Automatic control for above-the-knee prosthesis

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Abstract: -. The present work pertains to assisting disabled persons. This paper proposes a prosthesis equipped with an intelligent dynamic brake. More specifically, an automatic control of pneumatic electrovalves was studied and integrated on a microcontroller into a pre-existing knee prosthesis (PROTEVAL) in order to adapt performance of the artificial limb according to the velocity, the walking phase and situations.

The desired system had to be able to recognise certain parameters of knee and leg movement, such as spatio-temporal relationships and kinetic data. Several often-used electrical engineering techniques, especially fuzzy logic, were studied. Such work involved the selection of appropriate test algorithms capable of integrating information about the phase of movement (flexion or extension) and the walking speed.

A situation recognition module was developed for the sophisticated knee prosthesis control system able to adapt to different phases and speeds of walking. The goal of this module is to feed pertinent information to the prosthesis control system so that it could adapt its control based on the context (ascent and descent of an inclined plane, ascent and descent of stairs, walking on smooth or rough terrain,...).

The goal of this article is to describe the processes followed and the results obtained.

Key-Words: - control, fuzzy logic, identification, sensors, actuators, above-the-knee prosthesis, dynamic prosthesis, human gait, artificial gait, microcontroller.

1 Introduction

When a person wearing knee prosthesis begins to walk quickly or run, the artificial limb behaves as a pendulum, the swaying of which increases with the velocity of movement. This anomaly greatly hinders movement and limits the attainment of normal walking. The principal shutcoming of this system is that it is passive because its stiffness is fixed; it can not adapt to static and dynamic phases of walking. It is designed to produce a symmetric gait, enabling only one walking style.

The present paper proposes a prosthesis equipped with an intelligent dynamic brake. More specifically, a control of pneumatic electrovalves was studied and integrated on a microcontroller into a pre-existing knee prosthesis (PROTEVAL) in order to adapt performance of the artificial limb according to the walking phase and velocity.

The desired system had to be able to recognise certain parameters of knee and leg movement, such as spatio-temporal relationships and kinetic data [1]. These values were deduced from experimental measurements relative to the study of human subjects walking at speed between 0 and 18 Km/h [2]. The established database was then used to control the prosthesis.

Several often-used electrical engineering techniques, especially fuzzy logic, were studied. Such work involved the selection of appropriate test algorithms capable of integrating information about the phase of movement (flexion or extension) and the walking speed. This article describes how we were able, using fuzzy logic techniques, to feed pertinent information to the prosthesis control system so that it could adapt its control based on the circumstances.

In effect, the control is different not only doing each phase of a step (extension and flexion) but also according to the speed and the context (ascent and descent of an inclined plane, ascent and descent of stairs, walking on smooth or rough terrain,...).

In the following sections, two studies are described about the identification module. The first deals with the recognition of a subject's gait phase (flexion and extension) and walking speed. The second study is a bit more complicated, and the use of fuzzy logic is much more prevalent; the object being to determine whether a subject is walking on flat ground or an inclined plane, and, in the case of an inclined path, whether the subject is ascending of descending. The process consisted of choosing the criteria for making decisions, to construct the method and the algorithms for pertinent information extraction, and then to modify the fuzzy control system, adapting it to the situation at hand.

The goal of this article is to describe the processes followed and the results obtained. The parts concerning the study of normal human walking require very long detailed description which will only be mentioned briefly here.

2 System Design

The articulation of the knee of a prosthesis can be described as a mechanical system equipped with two segments, which are connected by either a rotary-type or a parallelogram-type joint. Generally, these mechanisms are equipped with a hydraulic or pneumatic brake. The system studied here uses of a pneumatic tube as a brake. The valves of the braking unit (proportional electrovalves) permit the adjustment of the rigidity of the artificial joint by controlling the airflow in the pneumatic circuit (Fig.1).

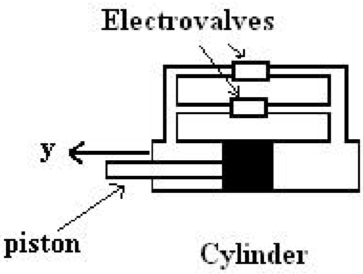

Fig. 1: pneumatic circuit and electrovalves

The rotation of the knee joint leads to a sliding of the piston. When the flexion angle of the knee becomes sufficiently large, the electrovalves close, stopping the airflow between the two chambers of the cylinder. This prevents the leg from flexing too much. The air contained in one of the two chambers at that moment increases the elastic energy of the piston. To avoid an abrupt return of the leg, the airflow through the electrovalves is controlled, thus regulating the gait of the amputee.

Sensors provide the information required by the microcontroller: measurement of the different parameters are obtained from a magnetic sensor which provides the angle of the knee, an inclinometer measures the angle between the thigh and the vertical plane, an accelerometer gives the acceleration of the thigh, and final sensor indicates the pressure of the upper chamber (Fig. 2)

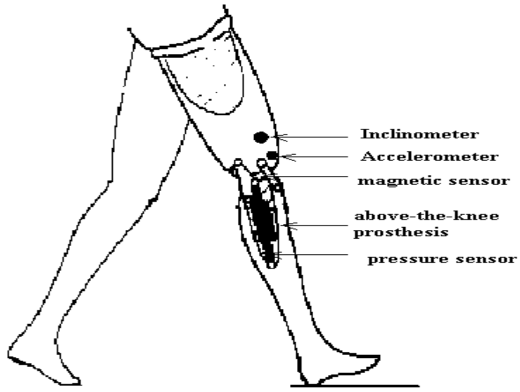

Fig. 2: The above-the-knee prosthesis and its sensors

3 Analysis of the fuzzy control

Mechanical system control requires the integration of many parameters. In effect, we distinguish between parameters intrinsic to the system being controlled (inertia, resistance, shock absorbency, gravity, etc.) and regulating parameters imposed on the system to achieve a desired behaviour. Generally, a mechanical system can be modelled by the non-linear differential equation with variable coefficients:

$$M(\mathrm{q}).\ddot{q} + C(\mathrm{q},\dot{\mathrm{q}}) + G(\mathrm{q}) = t \quad (1)$$

Where $\mathrm{q}, \dot{\mathrm{q}}, \ddot{\mathrm{q}}$ are the vectors of position, velocity and acceleration; M(q) : the inertial matrix. C(q) : the vectors of Coriolis and centrifuges forces ; G(q) : the vector of gravitation forces; τ(t): the torque of the knee

Synthesis of a control involves the establishment of a time function τ(t). The choice of a time function τ(t) then defines the type of control.

As opposed to a standard regulator or an adaptive control by feedback states, control by fuzzy logic[3] does not involve well-defined mathematical relations. The latter makes use of integration of many rules based on linguistic variables. These inferences are then modified by fuzzy logic operators. Figure. 3 schematically describes a fuzzy controller.

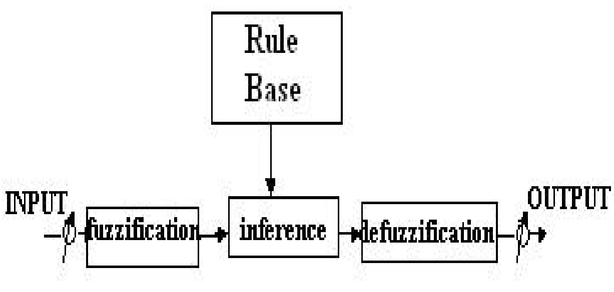

Fig. 3 : Internal scheme of fuzzy logic controller

Three major blocks are shown: fuzzification, inference, and defuzzification. Fuzzification translates the input variable into a linguistic variable. The process of inference selects and applies rules from the database appropriate to the input. Defuzzification calculates a real value of control which is applied to the entire process.

Fuzzy logic control was chosen to be implemented on a microcontroller, which assures adaptation of the above-the-knee prosthesis according the phase and the speed of the gait. The main reasons for this choice are:

- The prosthetic model associated to that of the leg is complex and does not take into account the movement physiognomy of an individual amputee, whereas fuzzy control has the capacity to integrate uncertainties into the model using properties of fuzzy sets.
- The system must react in real-time, which imposes certain constraints as far as calculation speed. In addition, the size of the internal electronic card must be as small as possible.
- Measurement data allowed the establishment of linguistic rules in order to model the behaviour of the prosthesis.
- Flexibility for future improvements.
- Simplicity of implementation.

4 Realisation of the Control System

This section presents the structure of the control system as well as the control algorithm implemented and the situation identification module.

4.1 Control structure

The prosthesis control system can be broken-down into four blocks (Fig. 4): a system for signal analysis, a control algorithm, a reference database and a base determining the mode of function.
The reference database contains selected values of the different parameters.

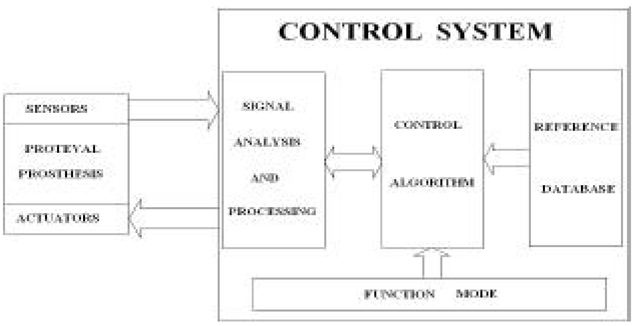

Fig. 4: Control system structure

For communication between the control system and the sensors / actuators, an electronic adaptation is essential.

The prosthesis allows the ascent or descent of an inclined plane, stairs, and also different gait rhythms. The parameters of such situations are fed into a fuzzy-neural network module, which identifies the situation using sensory vectors and modifies the function mode base.

4.2 Situation identification

The measure of the angle of the joint is made by a magnetic sensor, which reports the angle of the knee, and an inclinometer furnishes the angle between the thigh and the vertical plane. By integrating the information from the different sensors, the airflow across the electrovalves, which regulates the amputee's walking, is controlled.

The angle a of the thigh and the angle b of the knee (the angle between the thigh and the tibia), and the first and second derivatives of b, were deemed sufficient parameters for situation recognition. Our sensory vector is thus comprised of four components, of which two, $\dot{b}$ and $\ddot{b}$, are calculated from b :

$$c = \begin{bmatrix} a \\ b \\ \dot{b} \\ \ddot{b} \end{bmatrix}$$

, χ is the input vector of the identification system.

4.2.1 Step phase recognition

In the first study, the aim was to recognise the pendulum phase of the leg during movement (flexion and extension) and to estimate the person's walking speed. To do this, it was not necessary to employ fuzzy logic functions, as the simple relationship between the speed and the minimum amplitude of angle a of the knee is linear. The different gait phases are deduced from changes of variation of the amplitude of the same angle. The prosthesis controller uses this information immediately during the step.

The three curves (Fig. 6) represent three different speeds. It is clear that as the walking speed increases, the minimum of the curve is lower. The idea, then, is that to extract this information from the curve, and then to apply a function to it, in order to determine the speed.

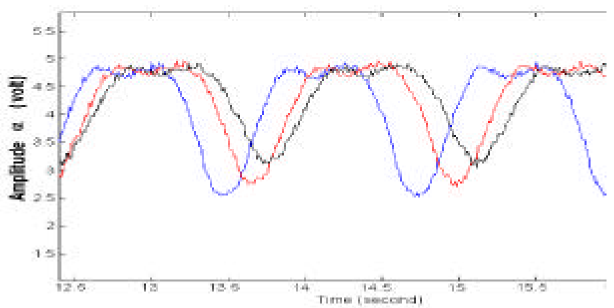

Fig. 6 : Different values of a as a function of walking speed.

This minimum allowed the identification of the switch from flexion to extension. In effect, it is at that precise moment that the leg begins extension anew [1][2]. This gait phase and walking speed information is instantaneously plugged into the prosthesis control algorithm.

Figure 7 represents a curve of a with the phases of flexion and extension during a step and the minimum of switching.

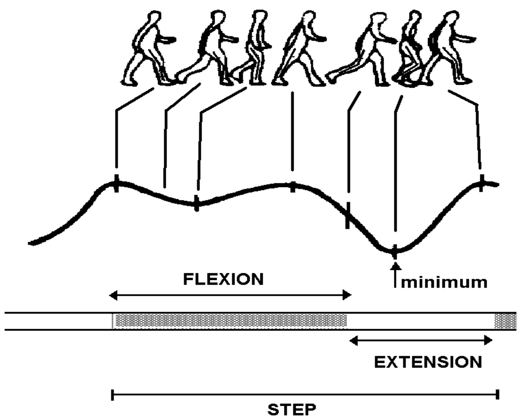

Fig. 7 : Different phases of human gait.

4.2.2 situation recognition

The second study is a bit more complicated than the preceding one, as fuzzy logic was applied. This time it is necessary to determine if the subject is walking on flat ground or an inclined plane, and in the latter case, if the person is ascending or descending stairs or a planar surface. Therefore, decision-making criteria for recognising these situations must be defined and the accuracy of the recognition tested. The situation identification is based on the input vector χ.

Figure 8 shows the angle a for three different situations: the subject descends, ascends an inclined plane, and walks on flat ground. The signals were filtered in order to facilitate the search for criteria and the simulation of the identification method, which results from them.

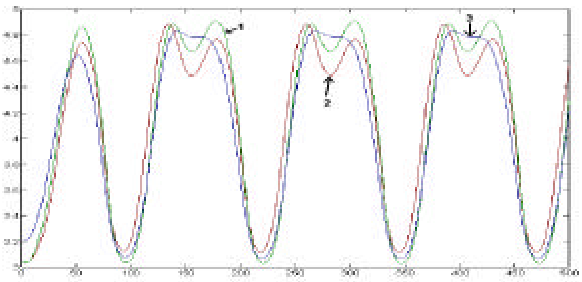

Fig. 8 : Values of the angle a based on the walking situation: 1 : walking ; 2 : descent ; 3 : ascent

Contrary to the previous study, the criteria here are not obvious. In order to study the curves closer, we traced the Fast Fourrier Transformations, during a period Ti (between two minima), using samples of each of the three preceding situations (Fig. 9).

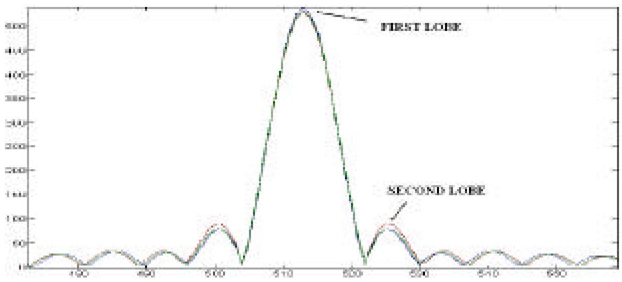

Fig. 9 : FFT using the three previous samples

Using the sensor data obtained during different situations, we have analysed the Fast Fourrier Transformations during a period of the vector χ in order to identify different cases, and we have chosen the height of the first and second lobes as decision criteria for each component of the sensory vector. In effect, these two amplitudes characterise well the type of situation. This new information is input into the fuzzy decision system which identifies the situation using a learning base relative to known situations. This learning function depends on the decision algorithm used.

4.2.3 Decision algorithm

A majority of the scientific community today recognises the fact that fuzzy systems and neural networks are closely linked. Neural networks are very useful for numerous applications of fuzzy set theory in the construction of membership functions and other entities based on sample data.

Fuzzy neural networks have the following properties :

a) The inputs and outputs are fuzzy numbers
b) The synapse weights are fuzzy numbers
c) The inputs associated with each neurone are not

grouped by summation but by another grouping operation

There are many models of fuzzy neural networks in the literature. For our work, we have chosen an adaptive neural network, ANFIS (Adaptive-Network-Based Fuzzy Inference System) [4]. This network, the architecture of which is represented in figure 10, is rather fast because we only model systems with several inputs but only one output. Such is the case for our application. In effect, given a sensory vector we wish an output characterising the situation.

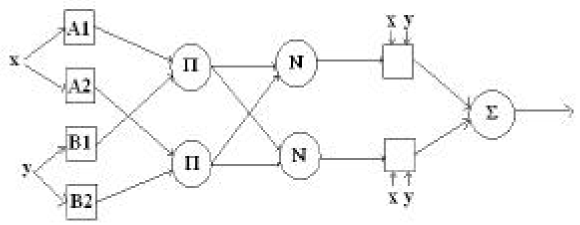

Fig. 10 : ANFIS architecture

All the real numbers characterising a standard neural network become fuzzy numbers. The role of this network is to take the lobe values furnished it, to fuzzify them in order to work with fuzzy variables and provide as output a matrix for situation identification

4.2.4 Application

To create the fuzzy decision system, we applied the hybrid learning algorithm ANFIS with feed-forward gradient to the training and test data. This function gives the matrix characterising the fuzzy system as well as the error obtained by applying the fuzzy system to these data. The learning and test matrices contain as many rows as learning samples. The number of columns corresponds to the number of inputs into the system. An extra row is added for the corresponding output. The error obtained by applying the ANFIS function to these matrices is on the order of 5.10^{-3} for the learning data and 1.10^{-2} for the test data.

Figures 11 and 12 illustrate the fuzzy logic membership functions obtained for the first and second lobes, respectively.

It is clear that there are three fuzzy sub-sets which correspond to three different situations which must be identified.

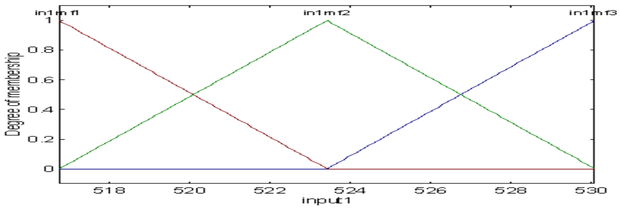

Fig. 11 : Membership functions for the value of the first lobe.

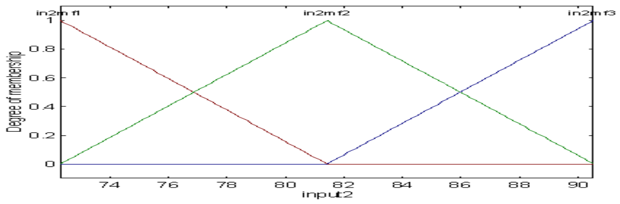

Fig. 12 : Membership functions for the value of the second lobe.

4-2-5 Results

To test the accuracy of our fuzzy system, we applied it to data obtained directly from sensors. In the ideal case of recognition, the fuzzy system gives, after defuzzification, the number 1 for descent, 2 for walking on flat ground, and 3 for ascent. With the real-time data obtained from sensors, we obtained respective values of 0.85 , 2 .02, and 2.98. Thus, the system indeed recognised the different walking situations.

The results, obtained from recordings on many patients, showed a good aptitude for the identification of different situations, and robustness to the noise of the sensors (Fig. 13).

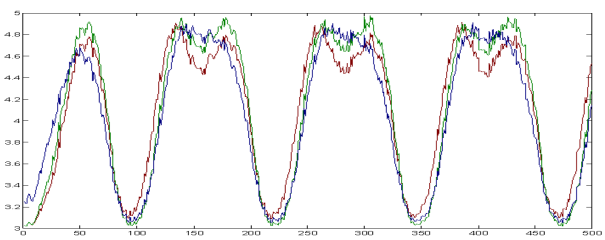

Fig. 13 : Raw data from magnetic sensors.

The three types of situations studied (descent and ascent of an inclined plane, and walking on flat ground) were difficult to distinguish using classical methods. The study of fuzzy logic and generation methods of fuzzy systems (such as ANFIS) enabled us to create a system which responds to given constraints.

This identification module is coupled to the control algorithm, in order to enhance the prosthesis control system.

5 Control system

The control structure utilised by the fuzzy controller is shown in Figure 14.

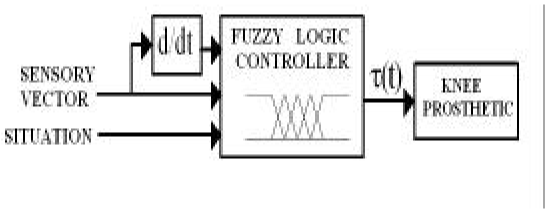

Fig. 14: Fuzzy logic control for the prosthesis.

In this case the control function τ(t) is given by the output of the fuzzy controller by:

$$t(t) = \frac{\sum_i m_{x^i}\left(x(t)^i\right) X^i}{\sum_i m_{x^i}\left(x(t)^i\right)} \qquad (2)$$

X^i: Linguistic term.
$x(t)^i$: Real value of input.
$\mu_x^i(x(t)^i)$: Degree of membership

The contribution sensory vector applied here for fuzzification is composed of five parts:

- the knee angle and its derivative,
- the angle between the thigh and the vertical plane,
- the acceleration of the thigh,
- the pressure in the chamber of the cylinder.

A variable defining the situation at hand is added to the input into the fuzzy controller. This is the output of the previous situation identification module.

The fuzzy controller has many parameters: the membership functions of fuzzy variables, the aggregation and composition operators, the base of rules, and the defuzzification method.

It is not always easy to describe a behavioural model using linguistic rules. To establish a base of applicable rules, modifications based on trial-and-error studies with doctors were performed. A reduction in the number of fuzzy subsets and rules was undertaken for the implementation of the algorithm. Thus, the input and output variables each possess three membership functions (Figure 15).

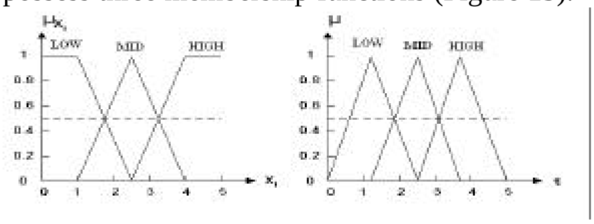

Figure 15: Example of membership functions

The aggregation of all these data is achieved by applying the classic disjunctive operator of Zadeh, Max (x,y), to the different degrees associated with the measurements[5]. This operator has the advantage of being associative (figure 16).

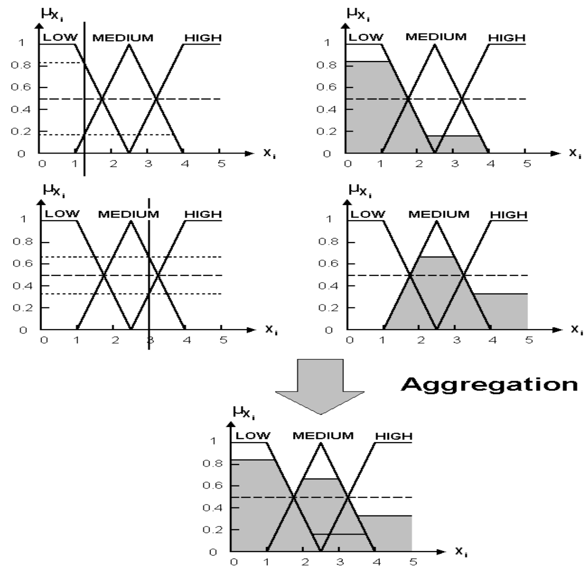

Fig. 16 : Example of aggregation of two inputs.

The defuzzification method chosen is the centre of gravity because it assures a better stability of the control (Figure 17).

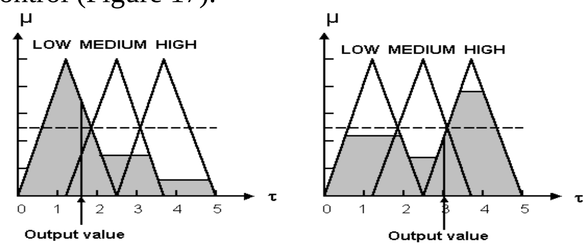

Fig. 17 : Example of two results of defuzzification.

The chosen system must be powerful enough to perform calculations, and must possess numeric and analogue converters. An architecture based on the i80196 microcontroller and the electronic interfaces for each sensor and actuator were constructed.

6 Experimental results

After simulation, the validity of the algorithm controlling the electrovalves of the prosthesis was measurable on a real, dynamic artificial limb. The tests were performed on many patients in collaboration with theirs doctors, therapists, and prosthetisists. Figures 18 and 19 show the result of prosthetic control on an amputee walking on a flat surface at different speeds.

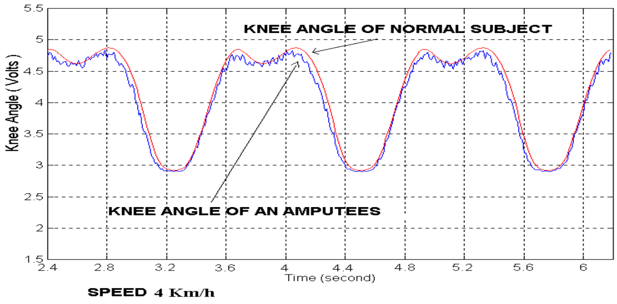

Fig. 18: Results of the control at 4Km/h on a flat surface.

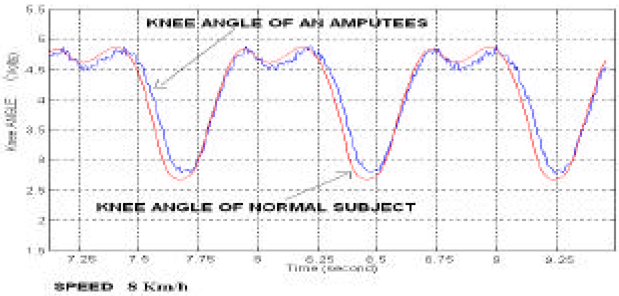

Fig. 19 : Results of the control at 8Km/h on a flat surface.

The curves obtained at different speeds regarding the angle between the knee and thigh of amputees were practically identical to those of a not amputees. The control system provides the automatic adaptation of the prosthesis to the walking speed of the patient.

The identification of different situations (flat ground, soft or bumpy terrain, descent, ascent, stair climbing, etc.) was achieved. Here are the results obtained for a particular situation (Fig. 20 and 21).

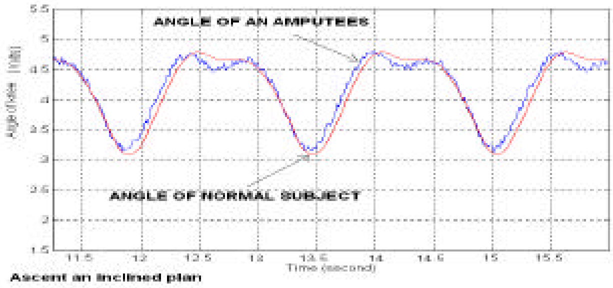

Fig. 20 : Results of fuzzy control for the ascent.

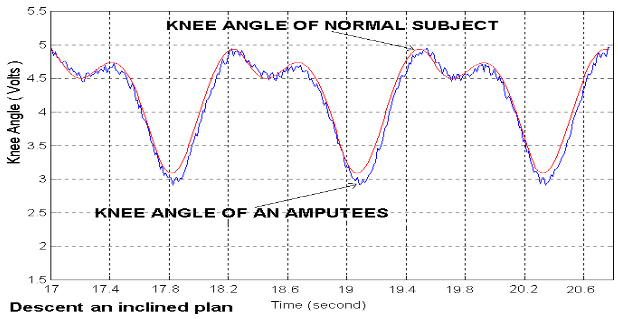

Fig. 21 : Results of fuzzy control for the descent.

One sees an active control of movement (flexion and extension), as well as a blocking and a modification of the stiffness of the knee for a walk on an inclined plane. These results show that the control algorithm adapts well to different circumstances, using information provided by the situation recognition module (Fig. 22).

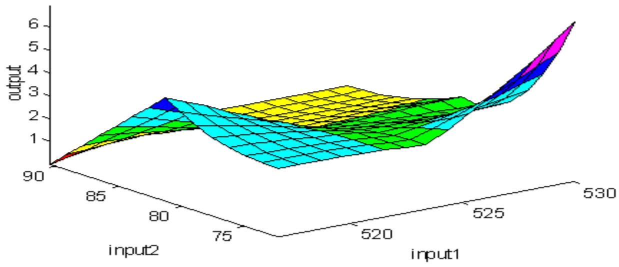

Fig. 22: System reaction to the identification of the situations

6 Conclusion

The end product of this research led to an innovative improvement of the walking quality and comfort for amputees using this knee prosthesis. In effect, the sophistication of the prosthesis allows a gait without circumduction, as well as an easy, smooth, symmetric walking of different types. The introduction of fuzzy logic into the control system is very beneficial.

The results obtained for situation recognition, using the ANFIS method, are good, even in the presence of increased noise. The tests of the prosthesis equipped with the recognition system, performed on patients in collaboration with their doctors, therapists, and prosthesists, gave excellent results.

The continuation of this work will allow the extension of this system to other types of situations, and then to implement them anew into the microcontroller of the knee prosthesis.

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