Manual Control for Driving an Intelligent Wheelchair: A Comparative Study of Joystick Mapping Methods*

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Abstract — **Electric wheelchairs are now more intelligent due to the use of algorithms that provide assisted driving. Typically, the user steers the electric wheelchairs with conventional analog joysticks. This implies the need for an appropriate methodology to map the position of the joystick handle (in a Cartesian coordinate system) to the wheelchair wheel velocities. This mapping of joystick positions to individual wheel speed can be done in an infinite number of combinations. However it is this mapping that will determine the response behavior of the wheelchair to the user manual control. This paper describes the implementation of several joystick mappings in an intelligent wheelchair (IW) prototype. Experiments were performed in a realistic simulator using 25 users with distinct driving abilities. The users had 6 different joystick control mapping methods and for each user the usability and preference order was measured. The results achieved show that a linear mapping, with appropriate parameters, between the joystick's coordinates and the wheelchair wheel speeds is preferred by the majority of the users.**

I. INTRODUCTION

Nowadays the scientific community gives high importance to the real application of new discoveries. In the area of assistive technologies, robotics performs an important role. In particular, electric wheelchairs are now more intelligent due to the implementation of algorithms that assists the driving user.

Most electric wheelchairs are manually steered with a joystick, although there are several other possibilities for the interface between a user and the wheelchair [1-4]. A conventional joystick maps the position of the handle into a Cartesian coordinate system where normalized axis (x, y) range from minus one to plus one, the x axis is oriented towards the right and coordinates at the origin correspond to the central (resting) position.

An electric wheelchair is typically driven by two individually powered wheels which rotate around a horizontal axis, and another two non-powered caster wheels, which besides rotating around a horizontal axis, also have the ability to rotate around a vertical axis. This vertical rotation axis allows the non-powered wheels to steer freely, minimizing friction during direction change. Assuming the terrain is flat and there are no obstacles, when the speed is the same on both powered wheels, the wheelchair moves in a straight line. Steering is determined by the velocity difference of the powered wheels, i.e. the wheelchair will rotate towards the wheel with the lower speed, and rotate around itself when the wheels rotate in opposite directions. The radius of curvature of the wheelchair is dependent on the wheel spacing and also on the traveled distances of each wheel.

The mapping of joystick positions to individual wheel speed can be done in an infinite number of combinations, and it is this mapping that will determine the response behavior to manual control. Several of these mappings were implemented, out of which a few were selected for inclusion in this paper. The level of satisfaction of the volunteers that tested different joystick mappings was measured and some interesting conclusions about mapping were achieved based on the users' feedback.

This paper is organized in six sections. The first section is composed by this introduction. The second section reports the related work and related issues that are under study. The third section briefly presents the IntellWheels project. The implementation of the proposed algorithms is described in section four. Next, the experimental work and results are presented. Finally some conclusions and directions for future work conclude the paper.

II. RELATED WORK

There are a significant number of scientific works related to robotic wheelchairs or intelligent/smart wheelchairs [5][6]. The study about the joystick mapping is also an issue of investigation. Choi [7] describes a more intuitive human interface by changing the prior mapping method of the joystick, which considers the consecutive operations of a motor of a wheelchair, to a new mapping method that corresponds to the internal model of a human being. They

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divided the existing joystick mapping method into two degrees of freedom, one in the vertical axis that can control the velocity and the other, in the horizontal axis for direction control, and controlled the wheelchair with an electromyography (EMG) signal. Dicianno et al. [8] concluded that individually customized isometric devices may be superior to commercially available proportional control for individuals with tremor, even though the used filtering did not improve the wheelchair driving as expected. In [9] an evaluation of the use of force feedback joysticks with a powered wheelchair is performed and it was concluded that on people without disabilities there were some advantages (less collisions). Niitsuma et al. [10] introduced a vibrotactile interface that could be controlled by users even if they had not used one before, and although through the experiments for the vibration stimuli, users could not detect exact orientation of obstacles, it was possible to detect a direction of the obstacle movement. In [11] a reactive shared control system was presented which allows a semi-autonomous navigation in unknown and dynamic environments using joystick or voice commands.

III. INTELLWHEELS PROJECT

The IntellWheels project aims at developing an intelligent wheelchair platform that may be easily adapted to any commercial wheelchair and aid any person with special mobility needs [12]. The project main focus is the research and design of a multi-agent platform, enabling easy integration of different sensors, actuators, devices for extended interaction with the user, navigation methods and planning techniques and methodologies for intelligent cooperation to solve problems associated with intelligent wheelchairs [13] [14].

A real prototype (Fig. 1) was created by adapting a typical electric wheelchair. Two side bars with a total of 16 sonars, a laser range finder and two encoders were incorporated.

Figure 1. The real prototype of the IW

In order to test the algorithms and methodologies a simulator was also developed. With this simulator a virtual world can be created where a user can drive a IW with behavior similar to the real prototype. The virtual wheelchair (Fig. 2) was modeled with 3D Studio Max [15], the virtual environment was modeled with 3D UnrealEditor and USARSim [16] was the platform chosen for the simulation of robots and environments. USARSim is based on the Unreal Tournament game engine [16] and is intended as a general purpose research tool with various applications from human computer interfaces to behavior generation for groups of heterogeneous robots [16].

Figure 2. The virtual prototype of the IW

The purpose of this simulator is essentially to support the test of algorithms, analyze and test the modules of the platform and safely train users of the IW in a simulated environment [17] [18].

A multimodal interface was also developed that allows driving the wheelchair with several inputs such as joystick, head movements or more high level commands such as voice commands, facial expressions, and gamepad or even with a combination among them. For example it is possible to blink an eye and say “go” for the wheelchair to follow a right wall [19] [20] [21].

The joystick mapping is important, because this mapping will determine the response behavior of the wheelchair to the user manual control. For that reason, different ways of mapping the joystick signal were tested. The next section presents different alternatives and considerations regarding the used mapping algorithms.

IV. IMPLEMENTATION OF JOYSTICK MAPPING ALGORITHMS

This section presents the implemented joystick mappings, aiming to achieve a more pleasant wheelchair driving experience. Considering that the joystick handle position is represented in a Cartesian coordinate system, with two axis, x and y, which vary between -1 and 1. These (x, y) coordinates can be used to determine the distance of the handle to the central (resting) position of the joystick (0, 0) and an angle relating to a reference vector (which is usually (0, 1)). The desired speed of the left wheel (L) or the right wheel (R) is represented by normalized values (between -1 and 1). With positive values the wheels rotate forward and with negative values the wheels rotate backward.

All mappings should meet the following conditions: θ is measured in relation to vector (0, 1); when θ is undefined , i.e when $(x, y) = (0, 0)$, both wheels will not be actuated; when $\theta = 0$, both wheels move forward at the same speed; when $\theta = \pm\pi$, both wheels move backward at the same speed; when $\theta = \pm\pi/2$, the wheels rotate in opposite directions and when $\theta = \pm\pi/4$, one of the wheels stops, and the other one rotates, making the chair turn around the stopped wheel.

A. *Algorithm **A** - First Alternative*

The mapping algorithm A proposed is very simple. The steering and power mapping is achieved through the use of both x and y in all instances and the wheelchair can rotate around itself when the joystick is pushed to the sides. Assuming that x and y are normalized and vary between -1 and 1 the system of equations can be observed in (1):

$$\begin{cases} R = y - x \\ L = y + x \end{cases} \quad (1)$$

Note that at the central position (0, 0) no power is sent to the wheels. When x is near 0, and the joystick is pushed forward/backward, the speed increases proportionally to y, and the wheelchair moves forward/backward. There is no rotation because x equals zero, thus left speed and right speed are equal.

For all other values of x, when the joystick is pushed to either left or right, the right speed is proportional to (y-x) and left speed is proportional to (x+y). It is important to notice that the right speed and left speed are clipped when (y-x) or (x+y) are above the maximum (or below the minimum) normalized values. This implies a loss of the useable joystick area. Additionally, some filtering was added, so that minimal (x, y) variation near the axis is ignored. When the wheels rotate in opposite directions, speed is halved on both wheels.

With this algorithm, steering the wheelchair requires accurate precision. The wheel speed variations that result from lateral joystick movements are quite steep, and when moving forward, little variations on the joystick horizontal axis result in a big adjustment of the direction.

Fig. 3 represents the left and right wheel speed mapping as a function of the x and y positions of the joystick. Fifty percent of gray matches speed zero, lighter areas correspond to positive velocities, where white represents the maximum, and darker areas represent negative velocities, where black represents the maximum negative velocity. All tones in between correspond to an intermediate speed.

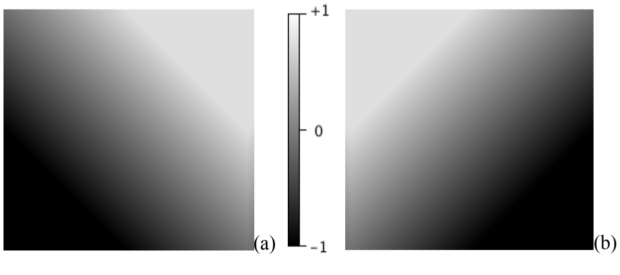

Figure 3. (a) and (b) represent the left and right wheel speed mapping, respectively, as a function of the x and y positions of the joystick – algorithm A.

Fig. 3 confirms that when the joystick is at (1, 1), i.e. to the front and right, the left wheel speed is clipped at its maximum, and the right wheel speed is at fifty percent gray, which means the right wheel is stopped. In this condition, the wheelchair will rotate around the right wheel.

When the joystick is maintained at x=1 and y is pulled from 1 towards 0, left wheel speed is maintained and right wheel speed becomes negative, reaching the maximum negative speed when y equals zero. Due to a constraint in the algorithm, the clipping at the maximum and minimum speed is quite strong (visible in the full white/full black areas) and results is a loss of useable joystick area.

The input variables were squared in order to attenuate the steep changes in wheelchair direction. Fig. 4 shows the wheel speeds when using attenuation and a significant improvement in terms of range extension.

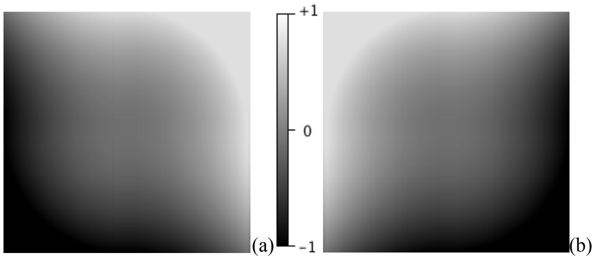

Figure 4. (a) and (b) respectively represent the left and right wheel speed mapping as a function of the x and y positions of the joystick – algorithm A with attenuation.

B. *Algorithm **B** – Second Alternative*

In this algorithm, the distance of the handle to the center of the joystick (ρ) is proportional the maximum wheel speed and the angle (θ) of the joystick relating to the vector (0, 1), i.e. the y axis, determines how the speed is distributed to the wheels. In order to keep ρ minor or equal to 1, the value is clipped when ρ is above one. Assuming that x and y are normalized and vary between -1 and 1, the control follows these conditions:

$$R = \begin{cases} \rho , if \ 0 \le \theta \le \dfrac{\pi}{2} \\ \rho . \dfrac{-\theta + 3.\pi / 4}{\pi / 4} , if \ \dfrac{\pi}{2} \le \theta \le \pi \\ -\rho , if \ -\pi < \theta < -\dfrac{\pi}{2} \\ \rho . \dfrac{\theta + \pi / 4}{\pi / 4} , if \ -\dfrac{\pi}{2} \le \theta \le 0 \end{cases} \quad (2)$$

$$L = \begin{cases} \rho . \dfrac{-\theta + \pi / 4}{\pi / 4} , if \ 0 \le \theta \le \dfrac{\pi}{2} \\ -\rho , if \ \dfrac{\pi}{2} \le \theta \le \pi \\ \rho . \dfrac{\theta + 3.\pi / 4}{\pi / 4} , if \ -\pi < \theta < -\dfrac{\pi}{2} \\ \rho , if \ -\dfrac{\pi}{2} \le \theta \le 0 \end{cases} \quad (3)$$

where $\rho = \sqrt{x^2 + y^2}$ and $\theta = \text{atan2}(-x, y)$.

If ρ > 1, ρ is clipped back to 1 or if ρ < -1, ρ is clipped back to -1.

As can be seen in Fig. 5 (a) and (b), the speed variation is extended towards the corners of the joystick, and clipping is minimized when compared to the previous algorithm, however, even though experimentally, this algorithm provides a more pleasant driving experience, steering is still not as smooth as desired.

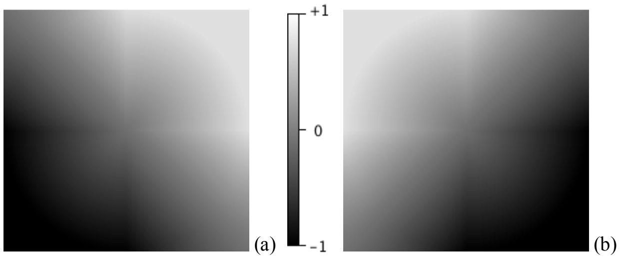

Figure 5. (a) and (b) respectively represent the left and right wheel speed mapping as a function of the x and y positions of the joystick – algorithm B.

It was also observed that as the joystick moved away from the y axis, the curvature radius would decrease very fast. In order to resolve this issue, the joystick axis values were attenuated with a quadratic function.

Fig. 6 (a) and (b) represent the left and right wheel speed mapping as a function of the x and y positions of the joystick, after attenuating the axis readings. Fifty percent gray matches speed zero, lighter areas correspond to positive velocities, where white represents the maximum, and darker areas represent negative velocities, where black represents the maximum negative velocity. All tones in between correspond to an intermediate speed.

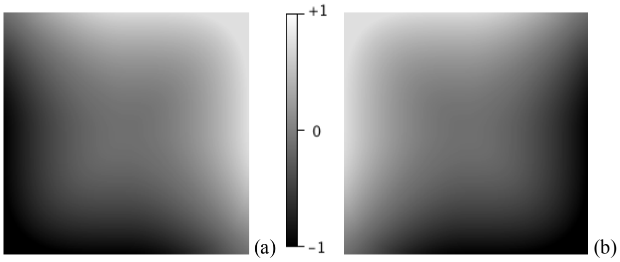

Figure 6. (a) and (b) respectively represent the Left and Right Wheel speed mapping as a function of the x and y positions of the joystick – algorithm B with attenuation.

Comparing Fig. 5 and 6, it is visible that with the input variables attenuation, the speed variation is more uniformly spread, extended towards the corners, and with minimal clipping. This attenuation can be felt while driving as a more natural, smoother and precise driving experience.

*C. Algorithm **C** – Third Alternative*

This mapping is an updated version of algorithm A. Assuming that x and y are normalized and vary between -1 and 1, the equations applied are:

$$\begin{cases} R = y - nx \\ L = y + nx \end{cases} \tag{4}$$

where the equations follow the next conditions that can be observed in the equation (5):

$$\begin{cases} if\ \frac{x}{2} > 0.1, & nx = 0.1 + (x/2 - 0.1)/2 \\ if\ \frac{x}{2} < -0.1, & nx = -0.1 + (x/2 + 0.1)/2 \\ else & nx = x/2 \end{cases} \tag{5}$$

This algorithm goes beyond the range of algorithm A, minimizing clipping as can be observed in Fig. 7.

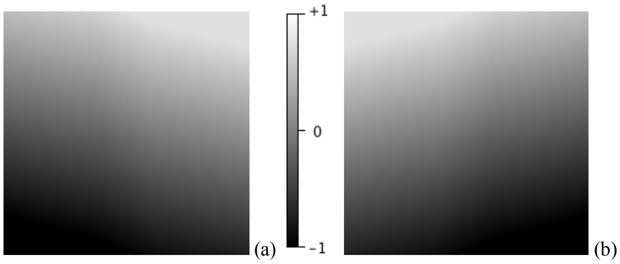

Figure 7. (a) and (b) respectively represent the Left and Right Wheel speed mapping as a function of the x and y positions of the joystick – algorithm C.

At this point, attenuation with an exponential function was also applied to algorithm C. Fig. 8 reports the difference in behavior.

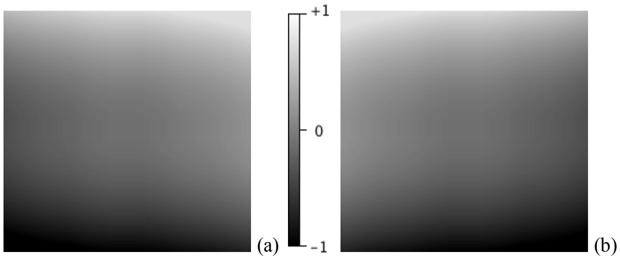

Figure 8. (a) and (b) respectively represent the Left and Right Wheel speed mapping as a function of the x and y positions of the joystick – algorithm C with attenuation.

V. EXPERIMENTS AND RESULTS

The implemented control algorithms were tested with real users, in a simulated environment, in order to verify the usability of the different mappings. A circuit was developed using the simulator. Fig. 9 shows the overall circuit.

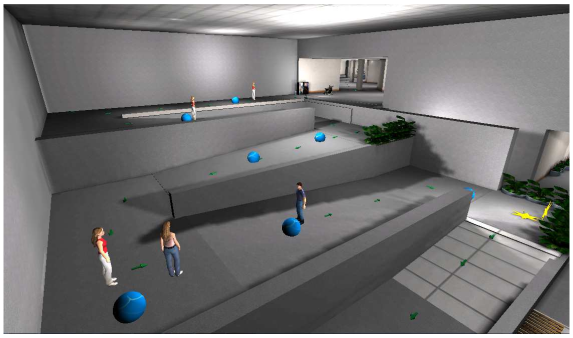

Figure 9. Circuit and tasks used for testing

A kind of serious game was created. The game objective was to follow a specific track collecting eight blue balls and at the end a yellow star. The green arrows just indicate the route and the blue balls were obligatory checkpoints, since they could be collected by passing near them. The people added to the environment were dynamic obstacles that should be avoided.

A quasi-experimental study was performed. The volunteers had an explanation of the purpose of the study and signed the inform consent. A questionnaire was elaborated and was composed of four parts: user identification; experience with videogames and joysticks; questions adapted from the Computer System Usability Questionnaire (CSUQ) [22] for each tested option and a final question about the preference order of the tested options. The questions from the CSUQ were measured in a Likert scale in order to obtain a final score from 0 to 100. The questions were:

- Overall, I am satisfied with how easy it is to use this control.
- It was simple to use this control.
- I can effectively complete this task using this control.
- I am able to complete this task quickly using this control.
- I am able to efficiently complete this task using this control.
- I feel comfortable using this control.
- It was easy to learn to use this control.
- Whenever I make a mistake using the control, I recover easily and quickly.
- Overall, I am satisfied with this control.

Two more specific questions were asked:

- I felt I had control of the wheelchair.
- It is easy to drive the wheelchair in narrow spaces.

All 25 individuals drove the simulated wheelchair with the six alternatives of joystick mappings: the algorithms A, B, C and all of them with the exponential quadratic function (D, E and F respectively). The order of the experiments was randomly set to avoid the bias relative to the experience of the user. After each round the volunteers answered to several questions related to each kind of mapping.

The sample of individuals is characterized for having a mean of age of 33 years old and 4 women and 21 men. The experience with videogames and joysticks is not considerable high (Fig. 10), although there are individuals that have considerable experience with joysticks.

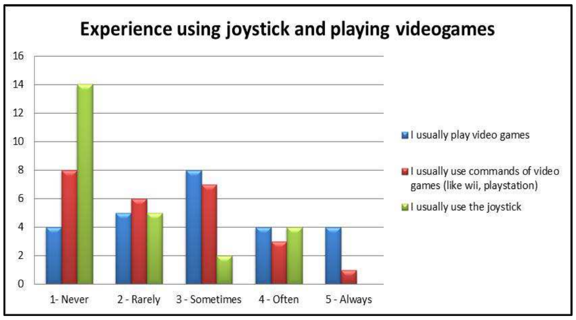

Figure 10. Responses about experience with joystick and videogames.

Table I shows the summary of statistics measures about the final score for all the mapping options.

TABLE I. SUMMARY OF STATISTICS MEASURES OF THE ADAPTED CSUQ SCORE

Adapted CSUQ – Final Score						
Statistics	***A***	***B***	***C***	***D***	***E***	***F***
Mean	56	63,4	**80,6**	64,6	**72,8**	**77,7**
Median	52,4	58,7	**85,7**	61,9	**76,2**	**82,5**
Std. Deviation	23,6	24,6	17,4	22,7	20,0	17,5
Minimum	22,2	14,3	33,3	25,4	14,3	33,3
Maximum	100	100	100	100	95,2	98,4

The opinions regarding the different joystick mappings indicate that the level of satisfaction is higher when using the option C. The next option is F, then E, D, B and finally A.

To confirm that the alternatives of mapping are significantly different the statistical Friedman test (related samples Friedman´s test two way analysis of variance by ranks) was applied to the final score. The level of significance used was 0.05. With a p value lower than 0.001 and lower than the level of significance it is possible to conclude that there are statistical differences between the distributions of the scores. To identify which commands are significantly different it was necessary to use a multiple comparison of means of orders (Fisher's least significant difference (LSD)). Table II shows the p values of the multiple comparisons, using the Fisher's least significant difference (LSD).

TABLE II. MULTIPLE COMPARISONS OF THE ADAPTED CSUQ SCORE

Multiple Comparisons LSD – Adapted CSUQ Score (p values)					
	A	***B***	***C***	***D***	***E***
B	0,199	--	--	--	--
C	<0,001	<0,001	--	--	--
D	0,022	0,308	0,001	--	--
E	0,002	0,064	0,012	0,399	--
F	<0,001	<0,001	0,424	0,011	0,085

It is interesting to verify that the score of option C is statistically different for all other options except F at a level of significance 0.05. Also, there are not statistical evidences to affirm that the distribution of scores F and E are different.

The results about the score are also confirmed with the order of preference as can be observed in Table III.

TABLE III. SUMMARY STATISTICS ABOUT THE ORDER OF PREFERENCE

Order of preference (1- Best to 6- Worst)						
Statistics	***A***	***B***	***C***	***D***	***E***	***F***
Median	5	5	**2**	4	**3**	**2**
Minimum	1	1	1	1	1	1
Maximum	6	6	5	6	6	6

The questions regarding the specific behavior during gameplay have their answers distribution in Fig. 11 and Fig. 12 for each tested option tested.

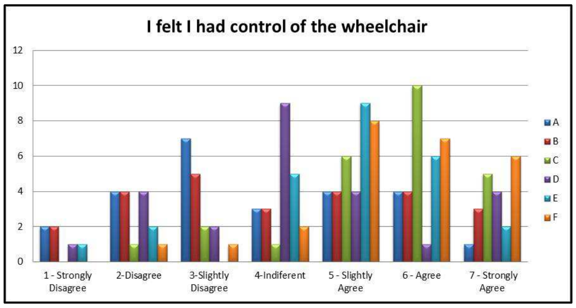

Figure 11. Responses about the feeling of control when driving the wheelchair using the different options.

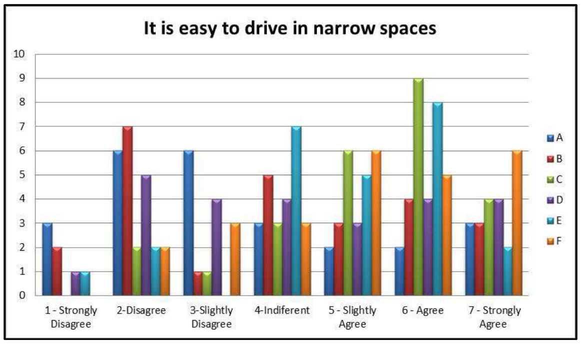

Figure 12. Responses about the experiment when driving in narrow spaces.

The feeling about control of the wheelchair is more visible using the options C and F. In terms of ease by driving the wheelchair in narrow spaces the control F had more responses as “Strongly Agree”. To confirm that the controls are significantly different the statistical Friedman test was also applied to the variables “Feeling about control of driving the wheelchair” and “easy to drive in narrow spaces”. The p values obtained were also less than 0.001, so there are statistical differences between the distribution of answers among each joystick mappings in terms of feeling about control of the wheelchair and how easy it is to drive in narrow spaces. The same multiple comparison of means of orders analysis was performed. Tables IV and V show the corresponding p values.

TABLE IV. MULTIPLE COMPARISONS OF THE FEELING OF CONTROL OF THE WHEELCHAIR

Multiple Comparisons LSD – Feeling of control (p values)					
	A	***B***	***C***	***D***	***E***
B	0,263	--	--	--	--
C	<0,001	<0,001	--	--	--
D	0,308	0,919	<0,001	--	--
E	0,004	0,068	0,012	0,054	--
F	<0,001	<0,001	0,919	<0,001	0,009

The feeling about having control of the wheelchair with the option C and F is statistically different with all other options except with each other.

TABLE V. MULTIPLE COMPARISONS OF EASE OF DRIVING THE WHEELCHAIR IN NARROW SPACES

Multiple Comparisons LSD – Ease of driving (p values)					
	A	***B***	***C***	***D***	***E***
B	0,223	--	--	--	--
C	<0,001	<0,001	--	--	--
D	0,023	0,281	0,008	--	--
E	0,006	0,112	0,032	0,606	--
F	<0,001	0,001	0,814	0,016	0,056

The question about driving the wheelchair in narrow spaces with the six options also had p values less than 0.05. In this case the option C is also statistical different from other options except with F.

VI. CONCLUSIONS

Typically, users control electric wheelchairs using conventional analog joysticks. Thus, they need appropriate methodologies to map the position of the joystick to the wheelchair motor velocities. This paper described the implementation of several joystick mappings and appropriate experiments performed in a realistic simulator in order to analyze the usability of the joystick mapping methods.

The study conducted enabled us to verify that the intuitive mapping method achieved was preferred by the majority of the users. Using this method, users could keep the control of the Intelligent Wheelchair, even in narrow spaces.

Future work will be concerned with conducting a deeper study of the control methods by testing different configuration parameters for each control type and test the controls with broad sample of wheelchair users. Another experiment will be concerned with the use of data mining algorithms to create user driving models and using them to create automatic control methods based on real user behavior.

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REFERENCES

[1] S. Nakanishi, Y. Kuno, N. Shimada and Y. Shirai, “Robotic wheelchair based on observations of both user and environment,” in International Conference on Intelligent Robots and Systems, 1999.

[2] Y. Matsumoto, T. Ino and T. Ogasawara, “Development of Intelligent Wheelchair System with Face and Gaze Based Interface,” in 10th IEEE International Workshop on Robot and Human Communication, Bordeaux, 2001.

[3] S. Ju, Y. Shin and Y. Kim, “Intelligent wheelchair (iw) interface using face and mouth recognition,” in 13th international conference on Intelligent user interfaces, Canary Islands, 2009.

[4] A. Sasou and H. Kojima, “Noise robust speech recognition applied to voice-driven wheelchair,” Journal on Advances in Signal Processing, vol. 1, no. 41, 2009.

[5] R. A. M. Braga, M. Petry, A. P. Moreira, L. P. Reis, Concept and Design of the Intellwheels Platform for Developing Intelligent Wheelchairs, Springer-Verlag, LNEE/ Informatics in Control, Automation and Robotics. Vol 37. April, 2009, pp. 191-203.

[6] R. Simpson, “Smart wheelchairs: A literature review,” Journal of Rehabilitation Research & Development, pp. 423-435, July/August 2005.

[7] K. Choi, M. Sato and Y. Koike, A new human-centered wheelchair system controlled by the EMG signal, International Joint Conference on Neural Networks, Vancouver, BC, Canada July 16-21, 2006.

[8] B. E. Dicianno, S. Sibenaller, C. Kimmich, R. A. Cooper, J. Pyo, Joystick use for virtual power wheelchair driving in individuals with tremor: Pilot study, Journal Rehabilitation Research & Development, Vol 46, No 2, 2009, pp. 269-276.

[9] A. Fattouh , M. Sahnoun , G. Bourhis, Force Feedback Joystick Control of a Powered Wheelchair: Preliminary Study, IEEE International Conference on Systems, Man and Cybernetics, vol.3, pp. 2640 – 2645, 2004.

[10] M. Niitsuma, T. Ochi, M.Yamaguchi, H. Hashimoto, Interaction between a User and a Smart Electric Wheelchair in Intelligent Space, International Symposium on Micro-NanoMechatronics and Human Science (MHS), Nov 2010, pp. 465-470.

[11] G. Pires, U. Nunes, A wheelchair steered through voice commands and assisted by a reactive fuzzy-logic controller, Journal of Intelligent and Robotics System, 34, pp. 301-314, 2002.

[12] R. Braga, M. Petry, L. L. Reis, A. P. Moreira, IntellWheels: Modular development platform for intelligent wheelchairs, Journal of Rehabilitation Research & Development, 48, 9, 2011, pp. 1061-1076.

[13] R. Braga, M. Petry, A. P. Moreira, L. P. Reis. Intellwheels: A Development Platform for Intelligent Wheelchairs for Disabled People. Proceeding of the 5th International Conference on Informatics in Control, Automation and Robotics. Vol I. Funchal, Madeira, Portugal, pp.115-121, 2008.

[14] M. Petry, A. P. Moreira, R. Braga, L. P. Reis, Shared Control for Obstacle Avoidance in Intelligent Wheelchairs, 2010 IEEE Conference on Robotics, Automation and Mechatronics (RAM 2010), June 28–30 2010, Singapore, pp. 182-187.

[15] K. L. Murdock, 3ds Max 2011 Bible, Indianapolis: John Wiley & Sons, 2011.

[16] S. Carpin, M. Lewis, J. Wang, S. Balakirsky and C. Scrapper, “USARSim: a robot simulator for research and education,” in Proceedings of the IEEE International Conference on Robotics and Automation, Roma, Italy, 2007.

[17] R. Braga, P. Malheiro, L. P. Reis, Development of a Realistic Simulator for Robotic Intelligent Wheelchairs in a Hospital Environment, In J.Baltes, M.Lagoudakis, T.Naruse, S.Shiry (Eds.), RoboCup 2009, LNAI 5949, pp. 23-34. Springer, Heidelberg, 2010, Graz, Austria, 2009.

[18] M. Petry, A. P. Moreira, L. P. Reis, R. Rossetti, Intelligent Wheelchair Simulation: Requirements and Architectural Issues, in 11th International Conference on Mobile Robotics and Competitions, Lisbon, 2011.

[19] B. M. Faria, S. Vasconcelos, L. P. Reis, N. Lau, A Methodology for Creating Intelligent Wheelchair Users' Profiles, ICAART 2012 - 4th International Conference and Artificial Intelligence, Algarve, 2012, pp 171-179.

[20] L. P. Reis, R. Braga, M. Sousa, A. P. Moreira. Intellwheels MMI: A Flexible Interface for an Intelligent Wheelchair, RoboCup Symp2009, In J.Baltes, M.Lagoudakis, T.Naruse, S.Shiry (Eds.): RoboCup 2009, LNAI 5949, pp. 296-307. Springer, Heidelberg, 2010, Graz, Austria.

[21] B. M. Faria, S. Vasconcelos, L. P. Reis, N. Lau, Evaluation of Distinct Input Methods of an Intelligent Wheelchair in Simulated and Real Environments: A Performance and Usability Study Assistive Technology: The Official Journal of RESNA, Accepted 05 Sep 2012.

[22] J. R. Lewis, IBM Computer Usability Satisfaction Questionnaires: Psychometric Evaluation and Instructions for Use, International Journal of Human-Computer Interaction 7, 1, 1995, pp. 57-78.