Powered Wheelchair Control : Human – Machine System Modelling

S. M. Meliani*, Z. Sari* and G. Bourhis**
*Université Aboubekr Belkaïd de Tlemcem,
Laboratoire d'Automatique, BP 230, Tlemcem 13000, Algérie,
sm_meliani@mail.univ-tlemcen.dz, z-sari@mail.univ-tlemcen.dz,
**Université Paul Verlaine-Metz,
LASC, Ile du Saulcy, 57012 Metz cedex 01, France,
bourhis@univ-metz.fr

***Abstract*— The objective of this work is to model the pilot-vehicle system made up of a person with disability and of an electric wheelchair. This modelling must induce an objective analysis method of the pilot-wheelchair couple in order to help to personalize the parameters of the vehicle on the one hand and to evaluate the interest of new functionalities on the other hand. After a review of the literature, we detail some experimental results to illustrate our matter.**

***Index Terms*—Powered wheelchair, assistive technology, human-machine modelling, crossover model.**

I. INTRODUCTION

For people suffering from a severe motor disability (tetraplegia, cerebral palsy, myopathy…), powered wheelchair proves to be essential to compensate for the handicap of mobility. Many models are proposed on the market. They are different by their characteristics mechanical (seat base, mobility mechanism) and electric (motorization, control modes), like by their possibilities of control (man-machine interface). These various points which, at the present time, are still the object of technological innovations make it possible for adapting to the great diversity of the users and of the situations. Many parameters such as for example acceptable maximum speed or acceleration are adjustable to take account of the physical possibilities of the user. This personalization of the wheelchair is carried out however in an empirical way for lack of tools or of objective methods for testing its adequacy with the user.

In addition for many potential users the access to the electric wheelchair is difficult or impossible because of too severe motor disabilities [12]. We can plan to mitigate these difficulties by developing new human-machine interaction modes or by introducing primitives of automatic navigation (obstacles avoidance, wall following, …) [13]. In every cases the difficulty of the assesment of these new functionalities arises. Indeed, for reasons physiological (significant fatigability), psychological (acceptability of the technical assistance) and of safety (reliability of the prototypes), it is often difficult to test in real conditions such assistive devices. Here also, tools able to objectively analyse the contribution of an adaptation or of a functionality to a given user would be of a great help. In particular they could allow tests in simulation which are easier to implement than in real situation.

Our work is situated in this context : the aim is to model the pilot-vehicle system in a task of manual control of an electric wheelchair. Indeed, if since the sixties many work has been undertaken to model the system made up of a vehicle (plane, car, ship) and of its pilot, few efforts of research have been accomplished to analyze the couple "person with disability – powered wheelchair". We propose to fill this gap, this with a double objective. The first one is descriptive : to better understand the specificities of the control of an electric wheelchair by persons with motor disability, the major difficulty being the great diversity of the functional capacities of these people. The second objective is normative: the pilot-wheelchair model must make it possible to define the optimal behavior mode of the person in a given driving situation. This induces a method of objective analysis of the piloting of a wheelchair. After a review of the literature we will describe some preliminary results concerning this modelling.

II. HUMAN-POWERED WHEELCHAIR SYSTEM MODELLING

A. *Electrical wheelchairs*

1) *Kinematic*

The mechanism allowing mobility on the currently marketed electric wheelchairs is a system with wheels. The majority of the commercialized powered wheelchairs are conceived on the principle of four wheels: two driving wheels and two free wheels according to an architecture similar to that of many mobile robots. This induces for the wheelchair a characteristic of non-holonomy which complicates control in encumbered environment. The instantaneous centre of rotation is always on the axis passing by the driving wheels. The essential difference between these wheelchairs is the position of the driving wheels. When the centre of rotation is at the front one, the space swept by the mechanical structure is reduced and makes the wheelchair easier to manoeuvre. On the other hand, a centre of rotation located at the back is more interesting in term of control stability. Let us note that in the marketed systems we can also meet structures with six wheels, the two driving wheels being in the middle, or with four driving wheels.

2) *Human-machine interface*

A broad range of man-machine interface sensors makes it possible to adapt the control of an electric wheelchair to the physical capacities of the user. The simplest control mode and the most usual one is of proportional type. It's generally controlled by the hand or, possibly, by the chin or the head. Other anatomical sites like the nape of the neck or the feet can also be exploited. In [14] the authors compare the performances of control with a standard joystick and with an isometric joystick. This last one proves to be more efficient for driving tasks in straight line and in circle. Moreover studies are in progress to allow people who can't use a joystick because of too important tremors to control an adapted version of this sensor. We can for example produce a fuzzy logic controller to mitigate uncertainty on the control input [11]. It may also be interesting to carry out a force feedback on the joystick to improve the control input itself [15]. Other more complex processes can be considered: in [16] a project of interface is described which uses the recognition of the direction of the face to predict the intention of the wheelchair pilot. The head motions, measured by infra-red sensors, can also be used for this purpose [17].

If a proportional control is not possible, we call upon an on-off type control, a sensor of breath or switches placed on the level of the head-rest for example. In [18] an original sensor is described, constituted of a laser pointer allowing to select, by head motions, a direction indicated on a control panel by a photosensitive area. Lastly, if the person with disability has access only to one on-off sensor, the only possibility of control of the wheelchair consists in carrying out a scanning on the various possible directions. Thus, an action on the switch makes it possible to choose a direction. This principle makes however any operation laborious and justifies to call upon a robotized assistance [19].

B. *Wheelchair pilot modelling*

We suppose that the user controls the wheelchair via an interface sensor of the "proportional" type (a joystick or an equivalent device). We thus exclude the hypothesis of an on-off sensor associated to a scanning system, which would require a specific study. The interface returns haptic information to the pilot : position of the sensor and, in certain situations still experimental [15], a force feedback. The "pilot-joystick" mechanical coupling has been modelled by some authors in the objective of compensating for the vibrations caused by accelerations of the wheelchair [1] or of any mobile [2], or for the tremors due to the motor control difficulties of the disabled pilot [3]. In [2] and [3] this compensation is carried out using a force feedback interface, whereas in [1] the authors propose to act on the mechanical characteristics of the joystick.

The human-machine interface generates two control signals making it possible to actuate two engines via a power module. The controller used for this purpose in the commercialized wheelchairs is often not very elaborated. Unfortunately few studies to improve it are reported in the literature. In [4] an adaptive controller is described which takes into account the weight of the user in the control algorithm. This parameter is indeed a significant disturbing variable for a good control of the wheelchair. More recently, Ding and al. proposed a robust adaptive controller making it possible to maintain the linear and angular velocities parameters to their set points in the presence of disturbances internal to the wheelchair or coming from the environment [5]. Fujii and Wada suggest a method to improve the maneuverability of the powered wheelchairs by limiting too significant accelerations prejudicial to people having difficulties in control precisely the human-machine interface [6].

This last study is based on a modelling of the pilot-wheelchair system according to the crossover model initially introduced by McRuer and Jex for a plane piloting task [7]. This model has been validated for a great number of compensatory and pursuit tasks. It postulates that a well trained and concentrated pilot adapts his control behavior so that if $Y_p(\omega)$ is the transfer function of the pilot and $Y_c(\omega)$ that of the controlled element, we have :

$$Y_{OL}(j\omega) = Y_p(\omega).Y_c(\omega) = \frac{\omega_c.e^{-j\omega\tau_e}}{j\omega} \quad \text{near } \omega_c \qquad (1)$$

ω_c and τ_e are functions of the tasks variables; τ_e includes the process and the operator delays. We can indeed reasonably suppose that this model is verified in some situations of the wheelchair control, in not-encumbered environment in particular and for pilots having no difficulty to control the human-machine interface. On the other hand the model will have probably to be adapted in more complex situations: difficult manoeuvres (narrow door crossing, …), control of the human-machine interface disturbed by the motor difficulties of the user…

Another model is possible under certain conditions to analyze the pilot-wheelchair system : Cooper and al. propose to apply the Fitts law to the performance evaluation of a powered wheelchair control task [8]. The objective is to compare the use of an isometric joystick and that of an usual joystick. The Fitts law has been defined at the origin to analyze the ratio speed/precision in pointing tasks [9]. The authors apply this law by cutting out an experimental course in segments of 30cm whose ends constitute the targets to be reached. An index of performance IP can thus be defined by the following classical formulation:

$$IP = ID/MT = \log_2(2A/W) \,/\, MT \qquad (2)$$

where IP is the index of performance, MT is the time of movement, A is the distance to the target and W is the width of the target.

We can note finally that these two models of the operator, crossover model and Fitts law may be connected mathematically : if ω_i is the bandwidth of the forcing function of Figure 1 (trajectory to be followed), Repperger and al. show that for $\omega_i << \omega_c$ the index of performance IP is proportional to the crossover frequency [10].

In what follows we present some experimental results in simulation. The final objective is to analyze the piloting of an electric wheelchair using the models described in the literature. For these first results we base ourselves on the crossover model evoked above while endeavouring to define his potential application fields.

III. METHODOLOGY

A. *Crossover model*

The crossover model may be defined starting from the general diagram Figure 1: the pilot acts on the error e(t) between an input reference control u(t) and the system output s(t) by producing an input c(t) on the control interface towards the controlled element [7]. For a compensation task, only the signal e(t) is displayed. The reference input u(t) (control input or internal perturbation) is supposed of limited bandwidth ω_i.

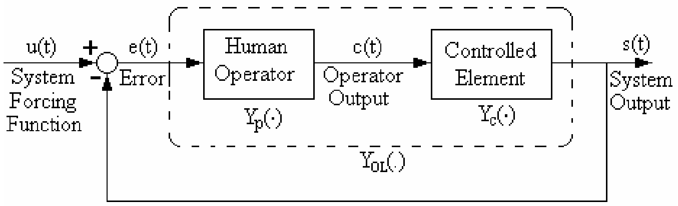


Fig. 1. The pilot-machine system

The pilot mission consists in following the reference in spite of the perturbations. He thus becomes a serial element in the closed-loop system and adapts its behavior according to the equation (1) previously evoked. The pilot model $Y_p(\omega)$, which depends on the controlled element, then may be expressed under the following general formulation:

$$Y_p(j\omega) = K_p \frac{(T_L j\omega + 1)}{(T_I j\omega + 1)} e^{-j\omega\tau_e} \quad (3)$$

where :

K_p = pilot static gain ;
T_L = lead time constant ;
T_I = lag time constant ;
τ_e = effective time delay.

The parameters K_p, T_L, T_I and τ_e are adjusted by the pilot, which is supposed well-trained and concentrated, so as to conform to the crossover model. They depend on the controlled element on the one hand, and on the experiment and the dexterity of the operator on the other hand.

For the experiments, it's easier to discretize the equations of the model. While passing from the continuous field to the discrete one, (1) becomes:

$$Y_{OL}(Z) = (1 - Z^{-1})\, Z\left\{\frac{Y_{OL}(s)}{s}\right\} = \omega_c t_e \frac{Z^{-(t_d+1)}}{1 - Z^{-1}} \quad (4)$$

where :

t_e = sampling period ;
$t_d = \tau_e / t_e$ = a number of samples representing the time delay. In our study, the sampling period is fixed to t_e = 66 ms.

The closed-loop discrete transfer function of the functional diagram Figure 1 is as follows:

$$Y_{CL}(Z) = \frac{S(Z)}{U(Z)} = \frac{Y_{OL}(Z)}{1 + Y_{OL}(Z)} = \frac{\omega_c t_e Z^{-(t_d+1)}}{1 - Z^{-1} + \omega_c t_e Z^{-(t_d+1)}} \quad (5)$$

Finally, after transformation, the discrete model obtained is given by the following equation:

$$s(n) = \omega_c t_e u(n-(t_d+1)) + s(n-1) - \omega_c t_e s(n-(t_d+1)) \quad (6)$$

The elaboration of the crossover model is initially carried out starting from a simulated environment (Figure 2) to facilitate the development of the method. This environment provides us the input forcing function made up of the wheelchair trajectory. Knowing the bandwidth ω_i of this reference signal determined by a Fast Fourier Transform (FFT), we extract the crossover model parameters, the crossover frequency ω_c and the effective time delay τ_e. Then, to validate the model, we compare the trajectories carried out by this one with trajectories coming from a real control via a joystick.

B. *Experimental environment*

The experimentation is carried out in a 2D environment where the wheelchair controlled by a joystick (Logitech Force Feedback 3d Joystick) is represented. The software runs under Matlab/Simulink^{TM}. It is divided into functional blocks and subroutines.

The functional blocks are toolboxes of the Matlab Simulink library:

- The "joystick interface" block makes it possible to read the joystick coordinates (x,y).
- The "Matlab Function" block stores the joystick position and translates it as a wheelchair movement in the environment. The data file give us the cartesian and polar co-ordinates of the trajectory.

The subroutines, carried out under Matlab, deal essentially with the trajectories data. They allow in particular:

- To determine the frequency spectrum of the trajectory for obtaining its bandwidth ω_i. The knowledge of ω_i is essential for the modelling of the pilot-machine system according to the crossover model.
- To test the model by comparing the trajectory obtained with him and that obtained manually via the joystick.

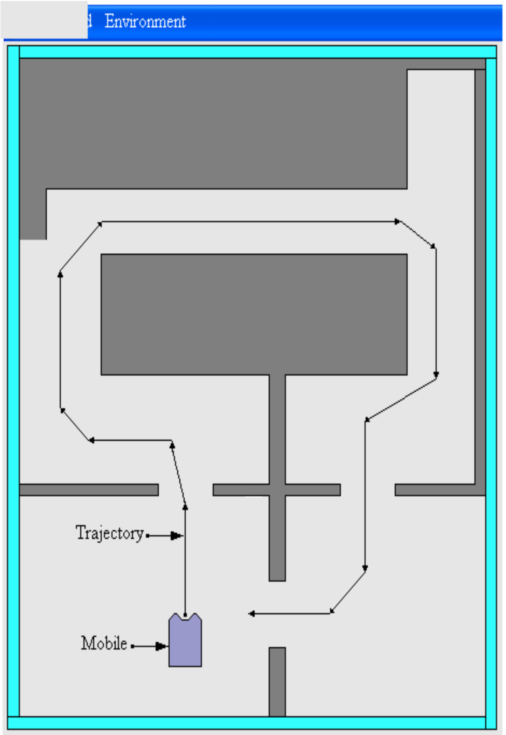


Fig. 2. 2D simulated environment and reference trajectory

C. *Determination of the model parameters*

We determine experimentally ω_c and τ_e from the following experiment (Figure 3). The cursor simulating the wheelchair is disturbed compared to a reference trajectory. It is requested to the human operator to try to cancel the error e(t). It is thus a compensation task. The electrical wheelchair which will be used for our experiments in real situations was identified, for a first approximation, as a second order system. We thus do this hypothesis to model the mobile behaviour.

The first stage consists in determining the crossover frequency ω_c according to the bandwidth ω_i of the input signal. In this goal we disturb the mobile by a signal u(t), of bandwidth ω_i, made up with a burst of sinusoids. Each sinusoid is defined by its amplitude and its frequency. The perturbation moves away the mobile from the reference line in the horizontal direction. The crossover frequency ω_c is obtained by plotting the diagram of the output signal amplitude, measured at the first moments of the perturbation, according to the frequency of each sinusoid. The difficulty of the experiment lies in the synchronization between the measured sample of the output signal and the maximum value of each sinusoid composing the reference signal.

The second stage consists in determining the value of the effective time delay τ_e. We obtain it by measuring dephasing between the input sinusoid and the output signal measured, this time, after compensation of the error.

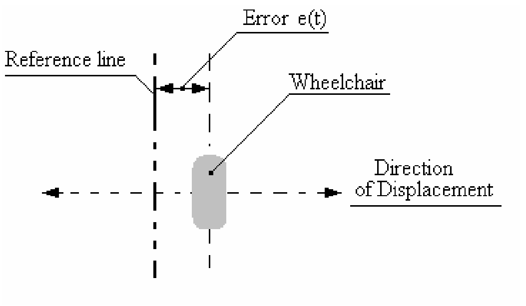


Fig. 3. Experimental display for the determination of the crossover model parameters.

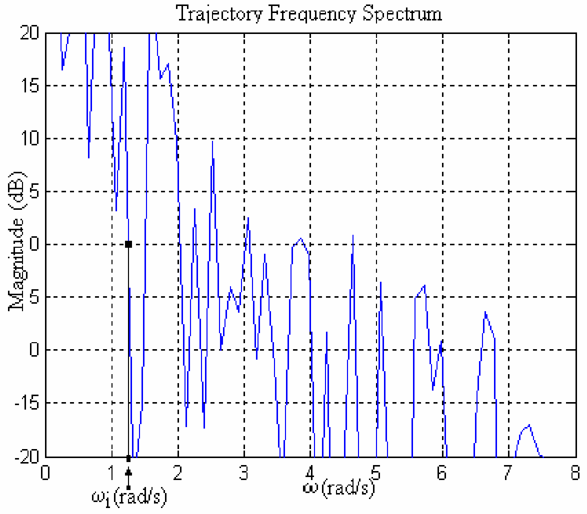
For the two parameters we then find the results already presented in [7]. We note in particular that ω_c is almost constant according to ω_i, equal to 3.2rd/s (it depends only on the controlled element), as long as we have $\omega_i << \omega_c$. The second parameter τ_e decreases according to ω_i almost linearly, the slope not depending on the controlled element. We did not check here this last point, the mobile being modelled by a second order only.

D. *Model validation*

The validation of the model mainly consists in testing the human-machine crossover model starting from a reference trajectory chosen in the environment of Figure 2. This trajectory is first of all carried out by moving the mobile using the joystick. We thus obtain a data file storing the sequence of the mobile coordinates. These data will be then regarded as the samples of the reference signal u(n).

After this step we determine the coordinates of the trajectory obtained by the modelled human-machine system. For that we deduce the sequence s(n) from the equation (6). The parameters ω_c and τ_e are obtained starting from the results previously obtained (III.C) and from the frequential analysis of the trajectory (Figure 4a). The x and y coordinates of the points constituting the modelled trajectory are obtained by replacing u(n) respectively by the x and y coordinates of the points of the trajectory obtained with the joystick.

We then note, comparing the two trajectories Figure 4b, a good agreement between the real trajectory and the simulated one. We can also observe a better correlation in the rectilinear passages than in the winding ones. This is a logical result insofar as we have done the hypothesis $\omega_i << \omega_c$. Consequently we'll have to refine the model in the segments of trajectory with broader frequency spectrum which corresponds to manoeuvres in encumbered or tortuous environments.



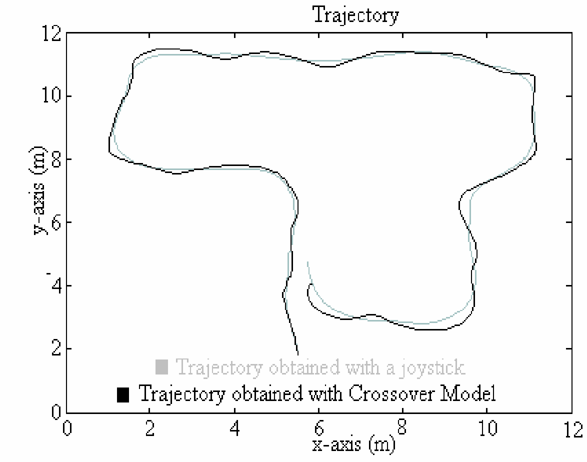


Fig. 4.a. Trajectory frequency spectrum
Fig. 4.b. Real and simulated trajectories

IV. CONCLUSION

We have presented in this article our first experimental results in simulation concerning the modelling of the human-machine system in a task of powered wheelchair piloting. The goal is to deduce from it a method of objective analysis of this task. The crossover model seems to be well adapted to this objective, at least for not very complex environments. More completed investigations in simulation and then in real situation will be however necessary to be able to conclude on this point.

ACKNOWLEDGMENT

This work is achieved in a CMEP-Tassili (Comité Mixte d'Evaluation et de Prospective interuniversitaire franco-algérien) program framework.

REFERENCES

[1] S. Shimada, K. Ishimura, M. Wada, “System design of electric wheelchair for realizing adaptative operation to human intention”, *IEEE international Conference on Robotics, Intelligent Systems and Signal processing*, Changsha, China, 2003, p. 513-518.
[2] R.B. Gillespie, S. Sövényi, “Model-based cancellation of byodynamic feedthrough using a force-reflecting joystick“, *ASME Journal of Dynamic Systems, measurement, and control*, to appear.
[3] S. Pledgie, K. Barner, S. Agrawal, T. Rahman, “Tremor suppression through force feedback”, *ICORR'99,* Stanford, CA, 1999, p.16-26.
[4] K.E. Brown, R.M. Inigo, B.W. Johnson, “An adaptable optimal controller for electric wheelchairs”, *Journal of Rehabilitation Research and Development*, vol.24, n°2, 1987, p. 87-98.
[5] D. Ding, R.A. Cooper, S. Guo, T.A. Corfman, “Robust velocity control simulation of a power wheelchair, *26th annual RESNA Conference*, Atlanta, GA, 2003.
[6] F. Fujii, K. Wada, “Analysis on the manual control characteristics of the human pilot during the operation of the powered wheelchair”, *Advanced Robotics*, vol.19, n°2, p.121-139, 2005.
[7] D.T. McRuer, H.R. Jex, “A review of quasi-linear pilot models”, IEEE Transactions on Human Factors in Electronics, Vol. HFE-8, n°3, 1967, p. 231-249.
[8] R.A. Cooper and al., “Analysis of position and isometric joysticks for powered wheelchair driving”, *IEEE Transactions on Biomedical Engineering*, vol.47, n°7, 2000, p.902-910.
[9] P.M. Fitts, “The information capacity of the human motor system in controlling the amplitude of movements”, *Journal of experimental psychology*, vol.47, n°6, 1954, p. 381-391.
[10] D.W. Repperger, C.A. Phillips, T.L. Chelette, “A study on spatially induced “virtual force” with an information theoretic investigation of human performance”, *IEEE Transactions on Systems, Man and Cybernetics*, vol.25, n°10, 1995, p.1392-1404.
[11] D. Corbett, P. Martinez, “Toward learning individual characteristics in a hybrid neuro-fuzzy wheelchair controller”, *International Journal of intelligent Systems*, vol.13, 1998, p. 561-570.
[12] Fehr L., Langbein W.E., Skaar S.B., “Adequacy of power wheelchair control interfaces for persons with severe disabilities : a clinical survey”, *Journal of Rehabilitation Research and Development*, vol.37, n°3, 2000.
[13] G. Bourhis, O Horn, O. Habert, A. Pruski, “Autonomous vehicle for people with motor disabilities”, *IEEE Robotics and Automation Magazine, Special issue on "Reinventing the wheelchair"*, vol.7, n°1, 2001, p.20-28.
[14] R.A. Cooper and al., “Force sensing control for electric powered wheelchairs”, IEEE Transactions on Control Systems Technology, vol.8, n°1, 2000, p. 112-117.
[15] M. Sahnoun, A. Fattouh, G. Bourhis, “Assisted Control for a Powered Wheelchair with a Force Feedback Joystick”, *Assistive Technology : from Virtuality to Reality*, A. Pruski and H. Knops Eds., IOS Press, p.601-605, 2005.
[16] Adachi Y. et al., "Intelligent wheelchair using visual information on human faces", *IEEE Int. Conf. On Intelligent Robots and Systems*, Victoria, Canada, octobre 1998, p. 354-359.
[17] H.V. Christensen, J.C. Garcia, “Infrared non-contact head sensor, for control of wheelchair movements”, *Assistive Technology : from Virtuality to Reality*, A. Pruski and H. Knops Eds., IOS Press, p.336-340, 2005.
[18] F. Prieur, C. Bordet, “Un nouveau type de commande non-manuelle pour fauteuils roulants électriques” (in french), *Handicap 2000*, Paris, June 2000, p. 119-124.
[19] Yanco H.A. et Gips J., "Driver performance using single switch scanning with a powered wheelchair : robotic assisted control versus traditional control", *RESNA'98*, juin 1998, p. 298-300.