

Solar tracking system with fuzzy reasoning applied to crisp sets

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Abstract - *In this paper, a low cost and an easy to implement solar tracker system is presented. The design of the system is based on the fuzzy reasoning applied to crisp sets. In this case, it can be easily implemented on general purpose microprocessor systems. Four light sensitive devices, such as LDR, photodiodes or phototransistors are mounted on the solar panel and placed in an enclosure. The four light detectors are screened from each other by opaque surfaces. Each pair of the light sensors is used to inform the controller on the orientation of the solar panel vertically and horizontally respectively.*

Résumé - *Dans cet article, un système de poursuite solaire à coût réduit et simple à implémenter a été présenté. La conception du système est basée sur le raisonnement flou appliqué aux ensembles nets tout ou rien. Dans ce cas, il peut facilement être implémenté sur des systèmes à microprocesseurs à usage général. Quatre détecteurs d'éclairage, tels que les LDR, les photodiodes ou les phototransistors sont montés dans une enceinte et placée sur le panneau solaire. Ces quatre détecteurs sont isolés deux à deux par des plans opaques. Chacune des deux paires de détecteurs est utilisée pour informer le contrôleur sur l'orientation du panneau solaire verticale et horizontale respectivement.*

Keywords: Renewable energy - Solar energy - Solar tracking - Fuzzy reasoning - Solar radiation.

1. INTRODUCTION

Renewable energy has known a great interest during the last two decades. Solar energy is viewed as the clean and renewable source of energy for the future, it is the least polluting and the most inexhaustible of all known energy sources. Most solar energy used today is harnessed as heat or electricity. Subsequently, technologies that enable the use of solar energy focus on solar thermal collectors and on the photovoltaic effect of semiconductors to generate electricity directly from sunlight. In the case of solar energy, it is shown that optimum of energy is obtained when the rays of the sun are incident normally on the collecting surface. This has led to the study of the solar radiation on the surface of the earth and to the development of systems which allow an energy collecting system to track the sun continuously [1, 2].

In the present contribution, the main goal of the authors in developing a sun finder and solar tracking was to provide as much as capability and flexibility as possible in an affordable system that can be implemented on general-purpose microprocessor systems. It has been emphasized on the application of fuzzy reasoning as a modern method [3-5]. Furthermore, the developed technique gets rid of the inference engine and the defuzzification, defining the main parts of fuzzy controller, by applying fuzzy reasoning to crisp sets as explained in section 3.

2. THE CIRCUIT

2.1 Sun light detector

The idea of the design consists of four light sensitive devices, such as LDR, photodiodes or phototransistors, mounted on the solar panel and placed in an enclosure. The four light detectors are screened from each other by opaque surfaces as shown on the figure 1.

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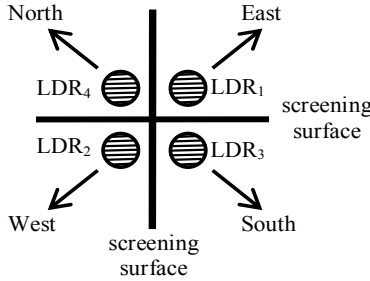


Fig. 1: Sun light detecting mechanism

The sensors are configured in a way that LDR₁ and LDR₂ are used to track the sun horizontally meanwhile LDR₃ and LDR₄ allow tracking the sun vertically. To free the controller from reading each sensor output, each pair of the sensors, LDR₁-LDR₂ and LDR₃-LDR₄, is associated with a differential amplifier. The outputs C_V and C_H correspond to the vertical and horizontal errors; they define the feedback responses which are used as fuzzy input variables of the fuzzy controller in order to generate the vertical and horizontal commands respectively in terms of speed and direction to an appropriate DC motor. The system of equations (1) gives the expression of C_V and C_H calculated from the microcontroller input circuit shown on the figure 2; the offset V₀ is added to discard the necessity of a bipolar power supply. The **Table 1** illustrates the interpretation of the variables issued from the sun light detecting mechanism.

$$\begin{aligned}
 C_V &= \frac{R_2}{R_1} (s_4 - s_3) + V_0 \\
 C_H &= \frac{R_2}{R_1} (s_2 - s_1) + V_0
 \end{aligned}
 \tag{1}$$

Table 1: Different situations of the solar panel

	C _V > V ₀	C _V < V ₀	C _V = V ₀
C _H > V ₀	Panel moves from: East to West South to North	Panel moves from: East to west North to South	Panel moves from : East to west
C _H < V ₀	Panel moves from: West to East South to North	Panel moves from: West to East North to South	Panel moves from: West to East
C _H = V ₀	Panel moves from: South to North	Panel moves from: East to west South to North	Panel Well oriented

2.2 Microcontroller interface

The schematic diagram of the central processor unit is shown in figure 2. The PIC16F877A single chip Risc microcontroller is the brain of the tracking system. This microcontroller contains 8 kbytes of program memory, a 256 Bytes of temporary data RAM and 1 kbytes of EEPROM. It also contains 8 multiplexed analog channels, a 10 bits analog converter and a PWM generator module. These features make the PIC16F877A a useful and powerful single chip microcontroller in designing embedded systems.

For more flexibility the outputs generated by the controller for either motor (speed, sens and stop) constitute the input of a programmable circuit GAL in order to generate the adequate command signals as shown in **Table 2**.

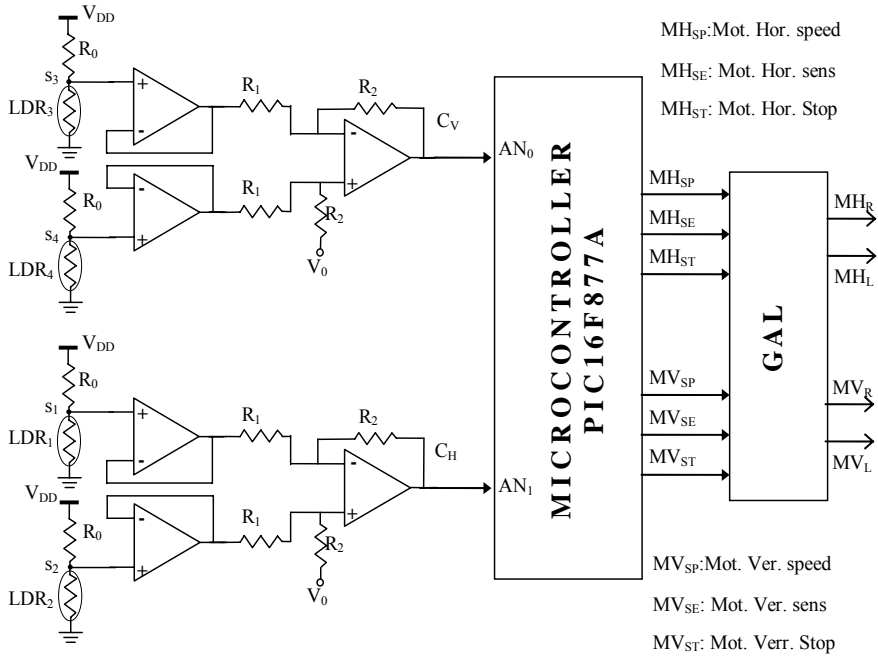


Fig 2: Input and output controller circuit

Table 2: Truth table of the controller output and corresponding actions

μC output			GAL output		Bridge H action
MH _{SP} (PWM)	MH _{SE} (SENS)	MH _{ST} (STOP)	MH _L	MH _R	Horizontal tracking Motor M _H
SPEED	X	0	0	0	STOP
	0	1	0	1	Turn Right
	1	1	1	0	Turn Left
MV _{SP} (PWM)	MV _{SE} (SENS)	MV _{ST} (STOP)	MV _L	MV _R	Vertical tracking Motor M _V
SPEED	X	0	0	0	STOP
	0	1	0	1	Turn Right
	1	1	1	0	Turn Left

2.3 Solar Panel Drive interface

The solar panel is maintained well oriented to the sun by means of two DC motors; M_H to track the sun horizontally and M_V vertically. Both of M_H and M_V are driven via H-bridge formed by two complementary pairs of Darlington transistors. The microcontroller system controls the H-bridge through an opto isolator to keep the low power circuit isolated from the high power circuit. As shown in figure 3, the use of H-bridge to control a DC motor provides the possibility to this later to turn left or right without the need of a bipolar power supply. **Table 2** summarizes the control signals and the corresponding actions.

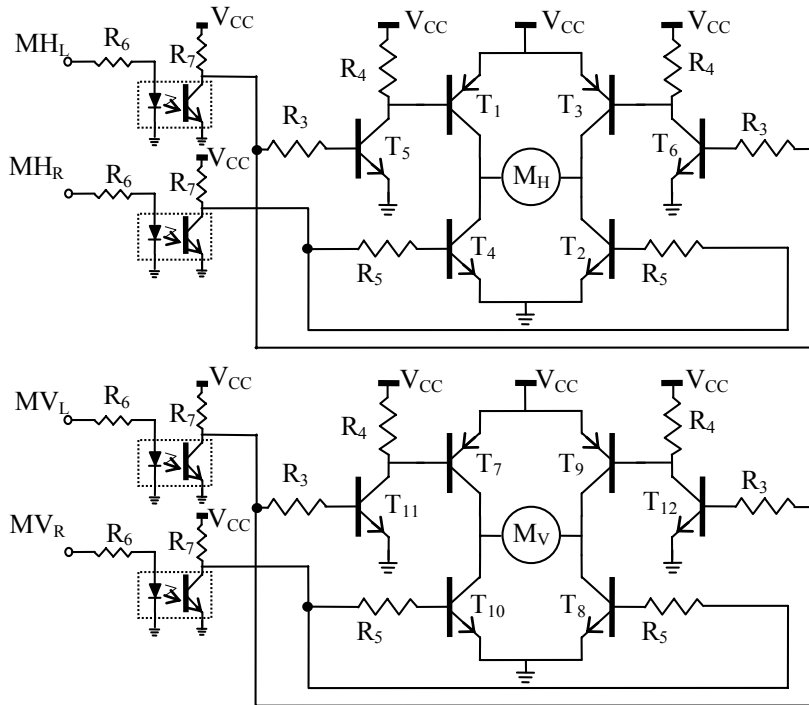


Fig. 3: Horizontal and vertical motors driving circuit

3. THE CONTROLLER

3.1 Fuzzy Control Basics

In most research literature, a fuzzy controller system is commonly defined as a system that emulates a human expert. In this case, the knowledge of the human operator would be put in the form of a set of fuzzy linguistic rules. These rules would produce an approximate decision in the same manner a human would do. A block diagram of a fuzzy control system is shown in figure 4. The fuzzy controller is composed of the following four elements [6-9]:

- *A rule-base*: a set of If-Then rules which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.
- *An inference mechanism*: also called an "inference engine" or "fuzzy inference module", which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.
- *A fuzzification interface*: converts the controller inputs into information that the inference mechanism can easily use to activate and apply rules.
- *A defuzzification interface*: converts the conclusions of the inference mechanism into actual inputs for the process.

3.2 The proposed controller design procedure

The design methodology is similar to the fuzzy controller general design method. As it can be seen on the figure 5, the structure of the proposed controller is kept merely the same as the fuzzy controller, except that in our case we should not care about the choice of the membership functions, the inference method and the defuzzification strategy.

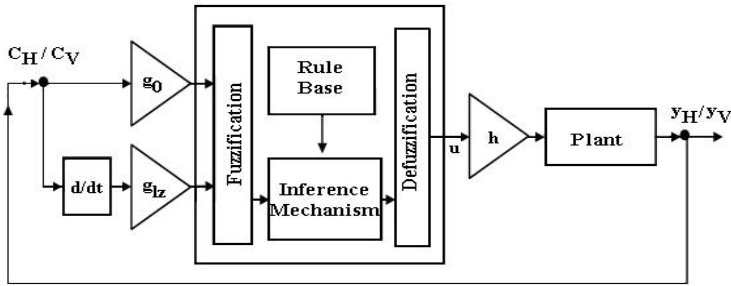


Fig. 4: The structure of a fuzzy controller

In order to simplify the processing steps involved in a fuzzy controller, two main modifications are brought to the designed controller.

The first modification concerns the choice of the membership functions for the inputs and the outputs of the system. For the inputs of the controller, we use crisp adjacent semi-closed membership functions; they are distributed all along the discourse universe. Since the membership degree for the crisp sets takes only two values 0 or 1 that is very simple to determine; the computing time necessary at this stage in the case of fuzzy controller for both fuzzification and inference operations is extremely reduced. Furthermore, we will not need to infer the rules, because only one rule from the rule-base is active. Once the membership functions of the input variables are known, the fired rule is straightforward determined and the corresponding output singleton is defined. In fact, at this stage, the decision making time is considerably reduced because the defuzzication step is completely avoided.

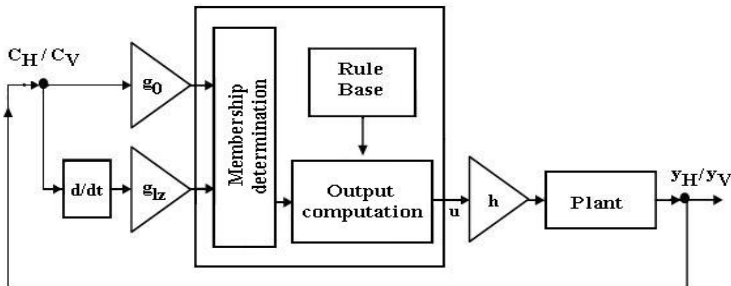


Fig. 5: The structure of the proposed controller

The second modification is related to the computation of the output. The main aim at this stage is to smooth the brief transitions due to the choice of the crisp membership functions. We first proceed to calculate the amount by which the input variables are shifted with respect to the centers of their respective crisp membership functions. Let's take the controller illustrated by figure 5, where the input variables are C_H/C_V and dC_H/dC_V defining the error and the error variation respectively. The gradual output control value is computed according to the equation 2.

$$\begin{aligned}
 y_H &= \text{rule}(i, j) - \frac{(\Delta C_H + \Delta d C_H)}{2} \\
 y_V &= \text{rule}(i, j) - \frac{(\Delta C_V + \Delta d C_V)}{2}
 \end{aligned}
 \tag{2}$$

where:

- i: the number of the crisp set to which belongs the error variables C_H/C_V
- j: the number of the crisp set to which belongs the variation of errors dC_H/dC_V

$\Delta C_H / \Delta C_V$: the difference between the errors values C_H / C_V and the center of their membership sets.

$$\begin{aligned}\Delta C_H &= C(i) - C_H \\ \Delta C_V &= C(i) - C_V\end{aligned}\quad (3)$$

$C(i)$: the center of the set number i , respectively for C_H and C_V .

$\Delta dC_H / \Delta dC_V$: the difference between the errors derivative and the center of their membership sets.

$$\begin{aligned}\Delta dC_H &= C(j) - dC_H \\ \Delta dC_V &= C(j) - dC_V\end{aligned}\quad (4)$$

$C(j)$: the number of the crisp set to which belongs the error variables variation dC_H / dC_V

rule(i, j): the singleton contained is the cell (i, j) in the rule base.

As it is shown on the figure 5, the controller consists of three main blocs. The membership determination bloc provides indices i, j of the sets to which belong the error and the error derivative C_H / C_V and dC_H / dC_V respectively. Instead of the defuzzification and the inference mechanism involved in a fuzzy controller, the output computation bloc applies simple arithmetic operation to compute the real controller output. The steps given below illustrate the output computing procedure.

- Compute $\Delta C_H / \Delta C_V$: the difference between the center of the i^{th} set and the error value.
- Compute $\Delta dC_H / \Delta dC_V$: the difference between the center of the j^{th} set and the error derivative.
- Extract the contents of the cell (i, j) in the rule table which represents the output singleton.
- Adjust the singleton value by the subtraction of the mean of $\Delta C_H / \Delta C_V$ and $\Delta dC_H / \Delta dC_V$.

The so computed value is a crisp (real) one, and does not need to be converted (defuzzified). This method simplifies all the fuzzy reasoning steps, and minimizes the computation time. Consequently, the decision making time will be very short. Thus, the implementation of such controller for real time applications will be easier than fuzzy controllers and does not require any special hardware resources.

4. THE PROPOSED CONTROL ALGORITHM

The steps involved in the design algorithm of the proposed controller are as follow:

1. The choice of the controller inputs and outputs

According to the structure given in figure 5 our controller is MISO type with two inputs and one output. We choose the error C_H / C_V and the error derivative dC_H / dC_V as the controller inputs. For the output, we choose the control input of the plant.

2. The discourse universe partitions

As in fuzzy control, we'll partition the discourse universes of the controller inputs into crisp sets having adjacent rectangular membership functions. While, for the output singletons are used to partition the discourse universe. These singletons represent the centers of the output rectangular membership functions. The choice of singletons output partition will simplify the computation of the output. The figure 8 depicts an example of such partition.

3. The rules elaboration

The knowledge about the dynamics and the behavior of the system to control are quantified in a table of rules of the form IF... THEN in the same manner as those used in fuzzy controllers design.

4. Tests of the controller

The last step in the design algorithm concerns the test and the tuning of the controller. At this stage several adjustments can be performed to obtain the desired response. It can be done by adapting the scaling gains of the controller or by modifying the rule base or the membership functions widths and centers.

5. THE SOLAR PANEL CONTROL

Since that a solar panel is actuated by two DC motors; we'll present the design of a fuzzy and the proposed controller for a DC motor position control. The utility and the efficiency of the proposed controller are confirmed by its application to a DC motor position control. The results obtained in the case of the proposed controller are compared to those obtained by a fuzzy controller. The two techniques are used to design controllers for the position control of a DC motor characterized by the scheme shown in figure 6.

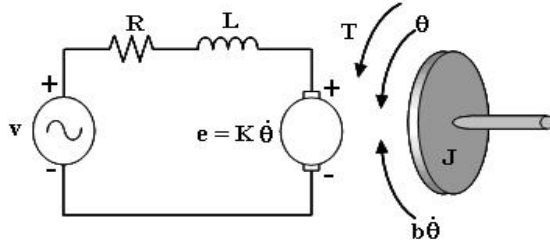


Fig. 6: DC motor representation

where:

- $J = 0.01 \text{ kgm}^2/\text{s}^2$: moment of inertia of the rotor
- $B = 0.1 \text{ Nms}$: damping ratio of the mechanical system
- $K = 0.01 \text{ Nm/Amp}$: electromotive force constant
- $R = 1 \Omega$: electric resistance
- $L = 0.5 \text{ H}$: electric inductance.

The differential equations of the system are given by:

$$\begin{aligned} J \left(\frac{d^2}{dt^2} \theta(t) \right) + b \left(\frac{d}{dt} \theta(t) \right) &= K i(t) \\ L \left(\frac{d}{dt} i(t) \right) + R i(t) &= v(t) - K \left(\frac{d}{dt} \theta(t) \right) \end{aligned} \quad (5)$$

The transfer function of the motor is given by:

$$\frac{\theta(s)}{V(s)} = \frac{K}{s(K^2 + Ls^2 J + Lsb + RJs + Rb)} \quad (6)$$

The system state space representation is given by:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{v} \\ \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{v} \end{cases} \quad (7)$$

where:

$$x = [i \quad \theta \quad \dot{\theta}] \tag{8}$$

$$A = \begin{bmatrix} -\frac{R}{L} & 0 & -\frac{K}{L} \\ 0 & 0 & 1 \\ -\frac{K}{J} & 0 & -\frac{b}{J} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}, \quad C = [0 \quad 1 \quad 0], \quad D = 0 \tag{9}$$

1. The fuzzy controller

For the design of a fuzzy position controller; the structure shown in figure 1 is used with triangular membership functions on normalized discourse universe for all inputs and output variables as shown in figure 7. The couple of *max* and *min* operators are used to infer the rules, and the center of gravity technique is used for the defuzzification. **Table 3** summarizes the rule base used to represent an expert description of the manner to control the DC motor.

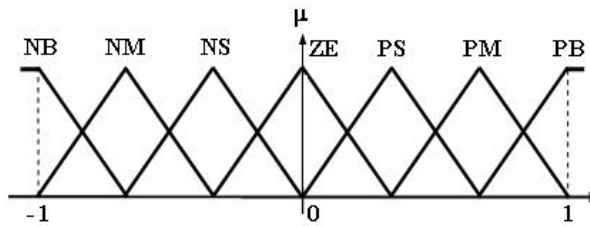


Fig. 7: Membership functions used in the validation examples

2. The proposed controller

As described above; the discourse universe of all inputs and the output of the proposed controller are partitioned into adjacent non overlapping crisp sets as shown in figure 8. The same rule base used for the fuzzy controller is used for the modified controller. The controller has the structure shown on figure 2.

Table 3: rule base

		$C_v (C_h)$						
		NB	NM	NS	ZE	PS	PM	PB
$dC_v (dC_h)$	NB	NB	NB	NB	NB	NS	PS	PB
	NM	NB	NB	NM	NM	ZE	PS	PB
	NS	NB	NB	NS	NS	ZE	PM	PB
	ZE	NB	NB	NS	ZE	PS	PB	PB
	PS	NB	NM	ZE	PS	PS	PB	PB
	PM	NB	NS	ZE	PM	PM	PB	PB
	PB	NB	NS	PS	PB	PB	PB	PB

3. Simulation results

The scaling factors are the same for the two controllers. In a first time a step input is used to compare the response of the DC motor. The result is represented by figures 9 and 10. Then a square wave excitation has been also used to test the controllers; the response of the system is shown in figures 11 and 12. For both cases of tests, we can notice that the proposed controller deals better than a fuzzy controller does. However, the control signals produced by the controllers, figures 10 and 12, show that fuzzy controller produces a smoother signal than the proposed one this fact is due to the nature of the crisp sets.

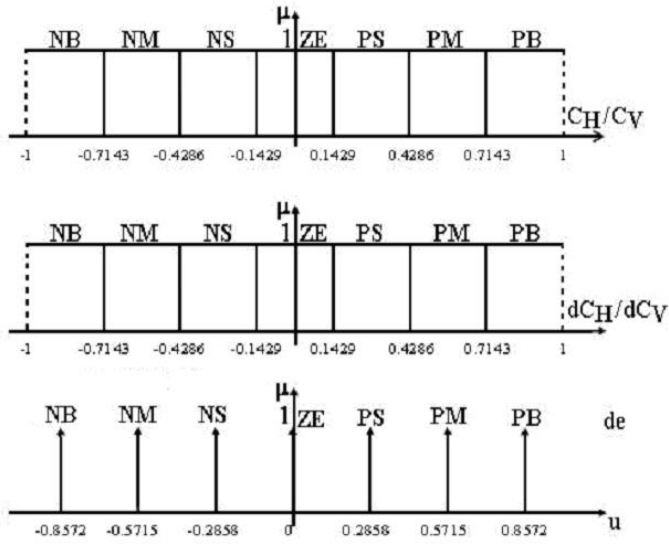


Fig. 8: Crisp membership functions used in the validation examples

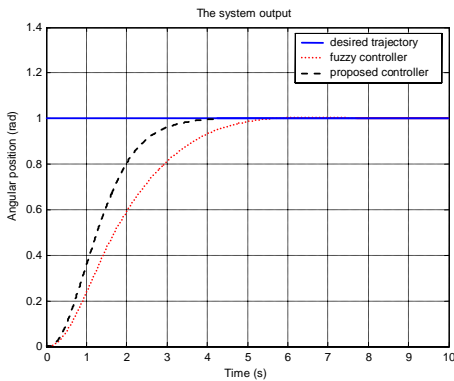


Fig. 9: Unit step tracking

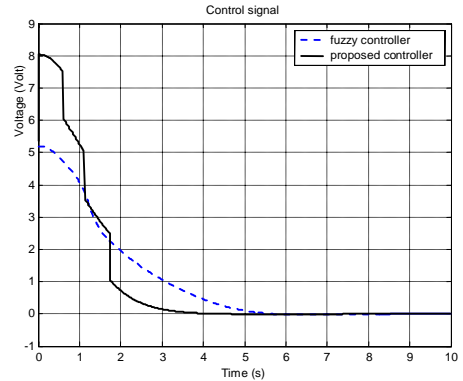


Fig. 10: Unit step control signal

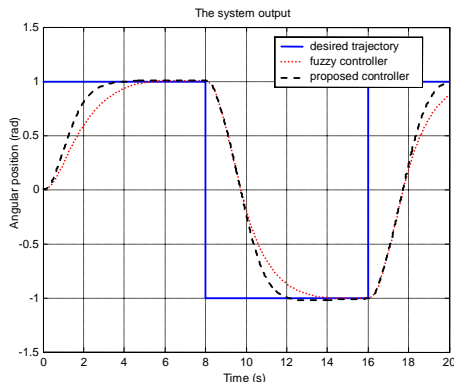


Fig. 11: Rectangular tracking

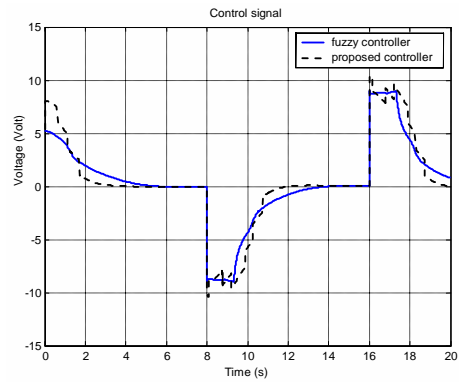


Fig. 12: Rectangular control signal

6. CONCLUSION

In this paper a new control method was proposed for the control of a sun tracker. In particular, we have presented two modifications that are brought to a fuzzy logic controller in order to reduce considerably the decision making time. The design of the proposed controller is simple because it is based on the fuzzy reasoning where flexibility and gradual control output are the main keys. Thus, the proposed controller behaves like a fuzzy controller with less time for the output generation.

The obtained simulation results are quite encouraging; they show the efficiency and the simplicity of the proposed method.

The most important advantage of our method is the short processing time and the decision making manner, so, increasing the number of membership functions does not affect the processing time since that only one rule from the rule base is used to produce a conclusion.

At this stage, our efforts are focused on the quality of the output signal and its smoothness. This is motivated by the avoidance of the crisp transitions due to the choice of membership functions. We are pursuing our research work to optimize the equation used to compute the output value which will improve the controller performance. The adequate criterion for the stability analysis of our controller will also be investigated.

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