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Implementation of an Intelligent Controller into a Robotic Device for Rehabilitation Intended for Lower Extremity Paralysis Patients

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Abstract: This paper presents the design of an intelligent controller for an inverted pendulum system. First briefly describe the most recent and current research on this topic, specifically in the last 10 years. Then a series of definitions which aims to delve the reader to understand more in detail the literature of this research will be proposed. Once and bases studied issue is known we proceed to develop the mathematical model of the system and then convert the equations of motion both transfer function as state variables, eventually stability analysis will be developed in open loop the two methods mentioned above, in order to carry out a digital simulation by blocks through Matlab Simulink©. Is presented through graphs, the behavior of the system variables under study. Then based on the results obtained above will proceed to design different fuzzy controllers, in order that only one of these is the one that achieves optimal response to obtain a good system stability. Also presented through graphs, the state variables of the system after being controlled by the fuzzy controller designed. To check its stability analysis is presented, from the graphical method of phase plane. Finally obtained the desired response, an application of the inverted pendulum system focused on the biomechanics, a robot which will help the rehabilitation of patients with lower limb paralysis will be designed, the application will be virtually simulated to verify proper operation.

Keywords: Inverted pendulum, fuzzy control, control algorithm, transfer function, state variables.

INTRODUCTION

Inverted Pendulum is a mechanical device that mainly consists of a rod that freely swings on a plane, fastened by one of its end points where it can freely rotate[1]. Rod of pendulum could be mounted on a movable or fixed base. A representation of these systems is shown below on **Figure 1.**

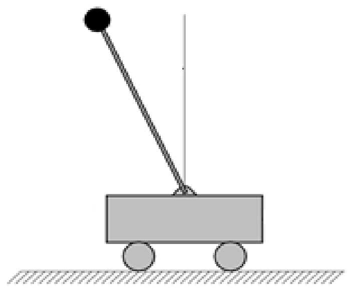

Figure 1: Inverted pendulum representation.

For Inverted Pendulum equilibrium be maintained at its vertical position, by diverse mechanical configuration a force of control can be applied to system, some of these configurations include Single Inverted Pendulum with movable base (SIP)[2], Single Inverted Pendulum for Fixed Base[3] and Furuta Pendulum[4].

On 2003, a balanced inverted pendulum system was built and implemented into the bi-directional vertical pendulum using a Proportional-Integral-Derivative control[1]. On 2003, at the Mechanical Engineering School, Western Australia University, Ooi as final project of degree carried out the construction of a two-wheel inverted pendulum[5].

Additionally, two-wheel inverted pendulums using Lego Mindstorm® platform were built. Hassenplug built a two-wheel inverted pendulum robotic device that continuously tries to adjust breakeven point using an accelerometer to detect tilt, called Legway[6].

Iral sets out an evolutive approach for a controller design of rotational inverted pendulum (RIP) including genetic algorithms (GA) methods, particle swarm optimization (PSO), and ant colony optimization (ACO)[7] . On 2012, an inverted pendulum system with one wheel which is the main support thereof was designed by Francisco Ibarguen, it was introduced to provide innovative ideas to use air energy in order to the system be balanced[8].

At[9, 10] the different applications of inverted pendulum of control systems used at Biomedical Engineering were shown.

Another fuzzy controller for inverted pendulum system stabilization was presented at[11] in accordance with single input rule modules (SIRMs), Dynamic connected Fuzzy Inference Model. A fuzzy logic controller for an inverted pendulum system is shown by the use of Java Applets© program through Internet-based education control[12]. A two-wheel inverted pendulum system design and implementation was introduced with a fuzzy control scheme and system technology incorporated into a programmable chip[6].

In this work a speed control for a robotic device intended for rehabilitation called LOKOMAT® is introduced, an extended analogy is observed among it and the inverted pendulum system, due to the complete human body and this system in its entirely are equal. Movable mass matches with legs mass, and pendulum mass with torso mass, therefore in order for patient to control LOKOMAT®, he only needs to bend his torso, so patient's walking must be in proportion to angle of inclination thereof. A control algorithm for fuzzy control considering patient's body as reference shall be used for controlling this robotic device.

The idea behind the control method designed at [11] consists of dividing the non-linear system operation area into small areas and those small areas must be treated as a set of local servo-linear systems through Davison-Smith method.

Function that matches the number with each "x" element into universe of discourse is called membership function[13]. Membership level of fuzzy sets could be represented by a mathematical function showing elements' membership level into a fuzzy set. In other words, if "A" is a fuzzy set, then membership function "$\mu_A(x)$" calculates which level of "x" element matches with A set [14].

Membership functions can be sorted out accordingly its shape, the most common and used function shapes, due to their simplicity and easy handling, to show membership functions are the following: trapezoidal, triangular, bell curve, gamma, pi, singleton shape, etc.

A fuzzy logic controller (FLC) uses fuzzy logic principles and allow converting linguistic strategies of control based on expert knowledge, on automatic control strategies[15]. Nowadays, there is no a unique methodology to build a fuzzy controller, however, this work is based on the method suggested by C.C. Lee [10], which consist of the following parts:

a) Fuzzification

b) Knowledge base.

c) Decision logics.

d) Defuzzification.

Applicable control systems include calculations and quickly decision making in order to maintain in appropriate position and direction elements' mass center of system.

Logic control purpose is to carry out a human strategy of control. Usual controls such as PID are expressed on mathematical functions, which is essentially different for human control due to it is impossible to represent mathematical functions. On the other hand, the fuzzy logic control was designed to exactly copy the human behavior[16].

The purpose of this work is to implement a precise intelligent control algorithm in order to control the speed of robotic device intended for rehabilitation of lower extremity paralysis patients called LOKOMAT®.

METHODS

An appropriate mathematical model that entirely represents the physical behavior of the inverted pendulum system is required to be found, this is very important to design a controller, due to with it and the proper parameters identification, the simulation and system behavior under any control action could be carried out, that is, the system could be tuned.

First, differential equation system describing variable movement is required to be found in order to F force may be applied to the system. Main variables that describe at any moment the system are system x position and pendulum θ angle in connection with vertical.

Figure 2 is the inverted pendulum free body diagram. On the inverted pendulum, the F, b frictional force, pendulum and cart weight are applied, M is cart mass, m corresponds to pendulum, and g is the acceleration applied by earth.

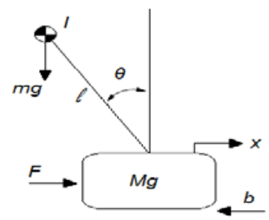

Figure 2: Inverted pendulum free body diagram.

Where:

M = cart mass

b = friction cart

I = pendulum inertia

X = cart position coordinate

m = pendulum mass

l = pendulum length

F = force applied to the cart

Θ = pendulum angle

In order to the analysis be simplified, the inverted pendulum could be divided into two bodies: the cart and the pendulum.

Adding and replacing forces to obtain two moving equations of said system:

$$(M+m)\ddot{x}+b\dot{x}+ml\ddot{\theta}\cos\theta-ml\dot{\theta}^{2}\sin\theta=F \text{ …………………………………. ……… (4)}$$

$$(I+ml^{2})\ddot{\theta}+mgl\sin\theta=-ml\ddot{x}\cos\theta \text{ ……………………………………………………. (5)}$$

Analytically, transfer equation of linearized system at inverted pendulum system is obtained, it is required that Laplace transformations of 4 and 5 equations are carried out to obtain the following result:

$$\frac{\Phi(s)}{U(s)}=\frac{\frac{ml}{[(M+m)(I+ml^{2})-(ml)^{2}]}s}{s^{3}+\frac{1}{[(M+m)(I+ml^{2})-(ml)^{2}]}[b(I+ml^{2})s^{2}-((M+m)mgl)s-(bmgl)]} \text{ …………………………….. (10)}$$

Also, it is needed to produce a transfer function in order to system response would be the x position of movable.

$$\frac{X(s)}{U(s)}=\frac{s^{2}(I+ml^{2})-mlg}{s^{4}[I(M+m)+ml^{2}(M+m)-m^{2}l^{2}]+s^{3}[Ib+l^{2}mb]-s^{2}[gml(M+m)]-s[gbml]} \text{ ………………………………..……... (13)}$$

Finally, transfer function of inverted pendulum system is converted into status variables that shall remain as follows:

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\Phi}\\ \ddot{\Phi}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & \frac{-(I+mL^2)b}{I(M+m)+Mml^2} & \frac{m^2gl^2}{I(M+m)+Mml^2} & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{-mlb}{I(M+m)+Mml^2} & \frac{mgl(M+m)}{I(M+m)+Mml^2} & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \Phi\\ \dot{\Phi}\end{bmatrix}+\begin{bmatrix}0\\ \frac{I+ml^2}{I(M+m)+Mml^2}\\ 0\\ \frac{ml}{I(M+m)+Mml^2}\end{bmatrix}u$$

$$y=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \Phi\\ \dot{\Phi}\end{bmatrix}+\begin{bmatrix}0\\ 0\end{bmatrix}u \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

In contrast to transfer function, pendulum angle, and also cart position for status variables analysis of multi-outputs system is controlled.

Open loop analysis of inverted pendulum system is unstable, therefore, an appropriate controller is required to be adapted, in this case specifically, a fuzzy controller intended to solve stabilization problem of system shall be adapted.

The model which is called Mamdani fuzzy model was used for this work, because it is one of the most easy fuzzy control methods to use.

To design the appropriate fuzzy control for the inverted pendulum system, different parameters and features must be taken into consideration, such as:

- Fuzzy controller
- Membership functions
- Number of membership functions
- Rules of inference
- Logic of decisions

To prepare this work, both to make this system, as well as for fuzzy controller design MatLab© packaging was used.

Based on the above-mentioned, diverse simulations will be carried out in order to note if the suggested designs comply with main purpose which is to stabilize the inverted pendulum system.

Features of PI controller are shown on **Table 1:**

Finally, a four variable output fuzzy controller was designed with the status variables method, and also with the transfer function method, so this controller is no longer operating on error and its drift, therefore it would not be any more a PI fuzzy controller.

Features of this controller, as well as the number of rules and input variable ranges are equal to that stated on the previous method.

After the inverted pendulum system was completely analyzed, it was created an application intended for the rehabilitation field.

LOKOMAT® was the selected system, which is shown on **Figure 3,** it is comprised of a robotized walking orthosis and a state-of-art system for body weight unloading putting together by a rolling strip.

Then with the transfer function method, a four-variable output fuzzy controller was designed. New features for this controller were stated and are shown on **Table 2.**

Table 1: PI fuzzy controller features.

PI Fuzzy Controller	
Controller type	Mamdani
Input variables	Angle and Angular speed
Output variables	Force
Input type membership functions	2 Trapezoidal and 3 Triangular
Output type membership functions	2 Trapezoidal and 5 Triangular
Method inference rule evaluation	MIN/MAX
Number of rules	25
Defuzzification method	Centroid

Table 2: Fuzzy controller features with four input variables.

Fuzzy Controller	
Controller type	Mamdani
Input variables	Angle, angular speed, position x, and linear speed
Output variables	Force
Input type membership functions	2 Trapezoidal and 1 Triangular
Output type membership functions	2 Trapezoidal y 5 Triangular
Method inference rule evaluation	MIN/MAX
Number of rules	81
Defuzzification method	Centroid

Figure 3: Locomotion functional therapy LOKOMAT®.

LOKOMAT® helps disabled patients to do walking motions on a treadmill combined with an intensive locomotion functional therapy with tools to evaluate patients.

Analyzing LOKOMAT® system, it was suggested to design an automatic speed control to help patient with his torso tilting so that user can control his own speed, both to walk slowly or even run.

For this purpose an inverted pendulum system analogies compared with patient body were carried out. The analogy of human body and an inverted pendulum system, where mass M of movable refers to legs mass and mass m which is pendulum mass will be, in this case, torso mass are shown on **Figure 4.** On the other hand, F variable is the force that will be applied by LOKOMAT® system, more force will be applied by system when more positive inclination of body is applied, and therefore patient's walking speed would be higher. Specific features for system controller were designed and are shown on **Table 3.**

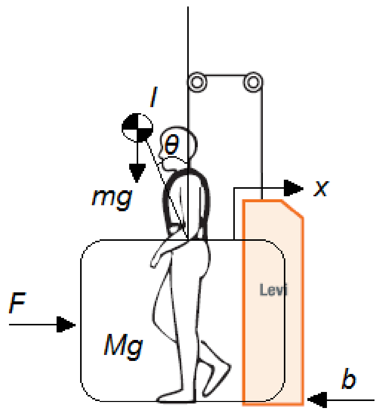

Figure 4: Analogy of the system LOKOMAT® and the inverted pendulum system.

Table 3: Fuzzy controller features with four input variables for the system LOKOMAT®.

Fuzzy Controller	
Controller type	Mamdani
Input variables	Angle, angular speed, position x, and linear speed
Output variables	Force
Input type membership functions	2 Trapezoidal and 1 Triangular
Output type membership functions	2 Trapezoidal y 5 Triangular
Method inference rule evaluation	MIN/MAX
Number of rules	81
Defuzzification method	Centroid

Figure 5: Person model in SOLIDWORKS©.

Once fuzzy controller for appropriate speed control of LOKOMAT® system is designed, then a simple simulation will be designed which in the first instance would create a human being with main joints required to have stepping movement.

This design created with SOLIDWORKS© software, shown on **Figure 5**, has 14 degrees of freedom allowing legs, arms and head movement.

After system was designed and the proper movement thereof was tested, in order to obtain the mechanical model of said system it was imported to Matlab© software. One section of mechanical model of system is shown on **Figure 6.**

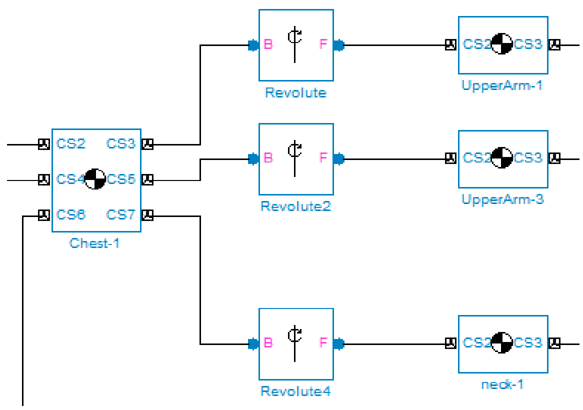

Figure 6: Mechanical model of the system.

After the system is imported, it is required to begin simulation; said system has a non-controlled movement, therefore, before fuzzy controller be included this issue must be solved.

To solve non-controlled movement, small controllers will be added into each degree of freedom so that movement be controlled; said controllers consist of an actuator that is handled by a sinus input signal whose range variation would be the movement degree of each joint; this design can be noticed on **Figure 7.**

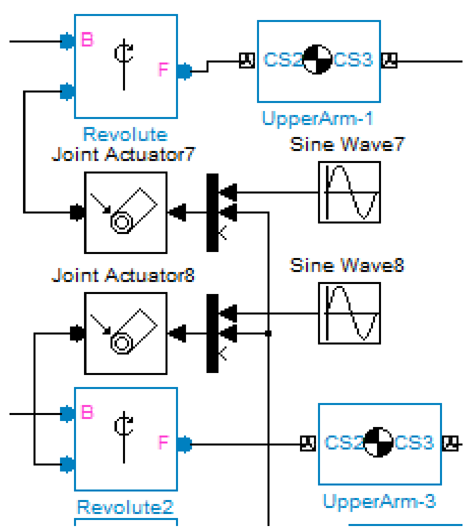

Figure 7: Blocks added to achieve a controlled movement.

Finally, fuzzy algorithm to control speed was added, it states that depending on body tiling system's speed will vary, for example, if one person tilts forward more his body, then his walking speed will be faster in contrast to minimum tilting. To the mechanical model is attached to previous designed controller and one of its ends is linked to legs speed, and at the other end body tilt angle is connected.

RESULTS

Analysis of PI fuzzy controller with two input variables (angle and angular speed) was unsatisfactory, therefore four input variables (angle, angular speed, position, and linear speed) be included.

Simulation including the above-mentioned variables was carried out again, it was found that system's response is correct, but it swings too much, and that means system is not stable. Pendulum that swings on cart position goes out zero, in contrast to angle, angular speed and movable speed, the reason is that the three last variables must be on zero in order to pendulum be stable unlike to movable position, because pendulum be stable at initial position is not needed. To reduce swing of system, four input variable ranges, as well as output variable (force), and also fuzzy rules were changed. Upon these changes were done, it was found that overdamping of system is lost and it becomes stable more quickly than in previous tests. After a pulse set, angle, angular speed and linear speed become stable, due to they are the movements required by system to maintain upright with minimum movement. Moreover, it not need that movable position that balances pendulum be at initial point, but it was found that it could be balanced at a point different from zero.

The last analysis was carried out using status variable method but observing the four input variables, it may be concluded that the system is unstable since the position runs to infinity, that means that pendulum which is moved by cart always goes on the same direction and a derailment may be caused on it. In addition, angle, linear speed and angular speed continuously swing because movable never stops. As in the transfer function method, ranges where said variables act were changed to stabilize the system concluding that movable position become stable.

For the last two studies (transfer function and status variables) diverse stabilization analysis by phase plane method were suggested, it was found that system goes around initial point less times, this means that system is no longer swinging and at minimum time reaches its stability; also it was noted that path begins on the fixed point, in this case on zero point, and after that it reaches again to the desired point with a position change. Therefore, it was found that system responds properly to the suggested fuzzy controller.

After the expected results were obtained, an application with biomechanical approach, intended to fuzzy control of LOKOMAT® system speed was created, and then simulation was carried out to obtain the answer which is shown on **Figure 8.**

Before analyzing answers from the different tests carried out for this research, it is important to point out that they graphically represent input signals (y axis) in connection with simulation time (x axis).

On **Figure 9,** behavior of LOKOMAT® system position could be noted.

On **Figure 10,** speed behavior of LOKOMAT® system is noted, it could be observed that system remains on zero because upon patient tilts his body, the system may try the body be stabilized, as soon as possible, attempting body will be positioned completely upright. When patient wants to stop his walking, and the system stops its operation, he only needs to go straight.

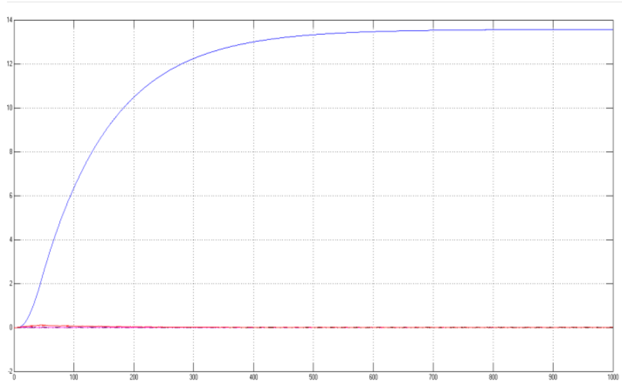

Figure 8: LOKOMAT® response system with fuzzy controller tuned.

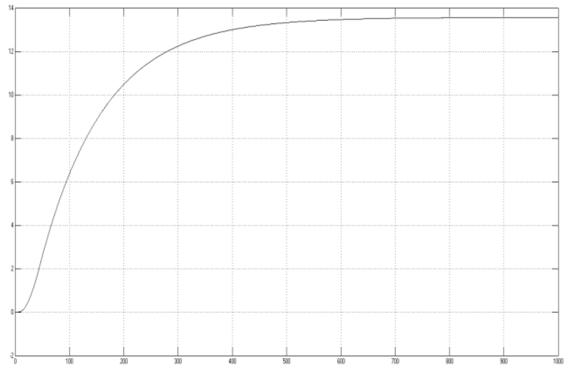

Figure 9: Behavior LOKOMAT® position.

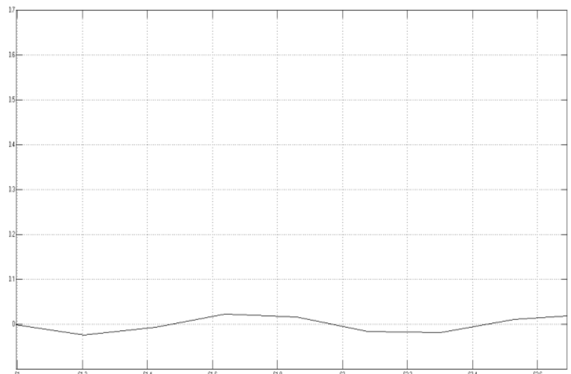

Figure 10: Behavior of the displacement speed LOKOMAT®.

Finally, an analysis of system stability with the designed controller was carried out, it was tested the angle (x axis) related to its derivate that is already known it refers to angular speed (y axis).

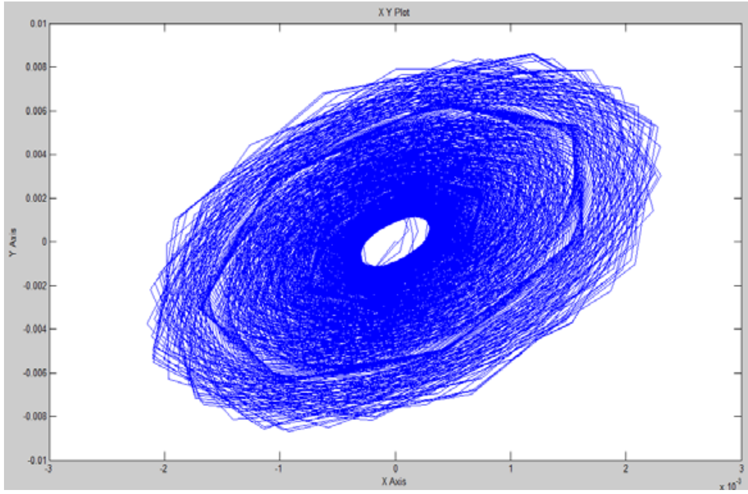

Figure 11: Phase plane analysis Angle Tilt angle-Angular speed LOKOMAT® with fuzzy controller.

On **Figure 11,** the system swings into a very small range that ends on zero can be observed, that means that said swings are negligible for system, therefore it could be stated that the system is highly stable.

Lastly, the system behavior is tested through x position variables (x axis) and travelling speed (y axis) which is shown on **Figure 12.**

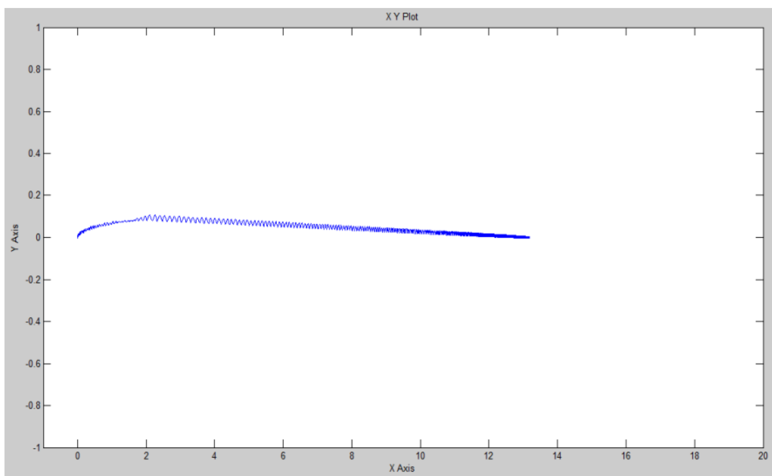

Figure 12: Phase plane analysis Position-Speed LOKOMAT® with fuzzy controller.

On **Figure 12** it can be noticed that travelling begins on the established point, in this case zero, and after a while it reaches to the established point with a position change.

Therefore, it is stated that system properly responds to the suggested fuzzy controller achieving good stability.

Upon the entire model is obtained, running simulation was carried out obtaining the following response.

On **Figure 13**, patient's movement accordingly with body tilt is shown.

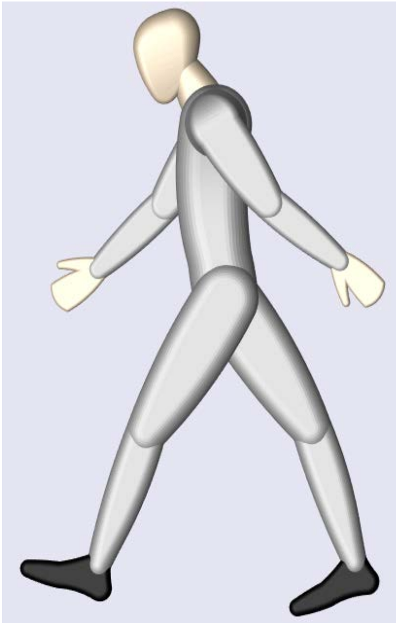

Figure 13: Behavior of the displacement speed LOKOMAT®.

CONCLUSIONS

After charts are analyzed, and based on the different responses of the inverted pendulum system the following conclusions were drawn:

In view of the results obtained previously, the system simulation was carried out on an individual concluding that LOKOMAT® system responds properly, and also it is concluded that speed behavior remains on zero, because, upon patient tilts his body, the system may try the body be stabilized, as soon as possible, attempting body will be positioned completely upright, if patient remains lean, movement speed of the system must not be zero until patient completely be upright.

This last simulation is very important, because speed control is completely achieved in regard to patient tilting, response speed is extremely fast due to it does not take a long time to automatically attempt the body be stabilized, the more tilting of patient, higher speed of system attempting to stabilize the body, and therefore patient will walk faster, if patient maintain continuous tilt, speed of LOKOMAT® system also will remain constant.

An important advantage of LOKOMAT® system is it could be adjusted to any type of user, because when the algorithm programming for fuzzy control was designed, it was included a section where system requires relevant patient data (height and weight), and automatically the system do calculations after these data is entered.

As a final conclusion, it could be stated that fuzzy controller included into LOKOMAT® system is extremely effective, because the response speed is extremely fast, and in contrast to other systems LOKOMAT® system's accuracy is more precise. This controller is suitable for this system because when it is used enough safety is provided to patient, and user's walking absolutely simulates the nature walking of an individual.

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