ABCM Symposium Series in Mechatronics - Vol. 2 - pp.265-272

COMPARISON OF CONTROL STRATEGIES FOR MOTORIZATION OF A SERVO ASSISTED WHEELCHAIR

Msc. Arley de Barros Lombardi Junior
Departamento de Projeto Mecânico - Faculdade de Engenharia Mecânica – UNICAMP
Rua Mendelv, CEP 13083-970 Caixa Postal 6122 – Campinas – São Paulo -Brasil
e-mail: arley @fem.unicamp.br

Prof. Dr. Franco Giuseppe Dedini
Departamento de Projeto Mecânico - Faculdade de Engenharia Mecânica – UNICAMP
Rua Mendelv, CEP 13083-970 Caixa Postal 6122 – Campinas – São Paulo -Brasil
dedini@fem.unicamp.br

Abstract. *The aim of this article is to compare three strategies for servo assisted wheelchair motorization control. A servo assisted wheelchair is a therapeutic wheelchair which allows the user increase his physical and pulmonary capacity without risk of development DORT. Because this wheelchair has a driven system which is turned on only when the propulsion force applied by the user is higher then a specific value. This value is set up to avoid dort and at the same time to increase the muscular capacity and independent mobility. The model used is based on doubled bicycle model, driven force applied over the rear wheels and the steering over the front wheels. This mathematical model allows developing control strategies for the driven system which will be simulated without a prototype. For these article three strategies was developed, one "on-off" control, one rule control and one fuzzy control and they were simulated for a standard propulsion cycle and for most common problematic propulsion cycle. The most appropriated strategy for the studied system was the rule control, because it has a best performance in terms of the system displacement. Besides the system controlled by this strategy is not so sensitive to a problematic propulsion force.*

Keywords*: control, servo-assisted, wheelchair, axiomatic design*

1. Introduction

Wheelchairs have suffered a great development in the last years, however studies of its dynamics behavior have practically not occurred, and it is important because allows the improvement of the users mobility.

Recently works Arva et al. (2000), Buttler (2000), Cooper and Boninger (1999) and Corfman et al. (2000) shown the importance of having a more independent life. This contributes to have a better development of usual abilities as interpersonal communication, psychosocial skills and other important skills for living in a society.

It is a very important factor in social interactions to have access and control over the territory, as stated by Butler (2000) and Di Marco et al. (2003). For a wheelchair user the ability to pass obstacles and locomotion are dependent on his wheelchair, the best wheelchair chosen is a primordial factor for having success and independence in all-day situations.

Power wheelchair allows a bigger mobility, mainly in indoors ambient that has a regular floor, but they have as disadvantage a muscular atrophy of the upper extremities members. (Stein et al., 2003 e Cooper and Boninger, 1999, Duran at al., 2001). It is a consequence of using only the joystick to drive the wheelchair.

A servo-assisted mechanism for a wheelchair can improve the user locomotion capability and at the same time it does not allow that him remain without making exercises. It is important because it allows the user to development the upper extremities muscles. The locomotion improvement occurs because with less effort is necessary to propel the wheelchair. So the physical effort to propel a wheelchair is no excessive and the upper extremities joints will not development repetitive effort lesion. (Lombardi Jr. and Dedini, 2005)

The servo assisted mechanism concept is a group of motors fixed to the wheelchair able to propel the system but only turns on when the user force acting over the propulsion ring is higher then a specific value set by a doctor or a therapist. (Lombardi Jr. and Dedini, 2005)

This work was divided in the following sections: a mathematical model for the system, including the definitions for the propulsion forces and the dynamical model for the wheelchair, after it was performed the study of the system behavior under the three control strategies ("on-off", rule and fuzzy), and finally conclusion.

2. Dynamical Model

The dynamical model is based on the Newton-Euler and Jourdan equations and the aim is to develop the dynamic equations for computational simulation. All equations were written on the non inertial base over the system CG.

These equations represent the system dynamical behavior related to the propulsion forces acting over the rear wheels, and with servo-assisted assembly the motor actuation is added in propulsion force. It is important to remember that the steering occurs on front wheel, and the steering forces are always equal to zero because the front wheels are free and the changing direction is made by different forces acting over the rear wheels.

In the fig. 1, it is represented the diagram of free body (DFB) of the wheel of system; this figure is enough to represent all important system forces, which are the transversal and longitudinal forces acting over the front and rear wheels. Each force is denoted by a sub-index from 1 to 4 which represents the number of wheel as shown on figure.

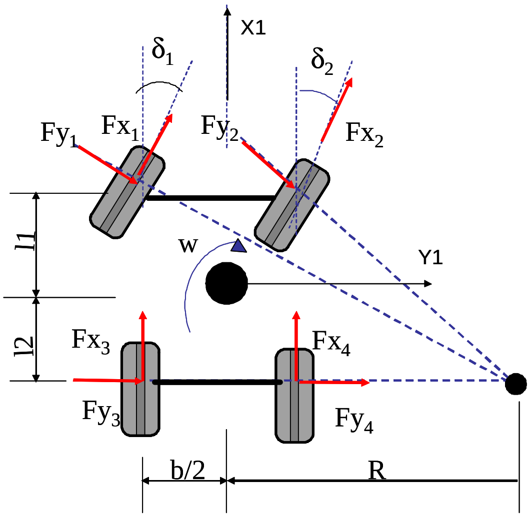

Figure 1. Free Body Diagram for the wheelchair

It can be observed that even the longitudinal force as the transversal forces are influenced by the resistance forces defined as presented by Lombardi Jr. and Dedini (2005), so for the transversal force the expressions are represented by the Eq.(1) for the front wheels 1 and 2 and Eq.(2) for the rear wheels 3 and 4:

$$Fy_i = Cy_f . y_i - \frac{m.g.l2}{2.L}.\cos(j).\sin(g) - Fat_i \tag{1}$$

$$Fy_i = -Cy_t . y_i - \frac{m.g.l1}{2.L}.\cos(j).\sin(g) - Fat_i \tag{2}$$

The expressions were developed for the most general situation for a pavement (with double inclination), which represents two rotations over the roll (axis X, represented by the variable g) and pitch (axis Y, represented by the variable j) angles. The wheels were considered rigid as presented in works by Becker (1997) and Lombardi Jr. (2002), thus the lateral force has a component resulting by multiplication of wheel sliding angle (y) and strictness movement coefficient of wheel (Cy). The variable Fat_i used on previous equations represents the lateral friction force, what is responsible for avoid lateral slip movement.

For the longitudinal forces the expressions are much similar to the expressions for the resistance forces despite of the terms *F3* and *F4* in longitudinal forces *Fx3* and *Fx4*, which are the forces applied by the wheelchair user during the manual propulsion or the forces applied by the user and the motorization system during the servo-assisted propulsion. The following expression, Eq.(3), for the front wheels and Eq.(4) for the rear wheels, represent the longitudinal force for the wheels.

$$Fx_i = -\frac{m.g.l2}{2.L}.\sin(j) - m.\frac{m.g.l2}{2.L}.\cos(j).\cos(b) \tag{3}$$

$$Fx_i = F_i - \frac{m.g.l1}{2.L}.\sin(j) - m.\frac{m.g.l1}{2.L}.\cos(j).\cos(b) \tag{4}$$

The variable m represents the rolling friction coefficient. Now, applying the Newton-Euler and Jourdan equations, it is possible to obtain expressions for $\dot{Vx}$, $\dot{Vy}$ e $\dot{w}_z$, respectively longitudinal, transversal and angular accelerations of the system. The equations resulting from this procedure are the following:

$$\sum Fx = m.ax \Rightarrow$$
$$Fx_3 + Fx_4 + Fx_1.\cos(d_1) + Fx_2.\cos(d_2) - Fy_1.\sin(d_1) - Fy_2.\sin(d_2) = m.(\dot{V}x - Vy.w_z) \tag{5}$$

$$\sum Fy = m.ay \Rightarrow$$
$$Fy_3 + Fy_4 + Fy_1.\cos(d_1) + Fy_2.\cos(d_2) + Fx_1.\sin(d_1) + Fx_2.\sin(d_2) = m.(\dot{V}y + Vx.w_z) \tag{6}$$

$$\sum Mz = Iz.\dot{w}_z \Rightarrow$$
$$\frac{b}{2}.(Fx_3 - Fx_4) + l1.(Fx_1.\sin(d_1) + Fx_2.\sin(d_2)) - l2.(Fy_3 + Fy_4) + l1.(Fy_1.\cos(d_1) + \cdots$$
$$+ Fy_2.\cos(d_2)) + \frac{b}{2}.(-Fx_2.\cos(d_2) + Fx_1\cos(d_1) + Fy_2\sin(d_2) - Fy_1.\sin(d_1)) = Iz.\dot{w}_z \tag{7}$$

The variables d_1 and d_2 represent respectively the steering angle in the front left wheel and front right wheel. It is important to observe that these angles are defined by the forces differences between the rear propulsion wheels, in other words the system has no independent steering but it is defined by the momentum due by propulsion force over the rear wheels.

Using the Eq.(5), Eq.(6) and Eq.(7), it is possible to simulate the dynamical behavior for a system composed by a wheelchair and a user, carrying out the aim of this paper. Following some graphics are being presented and are showing the dynamical behavior for a manual propulsion wheelchair, over a plane floor. The following simulations are based on the values: *m*, mass of the system, 110 Kg; *L*, distance between the wheelchair shaft, 0.5 m; *l1*, distance between the CG (center of gravity) and the front shaft 0.3 m; *l2*, distance between the CG and the rear shaft, 0.2 m; *b*, wheelchair width, 0.7m; *Izz*, inertia momentum of wheelchair, 6.78 m^4 , *m*, rolling friction coefficient, 0.015; h, CG height, 0.5 m The wheelchair geometric characteristics were based on ABNT 9050, an the inertia momentum (*Izz*) for the wheelchair was assumed as being equal to a cube with dimensions *b*x*L*x*h*. The others variables like *m* and CG localization were assumed based on experimental observation.

3. Considerations about the propulsion force

In this section only the two main factors for the biomechanical modeling are going to be presented, these factors are the propulsion standard and the force cycle characteristics.

For this study, it was considered that the movement happens only in the user sagital plan, what is consistent with the movement observed in recent studies of Souza (2000), Lombardi Jr. (2002). Each manual wheelchair user adapts to a propulsion standard, or in other words, the trajectory builds by the upper extremity during the propulsion. Souza (2000) relates that there are 4 standards paths for wheelchair propulsion, they are: arc, semi-cycle, simple looping and double looping, in this paper will be used only the arc as upper extremities movement.

In the same way it is going to be considered that the propulsion force has regular characteristics, and it can be divided in three parts (*T1,T2* e *T3*), where *T1* is the time necessary to the user applies the force begins at zero until the maximum value (*Fmax*), which is dependent on users characteristic (lesion level, physical condition), *T2* is the time when the force remains constant until the moment to release the hand, *T3* is the time to goes back the hand until the initial contact point to repeat the cycle. It was adopted the values *T3* equal to 1,0 s for plan paving e 0,4 s for slope paving *T2* was considerate 3 times bigger than *T1*.

Combining these two pieces of information mentioned previously, the propulsion force pattern is shown on the following figure, fig. 2:

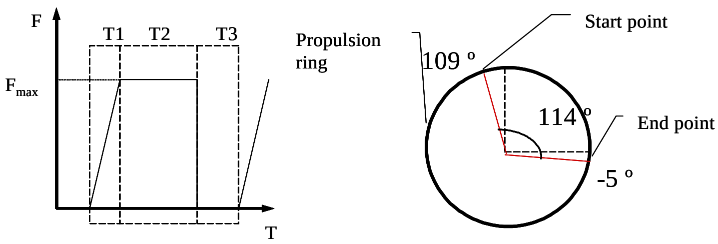

Figure 2. Characterizes of Propulsion Force definition

The maximum propulsion force value (*Fmax*) depends on the biomechanical characterizes of the subject, thus in this paper, as the aim is studying the dynamical behavior of the system will be assumed that the user is able to apply the necessary force for the movement. The force necessary for the movement is the sum of all forces of rolling movement over the wheel and the weight component if convenient (slope plane).

4. Manual wheelchair simulation

The aim of this section is to study the dynamical behavior of a wheelchair under the effects of the most common propulsion force characteristic. This information is important because based on this results it will be possible to quantify the improvement obtained using a servo assisted motorization system.

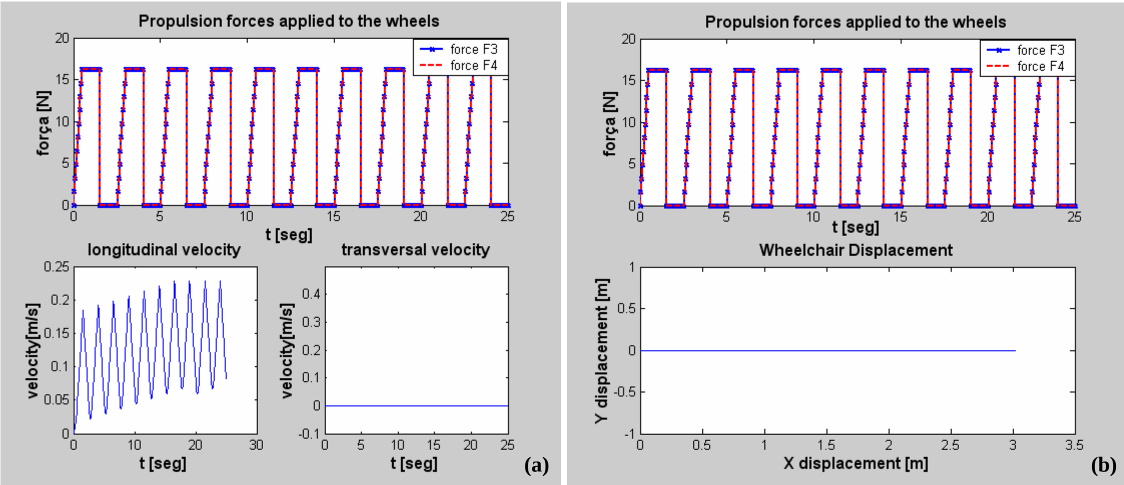

Figure 3. Wheelchair Velocity (a) and Wheelchair Displacement (b)

The propulsion force provide by the user was assumed as equal and enough for the movement, (F3 = F4 = 16.18 N) for the first simulation, in this simulation can be observed that the system has a linear displacement because this hypothesis.

Can be observed in the fig. 3 (a) that wheelchair has an irregular behavior in terms of the longitudinal velocity (forward movement) due by the propulsion force. When there are a propulsion force bigger then zero the wheelchair tend to increase its velocity, when it not occurs the tendency it to decrease the velocity because the rolling resistance force. The transversal velocity is zero, what it is mean that the wheelchair has no sliding movement.

The fig.3 (b) represents the wheelchair displacement when the propulsion forces are equal, as mentioned before the wheelchair system change its direction using different forces on the rear (or motor) wheels. To sum up the maximum displacement get by the system was 3.0m in longitudinal direction only and the maximum velocity was 0.23 m/s.

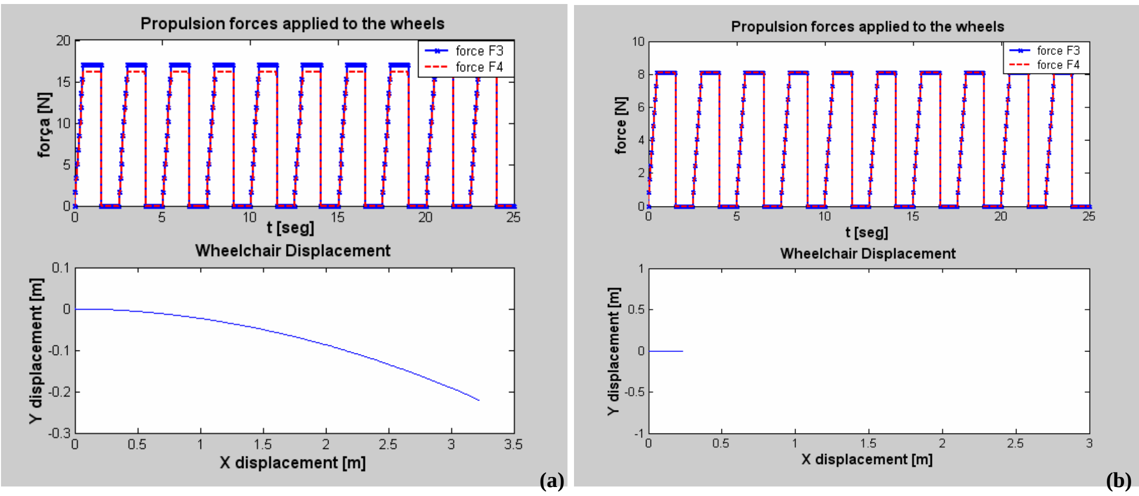

Figure 4. (a) Wheelchair displacement with different propulsion forces (sagital disparity) (b) Displacement with propulsion force equal to 8.90 (50% for the necessary force).

In the fig. 4 (a), is shown that a little difference between the forces can change so much the system displacement and its direction. This difference between the propulsion forces is named as sagital disparity, and it is a kind of deformity present on propulsion force which affects the wheelchair performance. In this simulation was used F4 = 16.18N and F3 was increased in 5 %. The maximum displacement obtained was 3.22 m in longitudinal direction and -0.3 m in transversal direction and the maximum velocity was 0.23 m/s.

In the fig.4 (b), is shown the total displacement for a system when the user is able to supply only 50% (F4 = F3 = 8.09N) of the force necessary for the movement, as resulting the total displacement reached by the wheelchair was 0.24 m, This displacement is smaller than the original situation and for this user his independent mobility will be prejudiced and he is being able to development DORT (damage over repetitive effort) because of the excessive muscular effort.

5. Control Stratégies

The design of control strategies for a global performance of a wheelchair drive system requires satisfaction of many design aspects including the turn on the motors, motors power. When it comes to a servo-assisted wheelchair the power and the turning on are not the only aspects to carry on, but as mentioned in previous works Lombardi Jr. and Dedini (2005), Lombardi Jr. (2002), it is important too paying attention for safety and users comfort.

Thus the control system is not going to be composed by only one function but for many sub functions which are performing the desired behavior. For a complex control system composed by complex control strategies, it is very difficult to development only one system able to perform all activities desired; moreover, it will be difficult to choose the best control strategy for a complex system.

Independence Axiom of the Axiomatic Design can easily distinguish between different designs and can provide an index showing which is the better. For a complex control system is possible to obtain decoupled designs each one referent to a specific function of a role control system. Axiomatic design provides a framework for describing design objects which is consistent for all types of design problems and at all levels of detail. Additionally, the design axioms provide a rational means for evaluating the quality of proposed designs, and the design process which is used guides designers to consider alternatives at all levels of detail and to makes choices between these alternatives more explicit.

Based on these information three strategies were implement to control the motors turn on and the motor power and their performance were evaluated bearing on mind the total displacement during system simulation. These strategies correspond to the first function of the servo assisted control system, which was divided in some sub function to be development based on Axiomatic design.

For the simulations was assumed that the user was able to perform only 50% of the total force necessary to wheelchair movement, in other words *Fmax* = 8.09N The control strategy must to perform with the other part of the propulsion force looking for the higher displacement. Of course the specific value for turning on the motor to realistic user must be set up by a therapist, but the performance of the control strategy can be evaluate for any value.

5.1. “ON-OFF” Strategy

The first strategy is “on-off” control, it is the basic control strategy and in most case it presents best results because has the better relation cost and performance. The first algorithm to the turning on the motors is a quite simple rule: if the force on the propulsion ring (*Fp*) exceeds a value, that in this case is defined as being 80% of the maxim value of the user’s forces (*Fmax*), the motors are turned on for maximum torque resulting in a enlargement of propulsion force defined as (*Fmaxm*), it is shown in fig. 5.

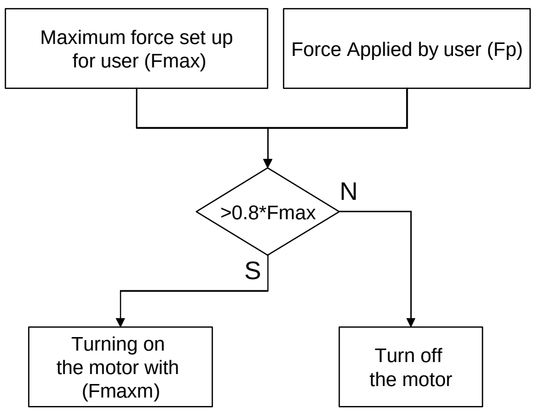

Figure 5. Block diagram for the “on-off” strategy.

The system was simulated for the same situation presenting on fig. 4. For the system without sagital disparity, fig.6(a), the total displacement has no suffer deviation and reach the value of 2,0 m but for the system with sagital disparity, fig.6(b), the total displacement has suffer a deviation and reach the values on longitudinal direction 1.6 m and on transversal direction 1.3 m, but in this time the deviation occurs to left side. The absolute values for system deviation were higher with on-off strategy than for the system without servo assisted motorization, fig. 4(a). The system performance was poor if compared with the situation of normal manual wheelchair, what it is mean that the user has enough force to propel the system. But for the system performance is higher than the system without auxiliary motorization as presented on fig. 4(b).

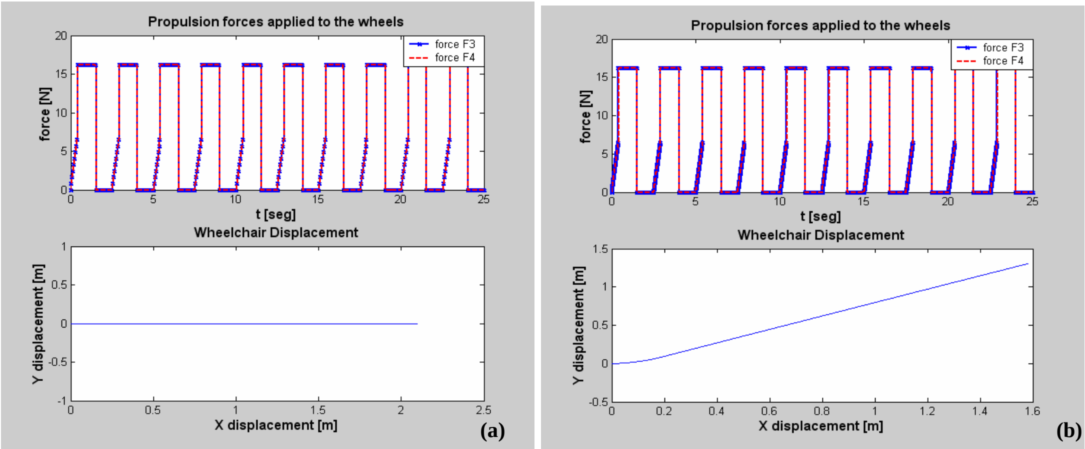

Figure 6. System Simulation with on-off control (a) without sagital disparity and (b) with sagital disparity.

5.2. Rule Control Strategy

One more complex strategy derived from the "on-off" strategy is the rule control. For this strategy it is determined ranges of application corresponding to ranges of actuations, in other words represent a system with rules as *if <statement> then <action>*. This kind of control strategy is more complex than the previous because it is necessary integrated circuit with logic ports and a more complex electronic assembly. Figure 7, presents a block diagram with the rules for this strategy.

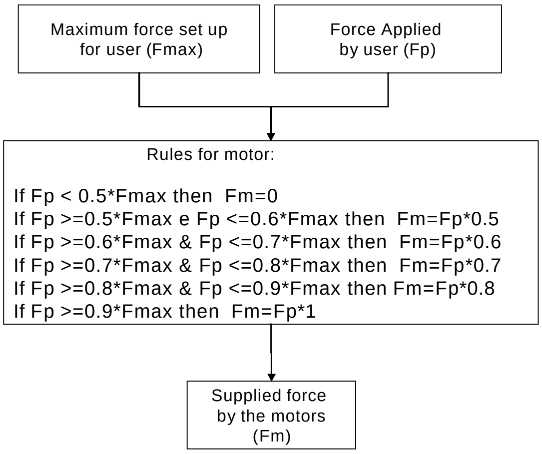

Figure 7. Block diagram for the rule control strategy.

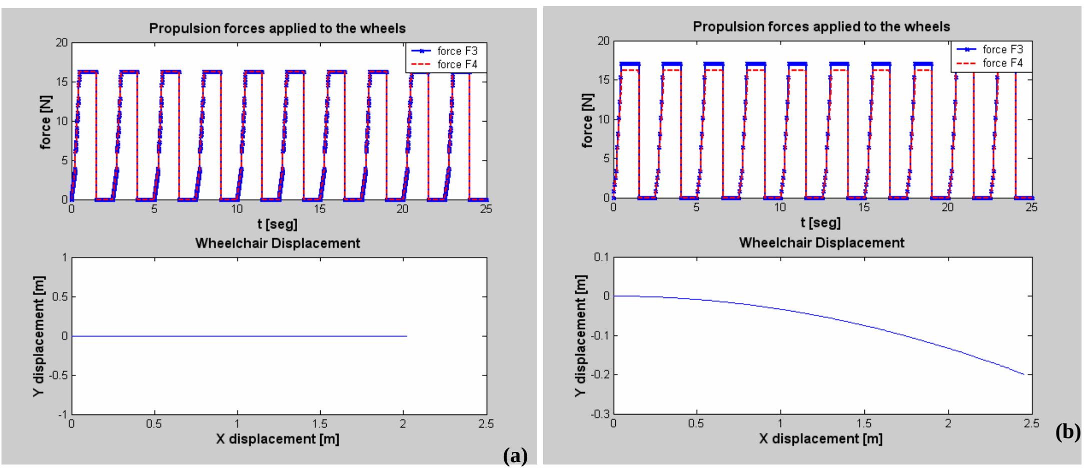

Figure 8. System Simulation with rule control (a) without sagital disparity and (b) with sagital disparity.

Again the system was simulated for two conditions fig. 8(a) without sagital disparity and fig.8(b) with sagital disparity of 5%, as the same situation presenting on fig. 4. For the system without sagital disparity, fig.8(a), the total displacement has no suffer deviation and reach the value of 2,0 m but for the system with sagital disparity, fig.8(b), the total displacement has suffer a deviation and reach the values on longitudinal direction 2,5 m and on transversal direction -0,3 m, the deviation occurs to the same side as shown on fig.4(a), thus more coherent with the system behaviour. In both situations the system performance was poor if compared with the situation of normal manual wheelchair, what it is mean that the user has enough force to propel the system. But for the system performance is higher than the system without servo assisted motorization as presented on fig.4(b).

5.3. Fuzzy Control Strategy

The fuzzy control instead of treating of the variables in a numeric form it applies the semantic rules, as *if <semantic condition> then <semantic action>* For controlling only one variable, the propulsion force, fuzzy strategy acts quite similar way to control rules. Fuzzy logic is important because it can control a plan without a mathematical model, what in some cases determine this model can be a very difficult problem. One way very simple to express the semantic rules for the fuzzy strategy is presented in tab.1.

Table 1 – Fuzzy logic Representation

		Output: motor Force								
		NN	MN	PN	ZN	Z	ZP	PP	MP	PP
	NN	1	0,5	0,1						
	MN		1	0,5	0,1					
	PN			1	0,5	0,1				
Input: Propulsion force	ZN				1	0,5	0,1			
	Z					1	0	0		
	ZP						1	0,5	0,1	
	PP							1	0,5	0,1
	MP								1	0,5
	PP									1

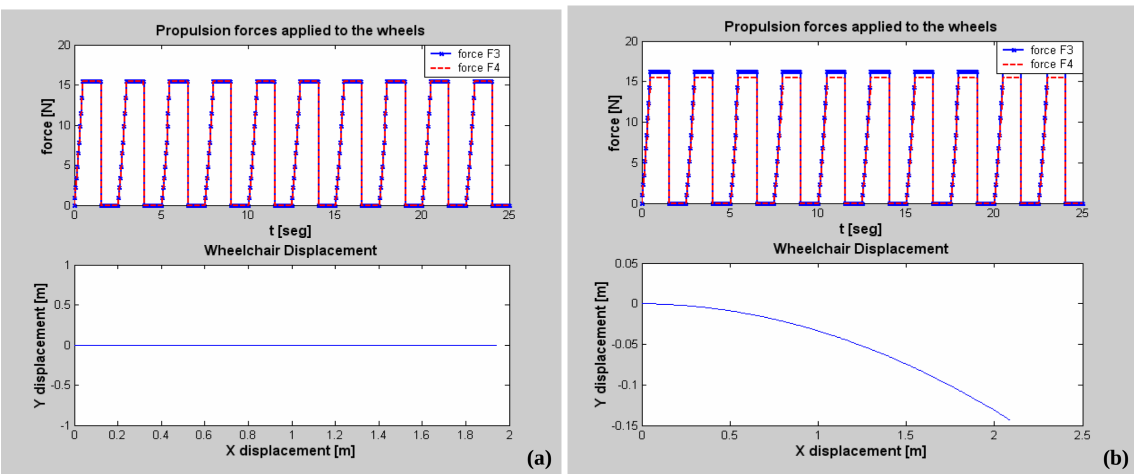

Figure 9. System Simulation with fuzzy control (a) without sagital disparity and (b) with sagital disparity.

The system was simulated for two conditions fig. 9(a) without sagital disparity and fig.9(b) with sagital disparity of 5%, as the same situation presenting on fig. 4. For the system without sagital disparity, fig.8(a), the total displacement has no suffer deviation and reach the value of 1,95 m but for the system with sagital disparity, fig.8(b), the total displacement has suffer a deviation and reach the values on longitudinal direction 2,1 m and on transversal direction -0.14 m, the deviation occurs to the same side as shown on fig.4(a), thus more coherent with the system behaviour. In both situations the system performance was poor if compared with the situation of normal manual wheelchair, what it is mean that the user has enough force to propel the system. But for the system performance again is higher than the system without servo assisted motorization as presented on fig.4 (b).

The displacement deviation do not be forced to zero because manual wheelchair users use this strategy to change the system direction, and if the sagital disparity becomes zero the wheelchair will not be able to change its direction.

6. Conclusion

It is presented in tab.2 the sum up of the main results of the simulations, it can be noted that without servo-assited motorization the total displacement is very low and consequently the user will need more effort to propel the wheelchair and this effort is going to be performed during more time to reach the same displacement. So the user will be more able to development DORT in upper body extremities as shoulder, elbow and wrist, reducing his independent mobility and his social interaction.

Table 2. – Sum up of the results

	Without Motorization			ON-OFF Control		Rule Control		Fuzzy Control	
	standard Propulsion	50% Propulsion	Sagital disparity	standard Propulsion	Sagital disparity	standard Propulsion	Sagital disparity	standard Propulsion	Sagital disparity
longitudinal displacement	3.0	0.24	3.22	2.0	1.6	2	2.5	1.95	2.1
transversal displacement	0	0	-0.3	0	1.3	0	-0.3	0	-0.14
Increment (relation to 50%)				733%		733%		713%	

Another important conclusion is that for the longitudinal displacement when there is no sagital disparity the behavior of the three control strategies are very similar, and for this situation it is necessary to use a constant gain to control strategies to reach the same displacement obtained for a system with standard propulsion.

For systems with very low sagital disparity the rule control shows more efficient than the other because again the displacement reach for this control strategy is near to the standard propulsion. This works presenting one methodological approach to development control strategies based on Axiomatic Design to fragment the control problem e looking for better isolated solution to reach a optimized global strategy.

7. Acknowledgements

The authors would like to thank to the Unicamp and Capes by the financial supplier.

8. References

ABNT 9050, 1994, – Associação Brasileira de Normas Técnicas – "Acessibilidade de Pessoas Portadoras de Deficiência a Edificações, Espaço, Mobiliário e Equipamento Urbanos", secção 5.

Arva, Juliana, Fitzgerald, Shirley G., Coope, Rory A., Corfman, Thomas A., Spaeth, Donald, Boninger, Michael L., 2000 "Physiologic Comparison of Yamaha JWII Power Assisted and Tradicional Manual Wheelchair Propulsion, Proceedings Resna 2000,p. 378 -380

Becker M., 1997, "Estudo de Robôs de Locomoção: Formas Construtivas, Dirigibilidade e Controle" , Dissertação de Mestrado, pp 13-59.

Butler, Charlene, 2000, "Where is of rehabilitatoin placed in the world-wide trend towards evidence based helsth care?" Asia Pacific Disability Rehabilitation Journal v11 n.1 10p.,

Cooper, Rory, Boninger, Michael L., 1999, "Walking on Hands", PN/Paraplegia News March 1999 www.pn-magazine.com/on /articles/hands.html

Corfman, Thomas, Cooper Rory, Fitzgerald, Shorley, Arva, Juliana, 2000, "Excursion an Stroke Frequency Diferences Between Manual Wheelchair Propulsion and Pushrim Actived Power Assisted Wheelchair Propulsion" – Proceedings of Resna 2000

Di Marco, Allie; Russell, Mary; Masters, Margot; 2003, "Standards for wheelchair prescription" Australian Occupational Therapy Journal v 50, p.30-39

Durán, Fabio Salinas; Lugo, Luz; Ramírez, Lina; Eusse, Edgar; 2001, "Effects of an Exercise Program on the Rehabilitation of Patients With Spinal Cord Injury" Arch Phys Med Rehabil v 82,October 2001

Lombardi Junior, Arley de Barros, 2002, "Desenvolvimento e Modelagem de uma Cadeira de Rodas Servo-Assistida para Crianças" Dissertação de Mestrado Universidade Estadual de Campinas, 200p.

Lombardi Junior, Arley de Barros; Dedini, Franco Giusepped, 2005, "Influences of a servo-assisted motorization over the dynamic behavior of wheelchair" Proceedings of XI Diname – International Symposium of Dynamic Problems and Mechanism, Ouro Preto.

Souza. Aaron L., Boninger Michael L., Koontz, Alicia M., Fay, Brain T., Cooper, Rory A., 2000, "Classification of Stroke Patterns in Manual Wheelchair Users", Resna

Stein, R.B.; Roetenberg, D.; Chong, S.L.; James, K.B.; 2003, "A wheelchair modified for leg propulsion using voluntary activity or electrical stimulation" Medical Engineering & Physics v 25 p.11-19

9. Responsibility notice

The authors are the only responsible for the printed material included in this paper.