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RESEARCH ARTICLE

MAMDANI-TYPE FUZZY CONTROLLER TO DETERMINE BLOOD PRESSURE LEVELS BY REFLECTION PPG

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Abstract

This document presents the design of a fuzzy control system applying photoplethysmography techniques to generate input data and Mamdani-type fuzzy logic for its processing and generation of system output values, through which blood pressure levels can be indicated based on the parameters recommended by the medical area for an adult person. The integral design of the system includes the acquisition of the input signals, obtained through the reflection photoplethysmography technique, by means the optical coupling between IR light-emitting diodes and photo receptors, which allow the flow of current proportional to the amount of reflected light by blood, which is related to the flow level of the cardiac cavities, derived from the systolic and diastolic stages of the cardiac cycle. The fuzzy control was designed with two inputs and one output of 5 triangular membership functions each using the hardware description language (VHDL), the fuzzification, inference, aggregation and defuzzification stages were designed using the COSAA method. The response values obtained using the Test Bench tool of ISE Design suite were compared with theoretical values and with values obtained with the Fuzzy Logic Designer tool of Matlab, the results showed an excellent approximation.

Introduction:-

The use of fuzzy systems has grown greatly because they have been applied in a wide variety of areas such as automatic control, digital signal processing, communications, expert systems, medicine, among others [1,2, 13]. The purpose of this research work is to design and simulate a Mamdani-type fuzzy controller, which allows blood pressure monitoring through the photoplethysmography (PPG), techniquethat can be used as an instrumentation tool that meets the general characteristics of sensitivity, precision, accuracy and robustness that allow ambulatory monitoring to detect abnormalities in the tolerance parameters of human blood pressure. High blood pressure is one of the main risk factors that allows the development of cardiovascular diseases in its various manifestations [3], this condition is considered a public health problem worldwide, developed mainly by the suffering of chronic diseases, bad eating habits and tobacco consumption [4]. The pumping of blood carried out by the heart causes this hematic fluid to exert a force against the walls of the blood vessels that transport it, the analysis of the imbalance of this pressure is essential to diagnose conditions of the cardiovascular system [5,6,7]. To determine anomalies in blood pressure levels, it is necessary to analyze the pulse signal, which can be monitored in various arteries of the vascular system. This monitoring is carried out using the PPG technique, generally in the radial and ulnar arteries, since they

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are superficial arteries and have collateral circulation. In this work, the monitoring of the pulsatile signal in the radial artery is proposed. The pulse waveform is made up of two branches (Anacrotic and Dicrotic) it is constituted by the sum of the incident wave (systolic wave) generated by the contraction of the heart and pumping of blood rich in O2 towards the periphery, and the reflected wave (diastole) generated by relaxation and CO2-rich blood entering the heart, separated by a cut (incisura dicrota) that is generated during the transition between systole and diastole. The systole produces an increase in the pressure of the blood vessels due to the expulsion of the hematic fluid, in turn the diastole causes a drop in pressure after the dicrotic notch that is generated between the transition between both phenomena due to the closure of the valve ventricular [5-8].

The processing of the pulsatile signal entails a delicate treatment, since by its nature it is susceptible to being distorted by various factors, among which the noise generated inside the human body, the distortion generated by systolic reflection waves caused by bifurcations in the arterial course, incorrect location of the PPG sensor, incident ambient light or epidermal dyschromia [9]. PPG is a non-invasive technique with multiple applications in the medical area, which allows detecting variations in the volume of the bloodstream generated by systolic and diastolic processes, whose measurements are made through the coupling between light-emitting diodes and photoreceptors that They allow current flow proportional to incident light reflected by the volume of blood flowing through the arteries.

The fuzzy logic design was carried out with two inputs and one output of five triangular membership functions and 10 bits of resolution each, four processing stages required by the Mamdani method were implemented: fuzzification, inference, aggregation and defuzzification using the COSAA center of area method through the implementation of alpha quantization levels [12-13]. The results obtained by the developed fuzzy control are validated using the Test Bench tool of ISE Design Suite 14.7 and compared with values obtained with the Fuzzy Logic Designer tool of Matlab through the centroid defuzzification method.

Diverse studies can be found focused on the design or implementation of systems for cardiovascular monitoring using PPG, such is the case raised in [7] where a wristband prototype is presented that, without any other means external to it, allows simultaneous acquisition, non-invasive of two physiological signals at three measurement points (ECG, finger pulse and wrist pulse) using photoplethysmography. The prototype has not yet been validated with a reference system and the functional tests were only carried out with 15 volunteers. In [8] a smartphone-based artificial intelligence PPG algorithm was developed for the detection of Atrial Fibrillation. The algorithm was implemented using a shallow neural network, trained using 2560 recordings selected from an online database (Heart for Heart) and consists of 3 main components: peak detection to measure R-R intervals, quality and rhythm classification. The neural network showed excellent performance for peak detection, as well as high sensitivity and specificity for headphone detection. Among the limitations is that the algorithm was only validated with volunteers suffering from AF. In [9] a PPG device was developed to measure the pulse wave speed (VOP), for the sampling and processing of the signal they used an Arduino uno microcontroller, at the software level the processing was done with Python, the results obtained for the calculation of VOP, they were close to reference values for adults under 30 years of age, although they require a control stage specially designed to control the brightness of the LEDs, as well as a more robust design that is less susceptible to disturbances generated by their own signalsof the human body.Studies focused on the implementation of measurement sensors using PPG in general are very promising, although there is still a long way to go, since in general the investigations carried out are based on patients suffering from an anomaly. The importance of this proposal lies in improving the accuracy and speed of response, as well as reducing the complexity of the entire FLC system.

Development:-

For the implementation of this control system, the reference inputs to the system were generated by assigning the voltage values previously acquired and processed in the acquisition stage through the PPG technique, these reference analog values are transformed into digital values which correspond to the input values of the fuzzification stage of the fuzzy control, these values were labeled as error (e1) and the derivative of the error (Δ1) defined by 1, the output of the inference machine is a value fuzzy which is defuzzified using the COSAA method [12-13].

$$\frac{de}{dt} = \text{Current error} - \text{Previous error} \tag{1}$$

The integral structure of the design of the proposal is shown in figure 1, which includes the input data acquisition stage, the analog-digital conversion and the implementation of the FLC through the hardware description language VHDL using the ISE Design Suite 14.7 development software and validated using the Test Bench tool, at the output of the controller there are defuzzified values which can be treated according to the FLC-user interface.

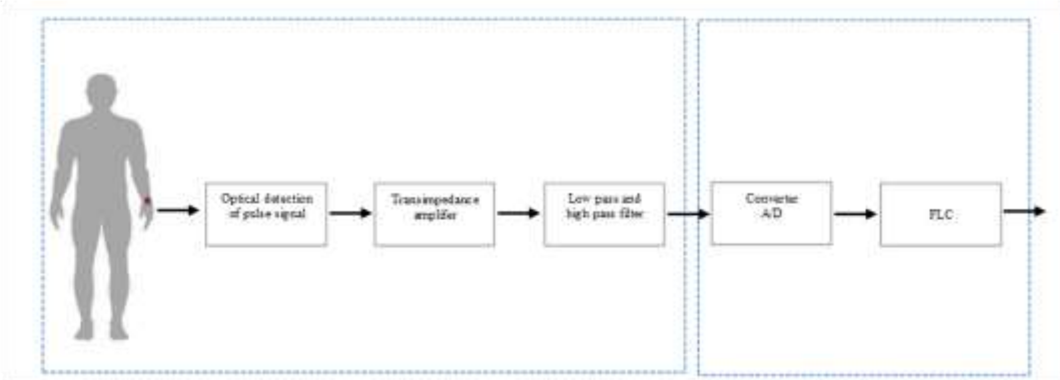

Fig1:- Integral diagram for obtaining the pulsatile signal.

Data acquisition:-
The acquisition of the signal from the radial artery was performed with the photoplethysmography technique to determine variation in blood flow levels non-invasively. By means of an infrared light-emitting diode at a wavelength of 900 nm, a beam of light is applied to the epidermis of the skin between the arm and the hand in proximity to the radiocarpal joint, keeping the body in a supine position, such that said light is reflected by the volume of blood in the radial artery and/or collaterals. Through a photoreceptor, the percentage of reflected light is captured, which polarizes in reverse allowing a current flow proportional to the light intensity, this current is treated by the OPA380 transimpedance amplifier that allows working with low levels of polarization current and offset voltage, obtaining at the output a voltage proportional to the product of the photodiode current and the magnitude of the RF feedback resistor. It was also required to implement a filtering stage through the LM358 general purpose operational amplifier with low-pass and high-pass arrangements, which allow covering a frequency range from 0.30 to 20 Hz, proposed based on the contraction and relaxation of the heart for a adult person. For the implementation in the fuzzy control, the values obtained by means of the technique described were necessary to transform these analog values to digital values, for which the Texas Instrument TLC083 ADC converter was used. With these digital voltage values, we define the fuzzifier inputs labeled as e1 and Δe1 by means of equation 1, the data acquisition stage by means of the optical coupling between emitter and receiver is shown in figure 2.

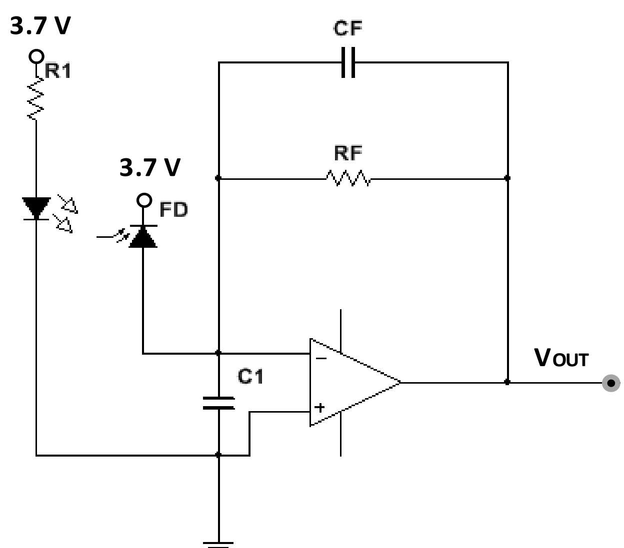

Fig2:- Implementation of optical coupling.

Figure 3 shows a signal generated in an oscilloscope by means of the tension values obtained with the various processing stages for the implementation of the reflection photoplethysmography technique, the reading was performed on a 45-year-old adult in the artery of the left arm, who was asked to rest for 15 minutes beforehand in a supine position.

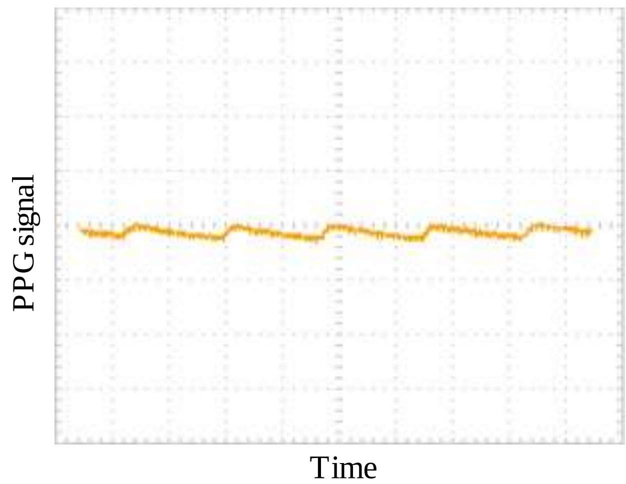

Fig3:- Obtaining a PPG Signal.

Fuzzy control: -

The design of the fuzzy system is carried out using the VHDL circuit description language, through the Xilinxs tool for design and synthesis ISE Design Suite and validating the operation using the Test Bench simulation tool, for the proposed design, a Mamdani type fuzzy control system was implemented, which involves the stages of fuzzification, inference, aggregation and defuzzification [14], the block diagram is shown in figure 4, were implemented2 inputs and an output of 5 membership functions of type triangular which were labeled as very low, low, normal, high and very high, as shown in figure 5.

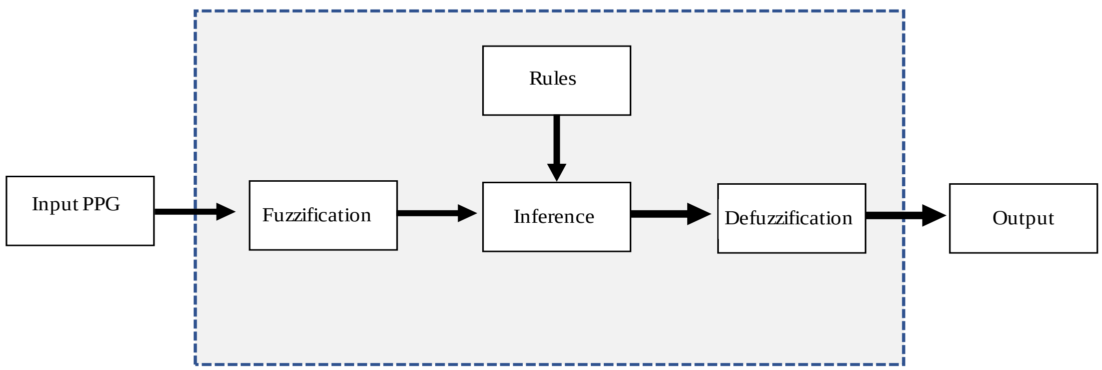

Fig4:- Fuzzy logic system diagram.

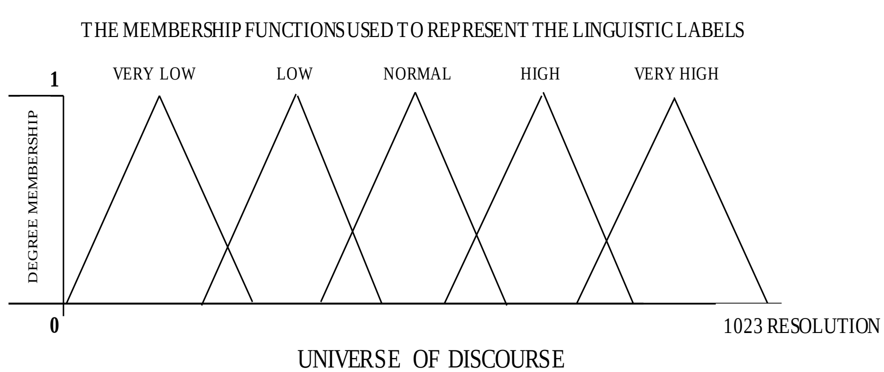

Fig 5:- Membership function.

Fuzzification:-

The fuzzification stage consists of the transformation of the input values to their corresponding fuzzy value, for the universe of discourse is assigned a resolution of 2n-1 bits, where n=10, equivalent to the input voltage values defined as e1 and Δe1, the degree of membership was adjusted to a range of 2n-1 bits where n=8, its structure was implemented through lookup tables in which its corresponding resolution value was assigned for each of the possible values input see figure 6, in figure 7 the schematic and simulation of Test Bench for the fuzzification stage is shown.

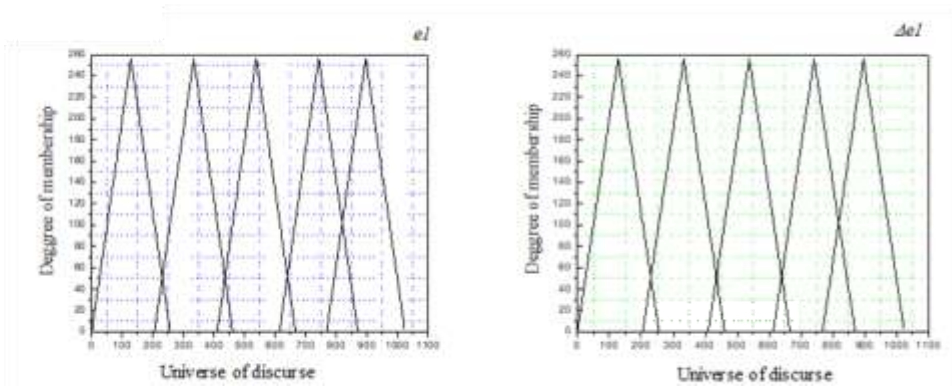

Fig6:- Fuzzy sets.

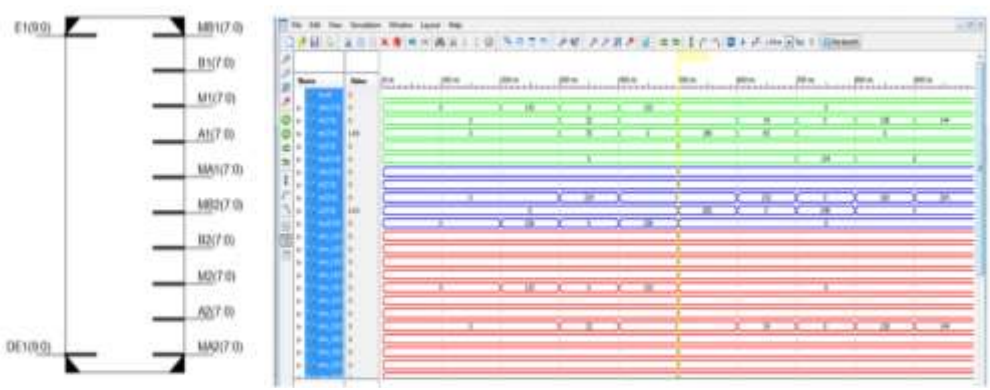

Fig7:- Schematic and simulation for the fuzzification stage.

Inference:-

The inference process was carried out by mapping between the different membership functions to determine the minimum values corresponding to this stage, in which the values obtained through fuzzification are organized in such a way that a 5x5 matrix, mapping between membership functions, where the first membership function of the input e1 is compared with each of the membership functions of the input Δe1, the association matrix between the fuzzy sets is shown in the table 1, the schematic corresponding to this block is shown in figure 8.

Table 1:- Fuzzy association matrix to determine the minimum values.

	Input 2				
	min(1 , 1)	min(1 , 2)	min(1 , 3)	min(1 , 4)	min(1 , 5)
	min(2 , 1)	min(2 , 2)	min(2 , 3)	min(2 , 4)	min(2 , 5)
Input 1	min(3 , 1)	min(3 , 2)	min(3 , 3)	min(3 , 4)	min(3 , 5)
	min(4 , 1)	min(4 , 2)	min(4 , 3)	min(4 , 4)	min(4 , 5)
	min(5 , 1)	min(5 , 2)	min(5 , 3)	min(5 , 4)	min(5 , 5)

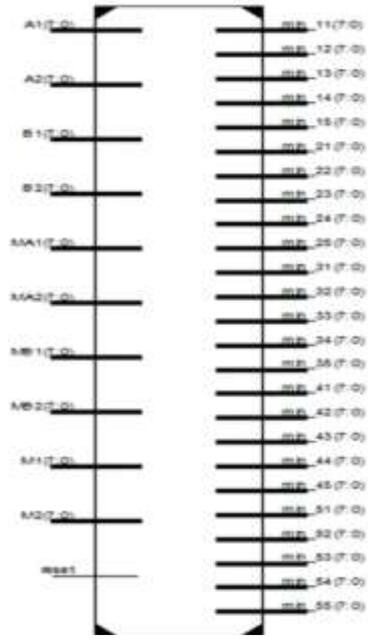

Fig 8:- Schematic for the inference stage.

Aggregation and defuzzification: -
The aggregation stage was carried out with the storage of the maximum values of each activated fuzzy rule, in this case an association matrix was also generated that allowed us to determine the maximum values from the minimum values of the inference stage. Finally, the defuzzification stage was implemented through the use of alpha quantization levels, in which the Center of Average Areas or Center of Slice Area Average (COSAA) method was used, since unlike the method COG center of gravity this method shows a higher response speed, the schematicof the defuzzifier is shown in figure 9.

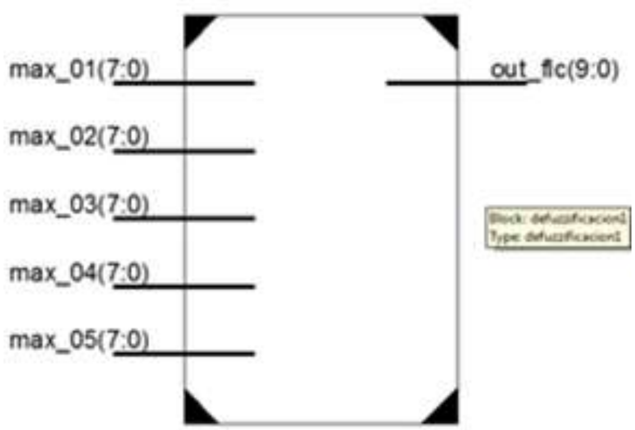

Fig9:- Schematics for defuzzification stage.

Results:-
To verify the functioning of the designed fuzzy control system, validation tests were carried out, for which it was necessary to instantiate between the four blocks that make up the Mamdani-type fuzzy control. Said test consisted of evaluating the performance of the controller using the Test Bench simulation tool of Ise Design Suite, the output values are compared with the values obtained with Fuzzy Logic Designer of Matlab, for which the same number of inputs was implemented, with the same number and type of membership functions, but with the centroid defuzzification method in figures 10 and 11 the simulation in Test Bench and Fuzzy Logic Desigener, respectively, are shown.

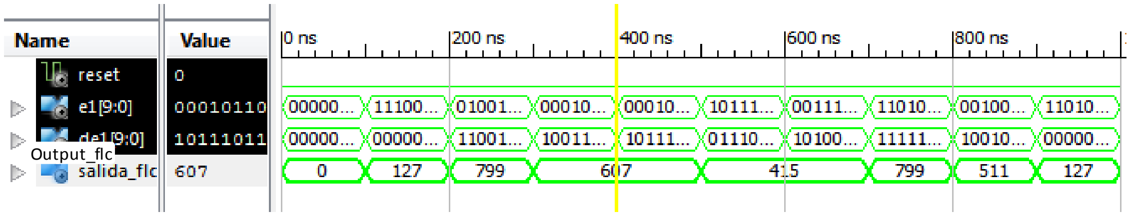

Fig10:- Simulation using the Test Bench tool.

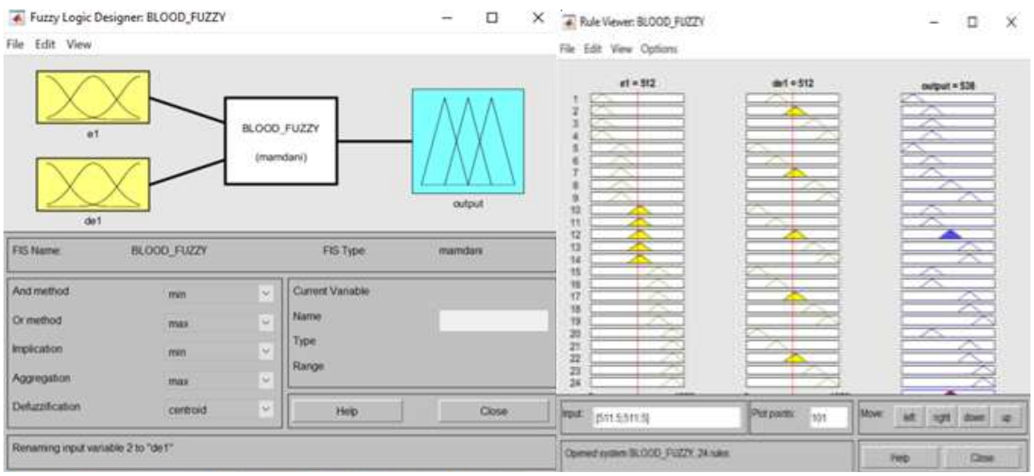
Fig 11:- Implementation of Matlab's Fuzzy Logic Designer.

Table 2 shows values obtained experimentally with the fuzzy control designed against values obtained experimentally with Matlab's Fuzzy logic, to compare these values various random values were applied to the inputs e1 and Δe1 in a universe of 20 samples, it can be seen that the response values between both are very similar since they present small variations between both, in order to correct these variations, it is proposed to adjust the dimensions of the membership functions in the universe of discourse, the graphic representation of the values obtained is shown in the figure 12.

Table 2:- Values obtained by simulation in MATLAB vs designed FLC.

Sample number	Input value *e1*	Input value *Δ e1*	Centroid defuzzified value	COSAA defuzzified value
1	45	130	512	510
2	78	120	512	509
3	127	432	217	216
4	230	512	333	331
5	650	328	333	335
6	710	832	836	835
7	1023	798	512	512
8	540	128	333	332
9	810	1023	512	511
10	910	511	742	741
11	325	611	333	334
12	710	452	661	663
13	369	458	333	334
14	758	256	333	331
15	158	132	512	512
16	325	210	150	149
17	459	754	733	731
18	490	580	538	539
19	325	650	473	472
20	0	0	0	0

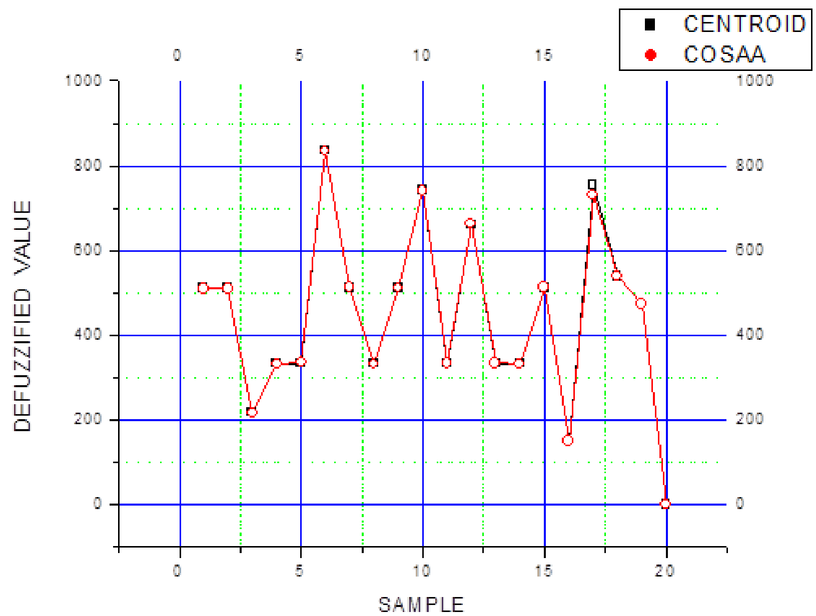

Fig 12:- Values obtained in Matlab vs Test Bench.

Conclusions: -

A fuzzy control system was designed that allows obtaining the interpretation of blood pressure levels in adults by applying the PPG technique, which may offer the possibility of giving an outpatient diagnosis of blood pressure levels. Comparing the values obtained through the designed controller and the values obtained with the Matlab fuzzy logic designer, it was possible to validate the correct functioning of the system, since it shows a good approximation to the values obtained with the Matlab software, considering that they were used different defuzzification methods. This project includes a first phase of design of a system of greater scope, since it is required to carry out the implementation of the fuzzy control algorithm in hardware, as well as the implementation of its corresponding communication interfaces between the stage of acquisition of values of input and for the display of output values that allow easy reading by the end user and thus be able to integrate the design of a complete system that meets the characteristics of a biomedical instrumentation equipment.

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