $V(t) \in R$, angular acceleration be $A(t) \in R$, and wheelchair movements be $W(t)$ at time t. The input is the horizontal gaze angle. Using the gaze angle and method of *Polynomial Function Approximating user's Gaze Curve* (PFAGC), the system computes the gaze angle, angular velocity and acceleration. Using these values, the system controls wheelchair movements. The output is in the form of seven wheelchair movements. According to the wheelchair movements, the system controls the velocity of the wheelchair.

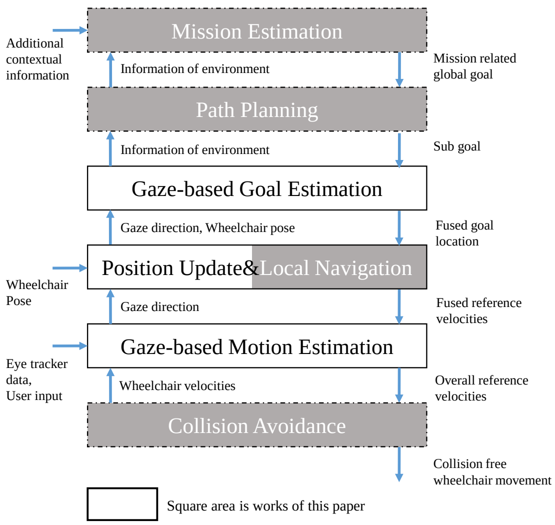
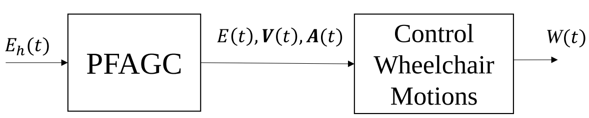


Figure 3. Structure of recursive nested behavior-based control



Input: Horizontal gaze angle $E_h(t)$
Output : Wheelchair Movement $W(t)$
$E(t)$: gaze angle
$\boldsymbol{V}(t)$: angular velocity
$\boldsymbol{A}(t)$: acceleration

Figure 4. Structure of this system

III. Wheelchair Motions

In this section, we describe the seven wheelchair motions and the method of recognizing between them in a wheelchair system.

A. *Seven Wheelchair Motions*

The seven wheelchair movements are as follows: Straight, Curve in Right, Curve Right, Curve out Right, Curve in Left, Curve Left, and Curve out Left. Fig. 1 shows more detail of the subdivided "turn right (left)". We also set "turn left" the same as "turn right." Straight means that the wheelchair goes straight. Curve in Right and Curve in Left mean that the wheelchair is going to turn right and left at interval (A) in Fig. 1. Curve Right and Curve Left mean that wheelchair just turned right and left at interval (B) in Fig. 1. Curve out Right and Curve out Left mean that the wheelchair finishes turning right or left and moves in a straight direction at interval (C) in Fig. 1. In this study, the system recognizes these seven wheelchair movements and outputs the velocity of each of the wheelchair's movements. We summarize the abbreviations corresponding to wheelchair movements in Table I.

TABLE I. Wheelchair Motions and Abbreviations

Wheelchair Motions	Abbreviation
Straight	ST
Curve in Right	CIR
Curve Right	CR
Curve out Right	COR
Curve in Left	CIL
Curve Left	CL
Curve out Left	COL

B. *Thresholds for Controlling Wheelchair Movements*

Here, an overview of the method of deciding wheelchair motions is described. Fig. 5 shows the flowchart of control of the seven wheelchair motions. Table II describes the range of each of the thresholds for each of the wheelchair's movements. To recognize the seven wheelchair motions, we set thresholds of the gaze angle, angular velocity, and acceleration for each of the wheelchair motions. Let the minimum thresholds of gaze be E_{min}, E^*_{min}, the maximum thresholds of gaze be E_{max}, E^*_{max}, the minimum thresholds of angular velocity be V_{min}, V^*_{min}, the maximum thresholds of angular velocity be V_{max}, V^*_{max}, the minimum threshold of angular acceleration be A_{min}, and the maximum threshold of angular acceleration be A_{max}. Preliminary experiments show that the

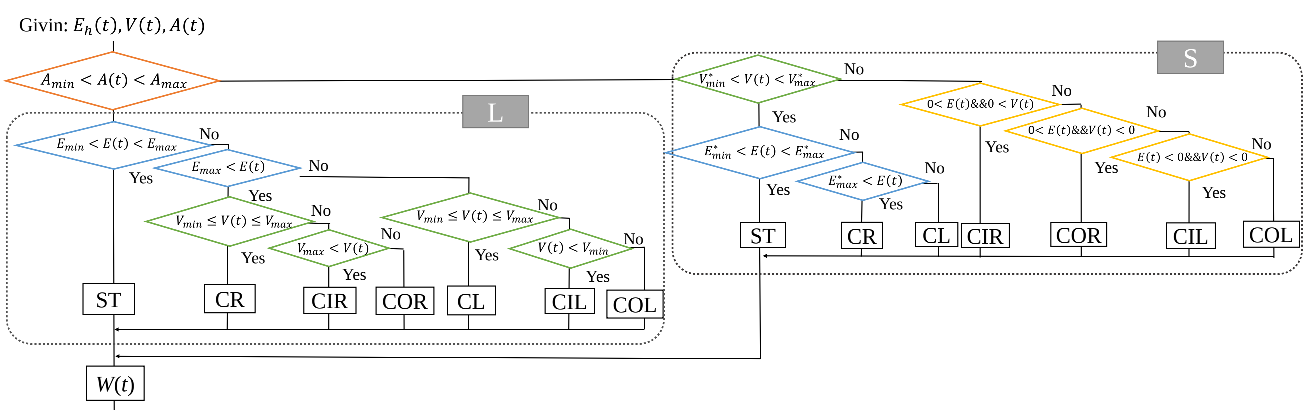


Figure 5. Flowchart for controlling wheelchair movements

values of gaze angle, angular velocity, and acceleration are different according to the wheelchair motions. Thus, we establish the thresholds for when the system should switch wheelchair motions; the system can then easily control wheelchair motions.

The reason we established the L and S groups in Fig. 5 and Table II, the seven wheelchair motions have some features for gaze angle, angular velocity, and acceleration. If wheelchair motions are CIR, COR, CIL, and COL, acceleration $\boldsymbol{A}(t)$ at time *t* is likely to be over A_{max} or under A_{min} (the S group in Fig. 5). On the other hands, if wheelchair motions are ST, CR, and CL, acceleration $\boldsymbol{A}(t)$ is over A_{min} and under A_{max} .Thus, considering acceleration first, the system can recognize CIR, COR, CIL, and COL, or ST, CR, and CL. However, even if the wheelchair movements are ST, CR, and CL, acceleration $\boldsymbol{A}(t)$may be over A_{max} or under A_{min}. Then, considering $V(t)$ and $E(t)$, the system can deal with various situations in the S group in Fig. 5. In the L group in Fig. 5, the main recognition is wheelchair motions of ST, CR, and CL. Considering $E(t)$, the system can recognize ST or CR and CL. However, even if wheelchair movements are CIR, COR, CIL, and COL, acceleration $\boldsymbol{A}(t)$ is likely to be over A_{min} and under A_{max}. Thus, we set the other thresholds of angular velocity V_{min}, V_{max} in order to recognize CR and CL or CIR, COR, CIL and COL. Utilizing this flowchart, the system can recognize the seven wheelchair motions.

TABLE II. THRESHOLDS OF GAZE AND ANGULAR VELOCITY AND ACCELERATION FOR EACH OF WHEELCHAIR'S MOTIONS

		Gaze Angle	Angular Velocity	Angular Acceleration
ST	L	$E_{min} \le E(t) \le E_{max}$	$V_{min} \le \boldsymbol{V}(t) \le V_{max}$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$E^*_{min} \le E(t) \le E^*_{man}$	$V^*_{min} \le \boldsymbol{V}(t) \le V^*_{max}$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$
CIR	L	$E_{max} < E(t)$	$V_{max} < \boldsymbol{V}(t)$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$0 < E(t)$	$0 < \boldsymbol{V}(t)$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$
CR	L	$E_{max} < E(t)$	$V_{min} \le \boldsymbol{V}(t) \le V_{max}$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$E^*_{man} < E(t)$	$V^*_{min} \le \boldsymbol{V}(t) \le V^*_{max}$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$
COR	L	$E_{max} < E(t)$	$\boldsymbol{V}(t) < V_{min}$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$0 < E(t)$	$\boldsymbol{V}(t) < 0$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$
CIL	L	$E(t) < E_{min}$	$\boldsymbol{V}(t) < V_{min}$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$E(t) < 0$	$\boldsymbol{V}(t) < 0$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$
CL	L	$E(t) < E_{min}$	$V_{min} \le \boldsymbol{V}(t) \le V_{max}$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$E(t) < E^*_{min}$	$V^*_{min} \le \boldsymbol{V}(t) \le V^*_{max}$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$
COL	L	$E(t) < E_{min}$	$V_{max} < \boldsymbol{V}(t)$	$A_{min} \le \boldsymbol{A}(t) \le A_{max}$
	S	$E(t) < 0$	$0 < \boldsymbol{V}(t)$	$\boldsymbol{A}(t) < A_{min}$, $A_{max} < \boldsymbol{A}(t)$

IV. POLYNOMIAL FUNCTION APPROXIMATING USER'S GAZE CURVE

In this section, we explain the method of deriving a polynomial function approximating a gaze curve and deriving the velocity and acceleration. The purpose of the approximation is to derive noise-reduced values for angular velocity and acceleration. In our study, to achieve these purposes, gaze angle, angular velocity and acceleration are computed by regression of the curve of gaze using a polynomial function. Here is the procedure.

Consider a time $t = t_n$ where we have *n* gaze data points $P_i(t_i, E_{\mathrm{h}}(t_i)) =$ $(t_1, E_{\mathrm{h}}(t_1)), (t_2, E_{\mathrm{h}}(t_2)), (t_3, E_{\mathrm{h}}(t_3)), \ldots, (t_n, E_{\mathrm{h}}(t_n))$ ($t_i < t_{i+1}, i = 1,2,3, \ldots n-1$). Then *n* gaze data points $P_i(t_i, E_{ht})$ are described by a polynomial function:

$$E(t) = a_0 + a_1 t_i + a_2 t_i^2 + \cdots + a_m t_i^m, \qquad (1)$$

where *m* is the dimension of the polynomial function, and $a_0, a_1, a_2, \ldots a_m$ are the constants. Let $\boldsymbol{a}$ be $[a_0 \quad a_1 \quad a_2 \quad \cdots \quad a_n]^T$. We will derive ***a*,** which minimizes the following squared error:

$$\begin{aligned} e &= \underset{\boldsymbol{a}}{\operatorname{argmin}} \sum_{i=1}^{n} \left\| \hat{\mathrm{E}}(t_i) - E_h(t_i) \right\|^2 \\ &= \underset{\boldsymbol{a}}{\operatorname{argmin}}\, \boldsymbol{a}^T \boldsymbol{W} \boldsymbol{a} - 2\boldsymbol{a}^T \boldsymbol{b} + \textstyle\sum_{i=1}^{n} E_h(t_i)^2, \end{aligned} \qquad (2)$$

where

$$\begin{aligned} \boldsymbol{W} &= \textstyle\sum_{i=1}^{n} \boldsymbol{c}_{\mathrm{i}} \mathbf{c}_{\mathrm{i}}^T, \\ \boldsymbol{b} &= \textstyle\sum_{i=1}^{n} E_h(t_i) \boldsymbol{c}_{\mathrm{i}}, \\ \boldsymbol{c}_{\mathrm{i}} &= \begin{pmatrix} 1 & t & t^2 & \cdots & t^m \end{pmatrix}^T. \end{aligned} \qquad (3)$$

From $\frac{\partial \mathrm{e}}{\partial \boldsymbol{a}} = 0$, the solution is represented by:

$$\boldsymbol{a} = \boldsymbol{W}^{+} \boldsymbol{b}. \qquad (4)$$

In our approach, first we apply the gaze angle data with a low-pass filter. Next, we set the filtered gaze curve as in equation (2) by using curve fitting and then calculate the angular velocity and acceleration. Let angular velocity be $\boldsymbol{V}(t)$ and angular acceleration be $\boldsymbol{A}(t)$ at time t. When the dimension of the polynomial function *m* = 2, equation (5) is set as equation (1):

$$E(t) = a_0 + a_1 t_{n+1} + a_2 t_{n+1}^2. \qquad (5)$$

Variables a_0, a_1, a_2 are calculated using equation (4). For the simplicity, we set *m* =2. Then, equation (5) is differentiated as follows:

$$\boldsymbol{V}(t) = 2a_2 t_{n+1} + a_1, \qquad (6)$$

$$\boldsymbol{A}(\mathrm{t}) = 2a_2. \qquad (7)$$

Angular velocity $\boldsymbol{V}(t)$ is calculated using equation (6) and acceleration $\boldsymbol{A}$(t) is computed using equation (7). We named this procedure of computing these values as PFAGC. The merit of this algorithm is its consideration of past gaze angles. Thus, this method has less noise than when just the differentiated angular velocity and acceleration of gaze are used. The significance of using a polynomial function for curve fitting is that the gaze curve is similar to a polynomial. Thus, by using a polynomial function, we get the ideal gaze curve, removing outlier data.

V. EXPERIMENT

In this section, we demonstrate the algorithm on a wheelchair system. In conducting the experiment, we measure whether the system controls each of the wheelchair motions or not according to the thresholds of gaze angle, angular velocity, and acceleration. We conducted this experiment on a Windows PC, not on an electronic wheelchair. The experimental device is a Windows 8.1 system with an, Intel® Core™ i7-4790 CPU. System RAM is 16 GB. The system is developed using C/C++. The system set up is as follows: the number of point for curve fitting is eight, and the sampling time is 0.1 [s]. The gaze angle data was captured on the wheelchair by a joystick beforehand. The subject went straight, turned right, and then went straight again (Fig. 6)

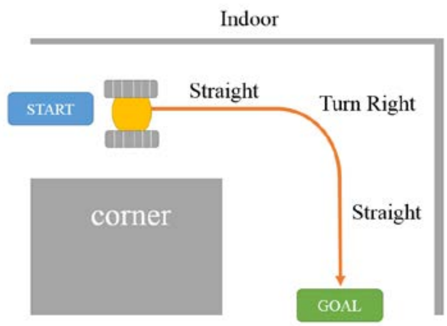


Figure 6. Road Map

The reference value is the rotation velocity of the joystick. Comparing it with our approached method, we confirm whether the system can output the exact wheelchair motions. Moreover, we compare the results with other methods of computing angular velocity and acceleration. One is the method where the gaze angle is differentiated. The angular velocity is simply the differentiated horizontal gaze data, and the angular acceleration is differentiated by the angular velocity. In this case, the input gaze data is not applied with a low-pass filter. We define this method as "*Differential Without Low-Pass Filter* (DWLPF)". The other algorithm also differentiates the gaze angle; however, the gaze angle is applied with a low-pass filter. We call this method "*Differential After Low-Pass Filter* (DALPF)". We then compared these three algorithms to determine which one is the most useful.

The result of the experiment is described in Fig. 7. Fig. 7 (a) is a graph of the horizontal gaze. Fig. 7 (b) is the graph of the angular velocity. Fig. 7 (c) is the graph of the angular acceleration. Fig. 7 (d) is the graph of the angular acceleration except for the values of DWLPF. Because the values of DWLPF were large, we excluded DWLPF in (d). Fig. 7 (e) shows the wheelchair movements. Because it is difficult to compare each data because of the values of DWLPF, Fig. 7 (f) shows the wheelchair movements excluding the data of DWLPF. Fig. 7 (g) is the rotation velocity of the joystick. The gray curve line is the original horizontal gaze angle from sensor. In addition, the blue curve line shows the algorithm of PFAGC, the red curve line is DALPF, the green curve line shows the algorithm of DWLPF, and the yellow curve line is the rotation velocity of the joystick.

Essentially, the joystick data is the rotation velocity. However, the outputs of the wheelchair's motions are the seven motions. To compare the joystick and other algorithm data easily, we made modifications discretely and arbitrarily using the condition of the joystick. When the value of the joystick is between -0.1 [rad/s] and 0.1 [rad/s], it is evaluated as going straight (ST). If it is less than -0.1[rad/s], it is evaluated as Curve in Left (CIL). If it is between 0.1 [rad/s] and 0.3 [rad/s], it is evaluated as Curve in Right (CIR) or Curve out Right (COR). If it is over 0.3 [rad/s], it is evaluated as Curve Right (CR). Using these conditions, we set the rotation velocity of the joystick as the wheelchair's motions. In terms

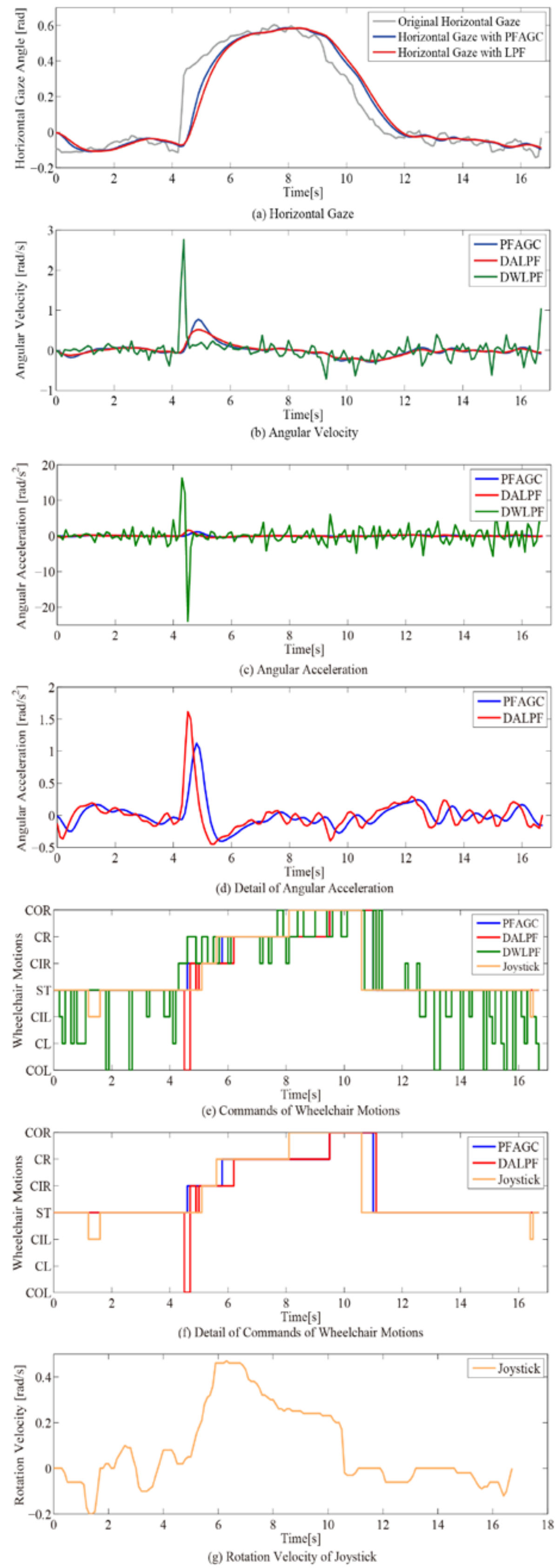


Figure 7. Results of experiment: comparison of three algorithms

of the rotation velocity of the joystick for the time between 0 [s] to 4 [s], the value is changed up and down; however, the wheelchair actually went straight. This was caused by the position of the wheelchair's wheels. When the wheelchair moved straight, for the time between 0 [s] to 4 [s], the wheels were not in the straight direction. The wheels changed wheel position to straight, the wheelchair and joystick were vibrated.

By this condition, we compared the joystick results to the other algorithms. Considering these conditions, we evaluate these results comparing our approach with the other methods. First, seeing (b) and (c) in Fig. 7, the angular velocity and acceleration computed by DWLPF includes noise. As the result, the output of wheelchair movements is unstable and changed continuously. However, the values with PFAGC removed more noise than DWLPF. Thus, the output of wheelchair movements is stable. As a result, DWLPF is not suitable to compute the angular velocity and acceleration. Next, we compare PFAGC with DALPF. Comparing our proposed algorithm to the method of DALPF, the value of the angular velocity is almost the same but the angular acceleration is different. The one with DALPF includes more noise than PFAGC. In reviewing (e) in Fig. 7, the wheelchair motions calculated by DALPF are unstable continuously. Moreover, when the wheelchair movements changed from ST to CIR and from CIR to CR DALPF showed more delay than PFAGC. Thus, PFAGC is more suitable than DALPF in the wheelchair system.

Finally, we compare wheelchair movements of the joystick with the three algorithms. When comparing commands of wheelchair motions derived by DWLPF and the joystick, DWLPF is obviously unstable. DWLPF changed wheelchair movements every time and was not stable. Wheelchair movements of DALPF seemed almost the same as the joystick, however, the wheelchair motions changed sometimes. The wheelchair movements of PFAGC are close to the joystick results. As a result of this experiment, PFAGC is useful in our proposed wheelchair system.

The reason for this result is as follows. When angular velocity and acceleration are calculated by PFAGC, PFAGC uses the polynomial function of the gaze curve. It includes past gaze data and removes errors. Thus, PFAGC can computes the angular velocity and acceleration while removing noise more effectively than DALPF. DALPF applies the low-pass filter. Even if applied with the low-pass filter, DALPF cannot remove sufficient noise.

VI. Conclusion

In this paper, we developed a wheelchair control system using a polynomial function approximating the user's gaze curve. The key design elements of our control system were 1) only the horizontal gaze curve is used and 2) system recognizes seven different wheelchair motions. Wheelchair systems of conventional studies recognized three wheelchair motions by only using the horizontal gaze. However, it was difficult for our wheelchair system to control seven wheelchair motions by using only the horizontal gaze. To solve this problem, our system considered not only the horizontal gaze angle but also the angular velocity and acceleration to control the seven wheelchair motions. We approximated the gaze using a polynomial function, determining the fine angular velocity and acceleration. The purposes of using a polynomial function approximation were "Simplicity," "Expandability," and "Noise Rejection." As the result of the experiment, in terms of the data of gaze angle, angular velocity and acceleration, our approach removed more noise than just differentiation. Moreover, the system output wheelchair movements with stability resembling that of a joystick. Thus, we achieved the purpose of developing a system using a polynomial function approximation. Our system requires thresholds of gaze, angular velocity, and acceleration to control each of the wheelchair's motions. These thresholds are different for each user. Before using our system for a user for the first time, we have to set up the thresholds manually. In future, we are going to develop a system to control these thresholds automatically for each user. Another future work might be to estimate whether gaze movement is related with wheel chair control or not.

References

[1] L. Montesano, M. Diaz, S. Bhaskar, and J. Minguez, "Towards an Intelligent Wheelchair System for Users With Cerebral Palsy," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 18, No.2, April, 2010.

[2] E. Wästlund, K. Sponseller, and O. Pettersson, "What You See is Where You Go: Testing a Gaze-Driven Power Wheelchair for Indivisuals with Severe Multiple Disabilities," ETRA'10 Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications, pp. 133-136.

[3] P. Novák, T. Krajník, L. Přeučil, M. Fejtová, and O. Stépánková, "AI Support for a Gaze Controlled Wheelchair," The 4th Conference on Communication by Gaze Interaction – COGAIN, 2008.

[4] M. R. M Tomari, Y. Kobayashi, and Y. Kuno, "Development of Smart Wheelchair System for a User with Severe Motor Impaorment," International Symposium on Robotics and Intelligent Sensors 2012, Procedia Engineering 41, pp. 538-546.

[5] R. Tomari, Y. Kobayashi, Y. Kuno, "A Framework for Controlling Wheelchair Motion by using Gaze Information," International Journal of Integrated Engineering, vol. 5, no. 3, pp. 40-45, 2013.

[6] K. Arai, and R. Mardiyanto, "A Prototype pf Electric Wheelchair Contorlled by Eye-Only for Paralyzed User," Journal of Robotics and Mechatronics, vol. 23, No.1, 2011.

[7] D. Purwanto, R. Mardiyanto, and K. Arai, "Electric wheelchair control with gaze direction and eye blinking," Artif Life and Robotics, December 2009.

[8] S. Pai, S. Ayare, and R. Kapadia, "Eye Controlled Wheelchair," International Journal of Scientific & Engineering Research, vol. 3, October 2012.

[9] C. S. Lin, C. W. Ho, W.C. Chen, C. C. Chiu, and N. S. Yen, "Powered wheelchair controlled by eye-tracking system," Optica Application, vol. XXXVI, no. 2-3, 2006.

[10] C. Bartolein, A. Wagner, M. Jipp, and E. Badreddin, "Multilevel Intention Estimation for Wheelchair Control," In Proc.of the European Control Conference, Koa, Greece, 2007.

[11] C. Bartolein, A. Wagner, M. Jipp, and E. Badreddin, "Easing Wheelchair Contoril by Gaze-Based Estimation of Intended Motion," Proceedings of the 17th World Congress The International Federation of Automatic Contorl Seoul, Korea, pp. 9162-9167, July 2008.

[12] E. Badreddin, "Recursive behavior-based architecture for mobile robots," Robotics and Autonomous Systems, vol. 8, 1991.

[13] M. Jipp, E. Badreddin, C. Bartolein, A Wagner, and W. W. Wittmann, "Congnitive Modeling to Enhance Usability of Complex Technical Systems in Rehabilitation Technology on the Example of a Wheelchair," In Proc. of the 2nd Int. Conference on Mechatronics, vol. 2, pp. 1165-1172, 2005.