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Fuzzy control design to pose mechanical structures used in solar farms

Diseño de un control difuso para posicionar estructuras mecánicas empleadas en granjas solares

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Abstract

Solar panels have problems in terms of the optimal capture of solar energy, reducing their efficiency due to the static position they maintain throughout the year. This article presents the proposal for the development of a fuzzy control to position a mechanical structure, which supports a solar panel seeking to obtain maximum capture in solar farms. The fuzzy control law defines rules that together cause a nonlinear control law by evaluating the performance of the controller through graphics and its simulation in the MatLab Simulink® software. The mechanical structure used has an arrangement of photoresistors at the ends of the surface, which determined the desired elevation angle, generating the control setpoint. Three experiments were developed to validate the operation of the resulting controller, concluding that the diffuse system decreases the position error with respect to the incidence of solar radiation on the photovoltaic cells and the rotational movement of the Earth.

Solar panel efficiency, Nonlinear control law, Fuzzy logic

Resumen

Los paneles solares presentan problemas en cuanto a la captación óptima de energía solar, reduciendo su eficiencia debido a la posición estática que mantienen a lo largo del año. En este artículo se presenta la propuesta del desarrollo de un control difuso para posicionar una estructura mecánica, la cual soporta un panel solar buscando obtener la máxima captación en granjas solares. La ley de control difuso define reglas que en conjunto causan una ley de control no lineal evaluando el desempeño del controlador mediante gráficos y su simulación en el software MatLab Simulink®. La estructura mecánica empleada cuenta con un arreglo de fotorresistencias a los extremos de la superficie, lo cual determinó el ángulo de elevación deseado, generándose la consigna de control. Se desarrollaron tres experimentos para validar el funcionamiento del controlador resultante, concluyendo que el sistema difuso, disminuye el error de posición con respecto a la incidencia de la radiación solar en las celdas fotovoltaicas y el movimiento rotacional de la Tierra.

Eficiencia del panel solar, Control no lineal, Lógica difusa

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Introduction

Currently, most of the structures that support solar panels are not mobile or have a manual movement system, causing maximum energy collection only when the sun's rays are perpendicular to the panel surface. In addition, the collection time is limited due to the lack of automatic adjustment in the orientation of the mechanical structure. Based on this drawback, we propose the application of a set of fuzzy rules that minimize the orientation error at any instant of time.

The operation of fuzzy control is based on the theory of fuzzy sets, which defines elements such as: membership functions, variables and linguistic terms and inference rules, whose assignment is carried out by an expert in the systems to be controlled (Amato, 2006; Cirstea *et al*., 2022; Harris *et al*., 1993). Some of the current applications of fuzzy controllers are focused on electrical systems (Boujoudar *et al*., 2023; Chaithanakulwat *et al*., 2023), to optimize energy demands. Thus, the advantage of the methodology proposed in this work is to dispense with a dynamic mathematical model of the system to be controlled (Amstrom & Murray, 2008; Jack, 2001). However, for future applications, it could be combined with a mathematical model in order to robust the closed-loop system, implying a decrease in the steady-state position error, (Slotine & Li, 1991; Tsui, 2022; Vidyasagar, 1993; Vukic *et al*., 2003). A possible disadvantage, however, is that the increase in inference rules generates unnecessary computational load and does not ensure higher system accuracy. This offers the possibility of embedding the system in a low performance device as presented by (Alamouti *et al*., 2023).

The proposed methodology will be applied to a mechanical structure that provides support and protection to two solar panels, allowing maneuverability in the specified range of angular movement in an interval between -80° ≤ θ ≤ 80°.

The mechanical structure supporting the solar panel is schematized with which, the possibilities of its mobility are analyzed. The essential characteristics of the fuzzy controller applied to the mechanical structure are also discussed.

On the other hand, the results obtained under simulation of the performance of the established fuzzy rules are presented, using MatLab Simulink® software. Finally, the conclusions of this work are presented.

Operating conditions

There is a restriction of the sun movement, since it has only the direction from east to west. For this reason, the structure of the solar positioner has a rotational movement conditioned to rotate a certain number of degrees of freedom (Lewis, 2003), forming an angle of elevation with respect to a horizontal plane. In this way, the angular value can be measured and thus generate the rotation of the structure to the desired position. Implying that the angular error at infinite time is zero, as stated in equation (1).

$$\lim_{t\to\infty} e(t) = 0 \tag{1}$$

Figure 1 shows the desired elevation angle which is a function of the perpendicularity of the receiving surface (solar panel) with respect to the sun's rays, the mathematical expression that determines this condition is:

$$N \circ r = 0 \tag{2}$$

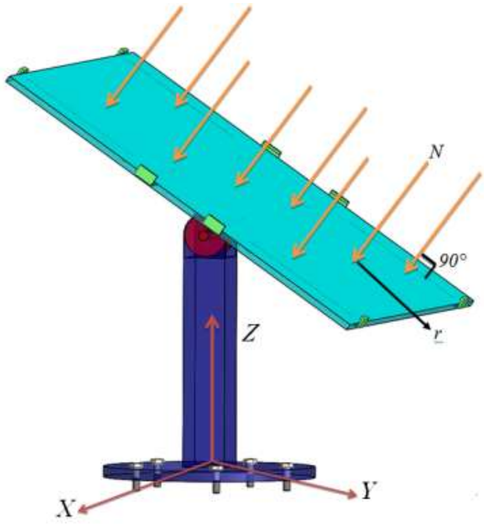

Figure 1 Perpendicularity condition. Where r, is a coplanar vector and N, the vector normal to the surface of the panel
Own source

Figure 2 shows the assignment of a global reference frame in the base denoted by the triad {X, Y, Z}, as well as the centers of mass of each of the links, their lengths from the global reference frame to the centers of mass lc1 and lc2, and the angles of movement.

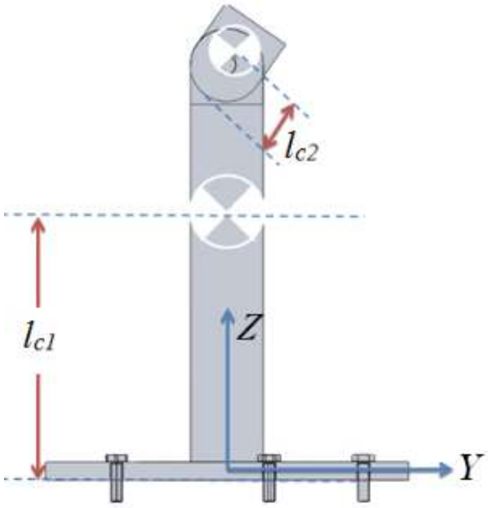

Figure 2 Diagram of the structure
Own Source

The mechanical structure has the following conditions:

1. The angular range of motion prevents the receiving surface (solar panel) from colliding with the mechanical structure.

   The configuration of the input signals obtained in a pair of photoresistive arrays, located at the ends of the receiving surface.

2. The orientation of the photoresistive arrays is in an east-west direction.

Methodology to be developed

Fuzzy Control

MatLab Simulink® software was used to observe the performance of the proposed controllers with the fuzzy model.

In order to obtain the maximum solar energy collection with the photovoltaic panel, it is necessary the existence of a set of fuzzy rules that define a control law, which commands the actuator and thus, the mechanical structure can be positioned at an appropriate angle. The system is in closed-loop configuration (Amstrom & Murray, 2008; Tsui, 2022) to gradually decrease the angular positioning error.

The principle of the operation to properly position the solar panel is based on the processing of the electronic signals transmitted by the photoresistors.

Taking into account the fact that, when receiving a higher amount of illumination, the photoresistors decrease their resistive value and determine the basis for the creation of the set of inference rules that control the elevation angle. In addition, the inputs are selected based on the resistive value delivered by each photoresistor (the output is the angular position).

According to the model to be controlled, the degrees of membership are assigned based on the resistive value, defining the ideal set as the one with the lowest resistive value, in a range from 0 to 100Ω. This condition occurs when the luminosity has a greater incidence on some photoresistance, not being an impediment to the reassignment of a new domain of definition for the resistive range. Thus, a set of six membership functions is generated for each photoresistor, triangular at the center and trapezoidal at the ends to avoid inconsistency in the data, as shown in Figure 3.

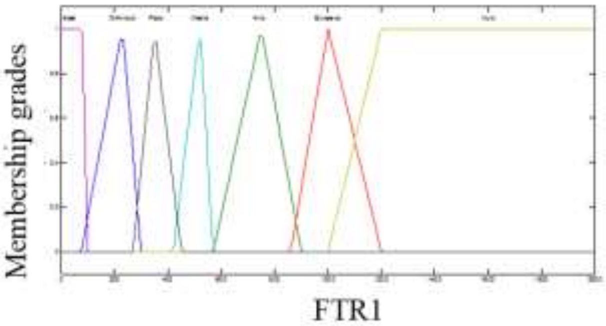

Figure 3 Membership functions corresponding to the inputs
Own Source

While the membership functions for the output are measured in degrees (angular), in a range of [-80°, 80°], with the intention of having a tolerance of ± 10° at each end of the receiving surface to avoid collisions with the structure. The negative references indicate the movement that the surface will generate towards the east, otherwise, the positive references will generate movement towards the west.

Figure 4 shows the membership functions defined for the output: where it is possible to notice a set of 31 linguistic terms, with which the inference rules are assigned to merge the inputs and the output. Subsequently, the Center of Mass (COM) method must be applied to defuzzify the values and issue a change command to the actuator.

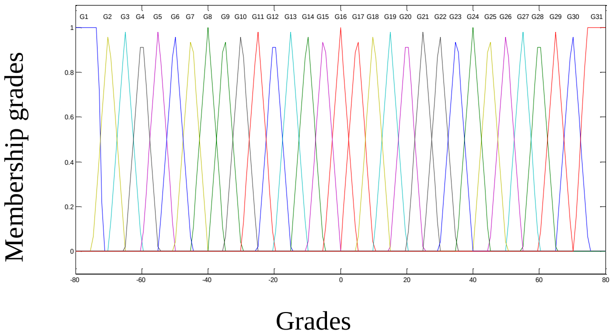

Figure 4 Output membership functions
Own Source

The assignment of the rules corresponding to the fuzzy control, starts from considering comparisons in adjacent pairs of photoresistances. Table 1 shows one of 10 relations created, defining the following linguistic terms: Ideal, Tiny, Little, Medium, High, Excessive and Null.

The inputs are set at 10° for each photoresistor, representing its sensing range from 0 to 2000Ω. The different outputs (G), are represented by intervals of 10° each, generating an overlap of 5°, starting with G1 (-80°,-70°), G2 (-75°,-65°), G3 (-70°,-60°) and so on.

There is the possibility of validating the adaptability of the controller to different situations, therefore, three states of motion within the previously established range were considered: initial, intermediate and final, whose control surfaces are shown in the results section.

To validate that the resulting control surfaces comply with the control objective established in Eq.1 of the operating conditions, three experimental tests were performed aligned to the previously determined motion states.

Results

The resulting control surfaces for the proposed motion states were as follows:

Initial: Considering active two photoresistors, specifically FTR9 and FTR10, the controller result was a rotation in -X direction (measurements in the range of [0°, 80°]). The control surface obtained is shown in Figure 5.

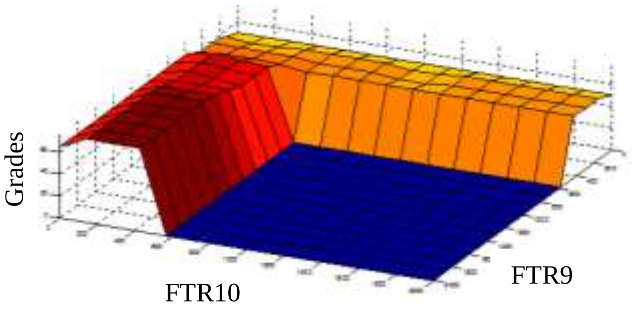

Figure 5 FTR9-FTR10 relationship surface
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Intermediate: It considers the central photoresistors active, inputting the input signals to the fuzzy controller, which generated as a response the positioning at 0° with respect to the Z axis. Figure 6 represents the behavior of this state of motion.

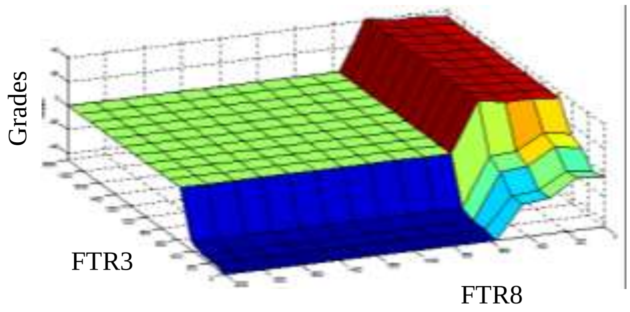

Figure 6 FTR3-FTR8 relationship surface
Own Source

Final: Considering two active photoresistors, specifically FTR3 and FTR4, the result of the controller was a rotation in X direction (measurements in the range of [80°, 0°]). The control surface obtained is shown in Figure 7.

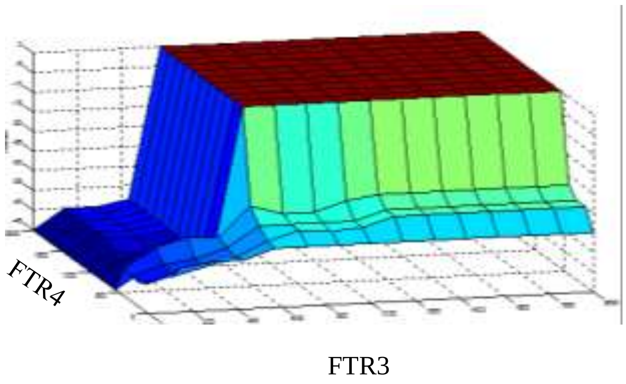

Figure 7 FTR3-FTR4 relationship surface
Own Source

As shown in Figures 5, 6 and 7, there are nonlinear responses, which describes the nature of the fuzzy controller created, without the need to have knowledge of the mathematical model of the system.

However, as previously indicated, by combining the mathematical model with a fuzzy structure, the response of the system is enhanced.

The results obtained in the validation of the control surfaces (fuzzy control law) are presented below.

Experimental test I: Null resistive values were observed in photoresistances 1 and 2, leaving the rest of the photoresistances at their maximum resistivity (Table 1), implying that the resulting movement is in the negative direction, proving that the assignment of the rules and the defusification method were correct (Figure 8).

output (°)	FTR1 (Ω)	FTR2 (Ω)	FTR3 (Ω)	FTR4 (Ω)	FTR5 (Ω)	FTR6 (Ω)	FTR7 (Ω)	FTR8 (Ω)	FTR9 (Ω)	FTR10 (Ω)
-70.38	0	0	2000	2000	2000	2000	2000	2000	2000	2000

Table 1 Resistive values of the experimental test I
Own Source

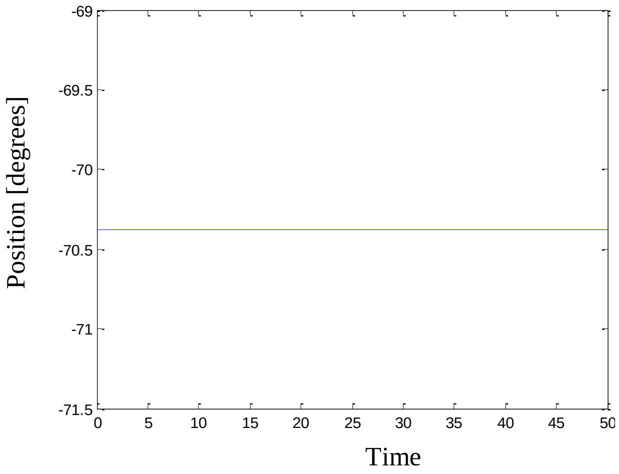

Figure 8 Experimental test I. Motion in east direction (-70.38°)
Own source

Experimental test II: Zero values were assigned to the central photoresistances (3 and 8) with the intention of positioning the receiving surface parallel to the ground, i.e. at 0°, generating an error of -3.34° (Table 2). However, the existence of stability in the system is verified (Figure 9).

output (°)	FTR1 (Ω)	FTR2 (Ω)	FTR3 (Ω)	FTR4 (Ω)	FTR5 (Ω)	FTR6 (Ω)	FTR7 (Ω)	FTR8 (Ω)	FTR9 (Ω)	FTR10 (Ω)
-3.34	2000	2000	0	2000	2000	2000	2000	0	2000	2000

Table 2 Resistive values of the experimental test II
Own Source.

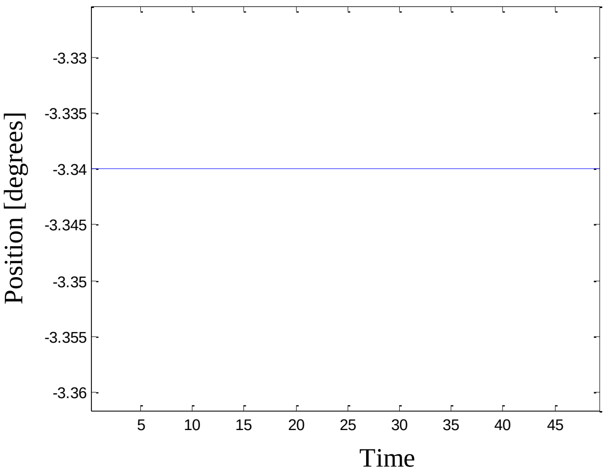

Figure 9 Experimental test II. Positioning parallel to the ground (-3.34°).
Own source

Experimental test III: The assignment of a minimum resistive value in photoresistors 8 and 9, the null value in photoresistor 10 and maximum values of photoresistors 1 (Chaithanakulwat and Cols., 2023) to 7, showed the desired positive positioning at 50°, i.e., a displacement in the westerly direction, obtaining an error of 0.49° (Table 3 and Figure 10).

output (°)	FTR1 (Ω)	FTR2 (Ω)	FTR3 (Ω)	FTR4 (Ω)	FTR5 (Ω)	FTR6 (Ω)	FTR7 (Ω)	FTR8 (Ω)	FTR9 (Ω)	FTR10 (Ω)
49.50	2000	2000	2000	2000	2000	2000	2000	100	200	0

Table 3 Resistive values of experimental test III
Own Source.

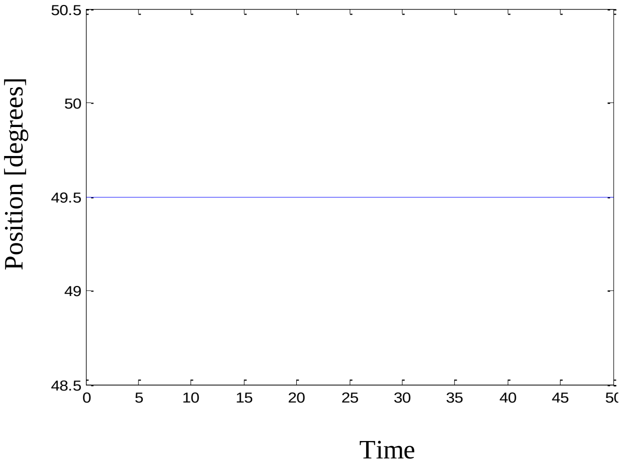

Figure 10 Experimental test III. Movement in westerly direction (49.50°)
Own source

The error values were less than 1° at the extremes (experimental tests I and III), compared to the error generated in experimental test II (3.34°).

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Conclusions

The experimental tests considered do not show an error exceeding 4°, which indicates that the proposed fuzzy rules, linguistic terms and defuzzification method are adequate. However, they are susceptible to be improved with the insertion of the mathematical modeling of the mechanical structure. Therefore, it is concluded that the fuzzy control system developed decreases the position error with respect to the incidence of solar radiation, at any instant of time, in the photovoltaic cells and the rotational motion of the Earth.

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