Artificial Intelligent Fuzzy Logic Controller Applied on 6DOF Robot Arm Using LabVIEW and FPGA

Ahlam Najim A-Amir and Hanan A.R. Akkar

***Abstract*—In this work an efficient Artificial Intelligent Robotic Fuzzy Logic Controller (AIRFC) system have been constructed to control the robot arm. A serial link Robot manipulator with 6 Degree of Freedom (DOF) from DFROBOT of code ROB0036 is used as a case study. A fuzzy logic type1 controller is implemented on LabVIEW to control each joint of the robot arm for nonlinearity measurements and a fuzzy logic type2 controller is applied which is more suitable for uncertainty. The hardware design is implemented and finally downloaded using the Field Programmable Gate Array (FPGA) kit named PCI-7833R from National Instrument. By using the LabVIEW FPGA MODEL the target board can be detected for software implementation of the controllers' systems. The work shows that in case of type2 fuzzy logic the rise time is less than that of type1 fuzzy logic for the shoulder, wrist roll and the gripper angles and it is higher for base, elbow and wrist pitch angles. The settling time is the same in elbow and wrist pitch angles and for the type2 fuzzy controller it is less for other angles.**

***Index Terms*—Artificial Intelligent; Robotic Arm; Fuzzy Logic; LabVIEW; FPGA.**

I. Introduction

These days many robotics industries interline a phase of rapid technological growth. An industrial robot does a defined task for a specified operation to pick and place parts from one location to another, and for use in industrial automation applications it must be designed with high precision to increase flexibility in product manufacturing, reducing the operating cost, increase output rates, improving quality of work for employees and improving product quality [1].

Robot arm Kinematics must be solved and be satisfied before designing and applying the control techniques. The ROB0036 robot arm modeling was done by developing the complete kinematics analysis and deriving the equations of the forward and the inverse kinematics based on Denavit-Hartenberg (D- H) representation [2],[3].

The Fuzzy Logic theory and its application to control systems by Mamdani gives a push to real world technology specially for Robotics field [4]. The principle of operation of the controller is mostly similar to a human operator since it performs the same actions like adjusting of the input signal which related only to the system output. The fuzzy logic contains the information that is given by the operator in the form of linguistic rules, The crisp data input

into fuzzy sets done through fuzzification, then the input fuzzy sets can be interpreted and compared to the rules depending on the rule base within the inference engine, finally the defuzzifier will convert the results of the inferences mechanism into crisp output values [5]-[8].

Performing of simulation with hardware being very helpful by using MATLAB and LabVIEW to optimize the robots task execution [9]-[11].

Interfacing of many hardware blocks with software module for real time processing is very important in different fields to achieve better control through software and hardware, it debase the manufacture time, accuracy, performance and lifetime of the particular system. So, FPGA can be applied for control systems and automation [12],[13].

Using of fuzzy logic modeling for complex nonlinear systems and real time model based control gives a big motivation to control robotic arms. The generated AIRFC system is designed to control the positions of six Servo motors connected to robot arm joints. Using of type1 and type2 fuzzy logic controllers uncertainty can be avoided in a simple manner for the perfect movement of the robot axis.

The FPGA card 7833R that configured with the Xilinx Virtex II 3M gate from the National Instrument (NI) was positioned in a PCI slot along with memory, input/output resources, with A/D and D/A converters, used to define functionality and timing of devices, suggested to carry the proposed robot controller, have eight independent analog input channels, eight independent analog output channels, and 96 digital input/output lines.

II. Literature Survey

Many researchers have been worked on proposing of controller systems applied to robotics and developing a new and best solutions to their Kinematics so as to obtain a response of less overshoot and steady state error. In 2010 testing of motional Characteristics was done by utilizing of Matlab Simulink and the program of AutoCAD to the AL5B Robot arm by Mohammed Abu Qassem et. al. [14]. Also, Zeinali, M., and Notash, L., proposed an adaptive fuzzy system construction for a wire actuated 4DOF parallel manipulator, that uses hybrid execution of wires and joints [15].

In 2013, Ponce-Cruz, P., et. al. utilize the KM (Karnik Mendel) algorithms with real time analysis to the interval type-2 FLCs applications, then applied to the mostly used National Instrument LabVIEW FPGA module hardware [16]. In 2014 Bambang Siswoyo et. al. developed a

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Compact Fuzzy logic controller into FPGA chip to control each joint of the robot arm manipulator, Results of the compact system implemented in the XILINX Spartan 3 XC3S1000FPGA [17]. In 2015 Ganesan, A., et. al. proposed a controller design for the 3-DOF robot manipulator using LabVIEW and National Instrument my Rio Kit, the FPGA processor assign many embedded logic circuits with analog and digital pins to generate signals for controlling processes [18]. In the same year other work is implemented on LabVIEW for control the robot movements using the the Zigbee Module by Punna, E., et al. [19].

III. Implementation of Fuzzy Logic

Fuzzy Logic is an analytical way used to represent the human behavior for thought process and the imprecise phenomena. The membership function (MF) is a relation that provides for every element of the set a particular membership value. The fuzzy set is a set where every element associates itself with the set with a membership value; its range is between 0 and 1. When:

$$\mu_A(x): X \rightarrow [0,1]$$

X : is the universe of discourse.
A : is a fuzzy set with every number of an associated with a membership value.
x : is a crisp value in X

The fuzzy control structure consists of five membership functions and 25 rules, two crisp inputs error (e) and change of error (de) are fuzzified in the fuzzy controller with five triangular membership functions and also the same for the output to drive the DC motor of the robotic arm, a Mamdani type structure are used for the inference engine. The two inputs are quantized to five fuzzy sets; (NL: Negative Large), (NS: Negative Small), (Z: Zero), (PS: Positive Small), and (PL: Positive Large). Also, there is a same fuzzy sets for the output (u). In case of type1 fuzzy logic the fuzzifier transforms the crisp input into fuzzy sets (fuzzification), the inference engine performs all of the logic operations in a fuzzy controller, the rule base contains the MFs and the controller rules, then the fuzzy sets output is transformed into numeric value by the defuzzifier component (defuzzification) as shown in Fig. 1.

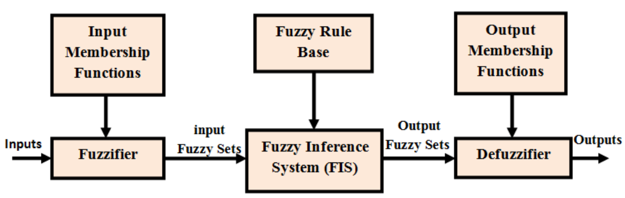

Fig.1. Fuzzy logic type1 structure.

In case of Interval type2 Fuzzy Logic Controller (IT2FLC), the structure is not different than type1 Fuzzy Logic Controller (T1FLC). It implies the fuzzification, the inference engine besides the defuzzification parts. The system fuzzification features the crisp values x as a number of MF values depending on the degree of its membership. The crisp value then pertains to most than one IT2FS set, the two memberships now make the footprint of uncertainty (FOU). Building a rule set for required expert relations from the selected input sets each membership can be obtained after the defuzzification process and applying the fuzzy logic AND, OR operations to obtain the consequence output set. The only difference now is that there is an IT2FLC outputs from the inference engine that must be converted to obtain a T1FLC, which then be defuzzified into a crisp output, this can be accomplished by using a type-reducer stage as shown in Fig. 2.

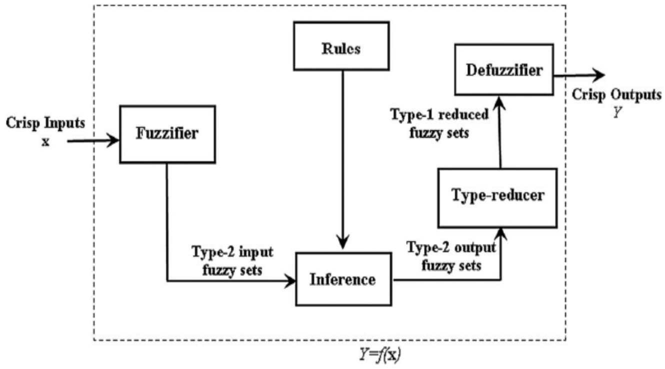

Fig. 2. Structure of IT2FLC.

The grade or the value of MF for each element in this fuzzy set is found as a crisp value within the interval [0,1] as shown in Fig. 3. Additional degree of freedom can be provided by the footprint of uncertainty (FOU), so the MF of these sets become three dimensional function, and many types of uncertainties can be handled using higher magnitudes and simpler rule base than the equal type1 fuzzy [19].

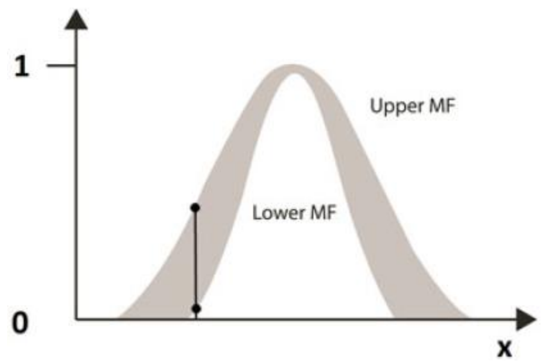

Fig. 3. Type Fuzzy Logic Membership Function [19].

IV. The Proposed Controller for the Manipulator Arm

A new artificial intelligent type1 and type2 fuzzy logic controller system models are used to control the movement of the 6dof ROB0036 manipulator arm implemented on FPGA hardware. An active AIRFC system are proposed to meet the requirement of the desired input path with suitable error, disturbance values and manipulate less error from the feedback position signals by the six servo motors that belong to the robot joints, the block diagram of the system are as shown in Fig. 4.

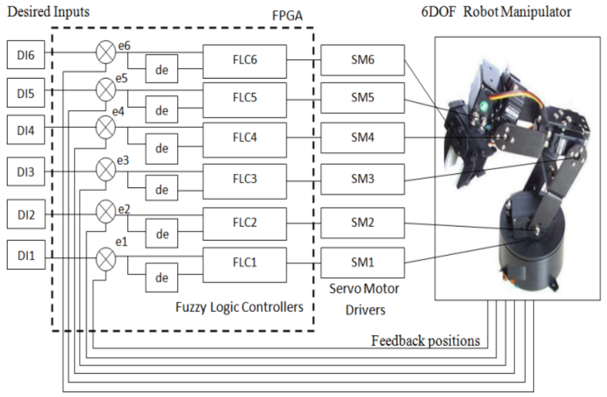

Fig. 4. The block diagram of the AIRFC system for 6DOF ROB0036 manipulator arm.

The execution of the intelligent controller is based on the high precision for reducing the overshoot, minimizing steady state error, damping unwanted vibration of robot manipulator, and handling the unpredictable disturbances.

The FPGA (Field Programmable Gate Array) based system design of this work could control independently the six servo motors of arm manipulators. So, the proposed controller is designed to be implemented on the FPGA device with minimum chattering and with high processing speed. FPGA-based controller has to be used in this application because it is a small size hardware kit and low cost. The FPGA is a complete, ready-to-use digital circuit development platform based on the LabVIEW FPGA Model.

V. Design of Type1 Fuzzy Logic Controller on LabVIEW

In this stage of the work a creation to the TIFLS is performed using the LabVIEW control and simulation function and the toolbox of fuzzy logic control, which is founded as an excellent platform for implementation, testing of control system, and support the design of fuzzy logic techniques.

The LabVIEW toolbox on fuzzy logic control is based on fuzzy techniques that has editions of the fuzzy desired variables and the corresponding triangular and trapezoidal MFs, with a rule base editor to write the if- then rules related to the design procedure of the fuzzy controller, and some defuzzification methods like the centroid, min-max, and center of maximum, that represent the mathematical operations among the two dimensional function acquired from all the aggregation of the fuzzy outputs.

Five triangular membership functions MFs (NL, NS, Z, PS, PL) are used to represent the inputs (e and de) as shown in Fig. 5 and Fig. 6 respectively.

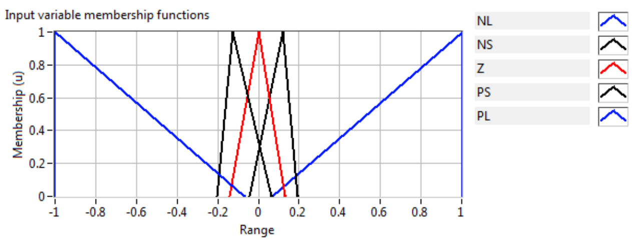

Fig. 5. Error input variable.

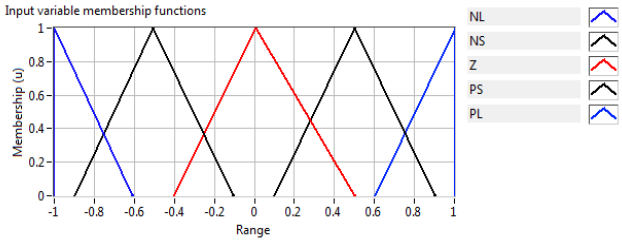

Fig. 6. Change of error (de) input variable.

The MFs of the output u(t) is also designed to be five fuzzy sets as shown in Fig. 7.

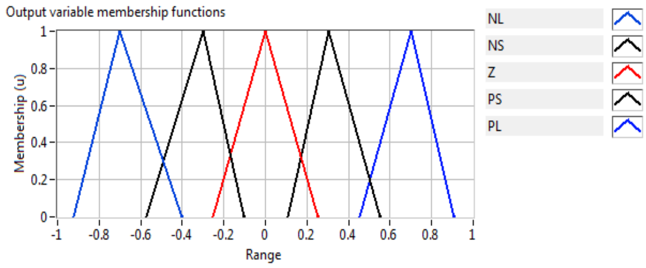

Fig. 7. Output u(t).

Table I illustrates the characteristics of inputs and outputs of the MFs.

TABLE I: Characteristics of Inputs and Outputs MFS

Variables	Term	Left Bound	Center	Right Bound
	NL	-1	-1	-0.068
	NS	-0.2	-0.124	0.06
Error (e)	Z	-0.14	1	0.13
	PS	-0.045	0.12	0.19
	PL	0.068	1	1
	NL	-1	-1	-0.6
	NS	-0.898	-0.51	-0.11
Cerror (de)	Z	-0.4	0	0.5
	PS	0.1	0.5	0.9
	PL	0.6	1	1
	NL	-0.92	-0.7	-0.4
Output	NS	-0.571	-0.3	-0.1
u(t)	Z	-0.254	0	0.254
	PS	0.11	0.31	0.554
	PL	0.452	0.7	0.91

Implementation of the rule based can be easily demonstrated with the relations shown in Table II.

TABLE II: Fuzzy Rule Base for T1FLS

de \ e	NL	NS	Z	PS	PL
NL	NL	NL	NS	NS	Z
NS	NL	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PL
PL	Z	PS	PS	PL	PL

Sets and rules are defined by using the control and simulation on LabVIEW and then applying the design depending on the requirements needed for controlling the motor movements for each joint in the robotic arm, the fuzzy logic designer represented as shown in Fig. 8.

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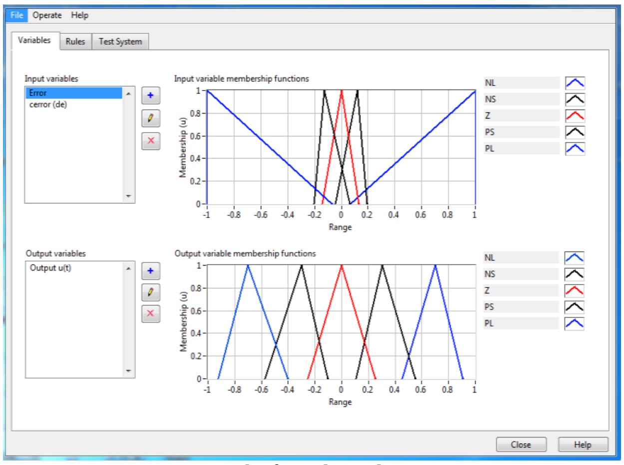

Fig. 8. The fuzzy logic designer.

VI. Design of IT2FLC System

In this section a second controller are proposed with an extra stage called type-reducer that is needed to reduce IT2FLS into TIFLS before the defuzzifier. The controller is built with five MFs (NL, NS, Z, PS, PL) for the inputs and the output, and using a Gaussian type MF.

The reason of choosing the gaussian in IT2FLC is the need to completely cover each input domain and generaly require only three or four parameters so it becomes simpler to design a guassian type2 MFs among other types. The new controller design achieved using a MATLAB toolbox for simulation, then loaded and manipulated on LabVIEW to be applied on the manipulator motors since there is no tools related to the design of the IT2FLC on LabVIEW.

To cover all the stages of the design a better choice of the TSK type in this controller is performed because the TSK rules are more popular, simple and more flexible in practice, the rule consequents are crisp functions and each one represented by a number. The fundamental components used for developing the toolbox of MATLAB and the construction of a generic TSK type rule structure from N rules are as follows:

The antecedent IT2FSs are $\tilde{X}_i^n \ (i = 1, \dots, I)$ and the consequent MFs are:

$$Y^n = [\underline{y}^n, \overline{y}^n]$$

So, If

$$x_1 \ is \ \tilde{X}_1^n \ \text{ and } \dots\dots \text{ and } \ x_I \ is \ \tilde{X}_I^n \ \ then \ y \ is \ Y^n \qquad (1)$$

$$\left.\begin{aligned} \underline{y}^n &= \underline{a}_1^n x_1 + \dots + \underline{a}_I^n x_I + \underline{b}^n \\ \overline{y}^n &= \overline{a}_1^n x_1 + \dots + \overline{a}_I^n x_I + \overline{b}^n \end{aligned}\right\} \qquad (2)$$

$\underline{y}^n$ and $\overline{y}^n$ seems to be linear functions or crisp consequence. The steps of the IT2FLS output calculations are:

1. Determine the MF interval of each x_i' on $\tilde{X}_i^n$, $\underline{\mu}_{\tilde{X}_i^n}(x_i')$ and $\overline{\mu}_{\tilde{X}_i^n}(x_i')$ for (I = *1, ..,I*) and (*n = 1, ...,N*).
2. Calculating of $F^n(x')$, the rule firing interval of the n^{th}.

$$F^n(x') \equiv \left[\underline{f}^n, \overline{f}^n\right], \ \text{for } n = 1, \dots, N \qquad (3)$$

$$\left.\begin{aligned} \underline{f}^n &= [\underline{\mu}_{\tilde{X}_1^n}(x_1') * \dots * \underline{\mu}_{\tilde{X}_I^n}(x_I')] \\ \overline{f}^n &= [\overline{\mu}_{\tilde{X}_1^n}(x_1') * \dots * \overline{\mu}_{\tilde{X}_I^n}(x_I')] \end{aligned}\right\} \qquad (4)$$

3. Performing the Type Reduction (TR) in order to combine the function $F^n(x')$ with the related rule consequents. The commonly used type is the center of sets TR method using the iterative KM algorithms with R and L switching points:

$$[y_l, y_r] = Y_{cos}(x') = \bigcup_{\substack{f^n \in F^n(x') \\ y^n \in Y^n}} \frac{\sum_{n=1}^{N} y^n f^n}{\sum_{n=1}^{N} f^n} \qquad (5)$$

$$y_l = \frac{\sum_{n=1}^{L} \underline{y}^n \overline{f}^n + \sum_{n=L+1}^{N} \underline{y}^n \underline{f}^n}{\sum_{n=1}^{L} \overline{f}^n + \sum_{n=L+1}^{N} \underline{f}^n} \qquad (6)$$

$$y_r = \frac{\sum_{n=1}^{R} \overline{y}^n \underline{f}^n + \sum_{n=R+1}^{N} \overline{y}^n \overline{f}^n}{\sum_{n=1}^{R} \underline{f}^n + \sum_{n=R+1}^{N} \overline{f}^n} \qquad (7)$$

4. Find and compute the (defuzzified) crisp output by:

$$y = (y_l + y_r) / 2 \qquad (8)$$

Two inputs error (e) and change of error (de) are represented by five Gaussian MFs for each respectively, using specific characteristics for the upper MF (UMF) and the Lower MF (LMF) for the MFs individually. The uncertainty of type2 fuzzy set is defined by FOU region that can be described between the UMF and LMF and in this case the two is designed to be with the same center. The FOU region changed when the height of the lower MFs is varied, in this case the UMF and the LMF heights is choose to be 0.5 and 1 respectively. Figs. 9 and 10 show the new design of the two inputs MFs editors.

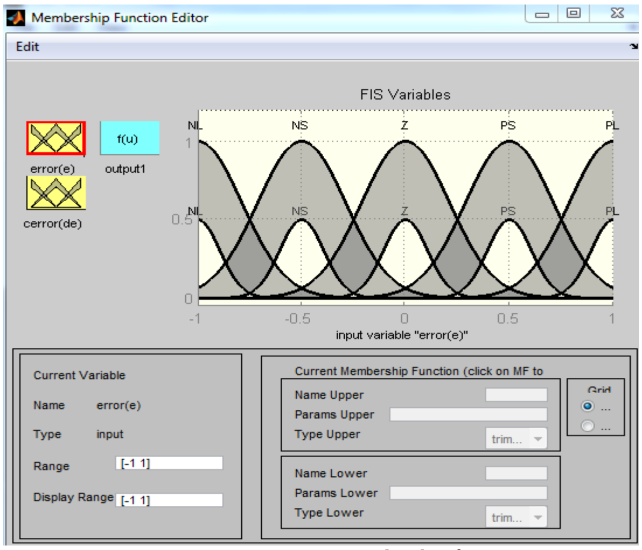

Fig. 9. Error input Gaussian membership functions.

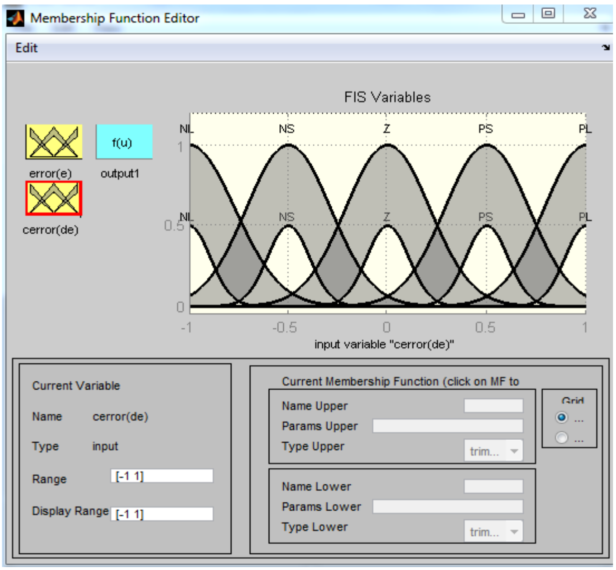

Fig. 10. Change of error Gaussian membership functions.

The design of the rule base editor will be the next step in this stage, since there is five MFs, the number of rules, 5^2 = 25 rule as shown in the applied rule base of Table III and Fig. 11.

TABLE III: FUZZY RULE BASE FOR IT2FLC

de \ e	NL	NS	Z	PS	PL
NL	NL	NL	NL	NS	Z
NS	NL	NL	NS	Z	PS
Z	NL	NS	Z	PS	PL
PS	NS	Z	PS	PL	PL
PL	Z	PS	PL	PL	PL

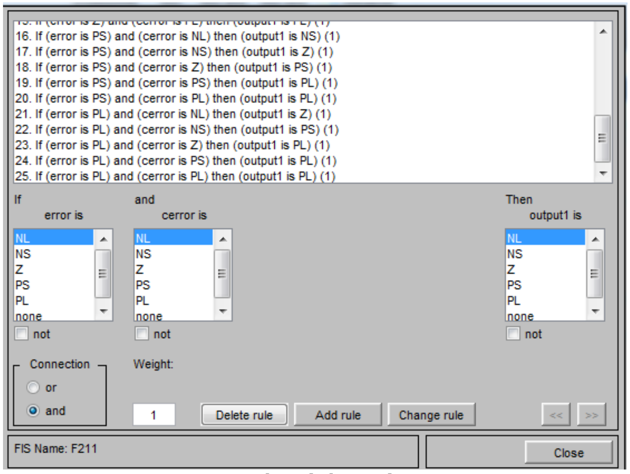

Fig. 11. The rule base editor.

The main difference between Mamdani type and Sugeno is that the Sugeno output membership functions are either linear or constant, so the MFs of the output editor will be as shown in Fig. 12.

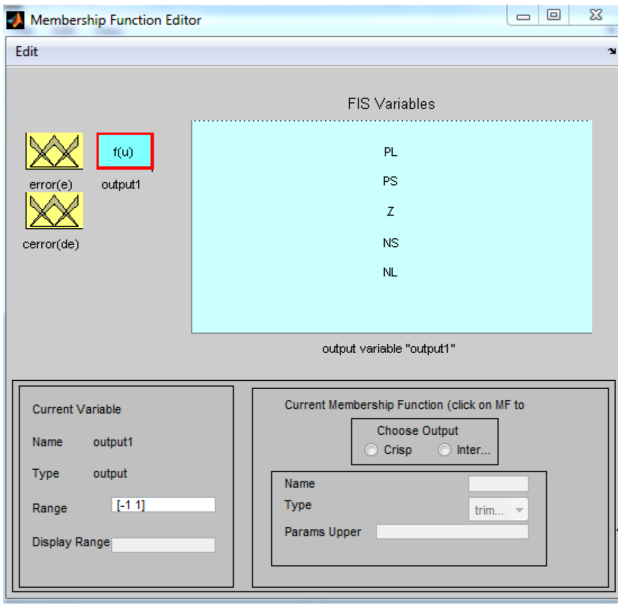

Fig. 12. The IT2FLC output.

VII. SIMULATION RESULTS AND DISCUSSION OF THE ROBOT ARM SYSTEM

Using of the artificial intelligent system AIRFC for control techniques has been proved successfully in this work. The schemes are designed for control of multiple-input-single-output (MISO) robotic systems. Two types of fuzzy controllers Type1 and Type2 are used for controlling the nonlinear robotic system and implemented to avoid the problems of uncertainty. The design of TIFLC is performed to drive the motors of the manipulator arm and detect the position and orientation of the end effectors as related to the base of the serial links robot. The position signal feedback from motors is considered to find the next inputs applied to the controllers. Fig. 13 shows the system tester with the surface diagram for any selected values for the inputs within the required range (1, -1) of the MFs.

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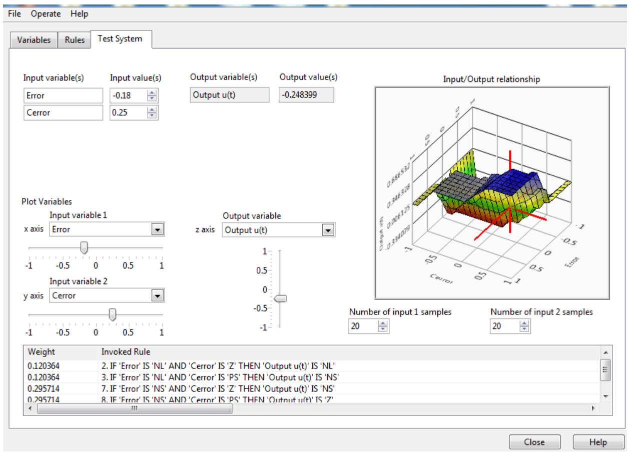

Fig. 13. The test system for the T1FLC on LabVIEW 2015.

The feedback position signal of the six servos must be taken into consideration for each movement. The system performed with the aid of the PCI 7833R hardware FPGA board from National Instrument since it is more compatible to work with LabVIEW. The block diagram of the controller is shown in Fig. 14.

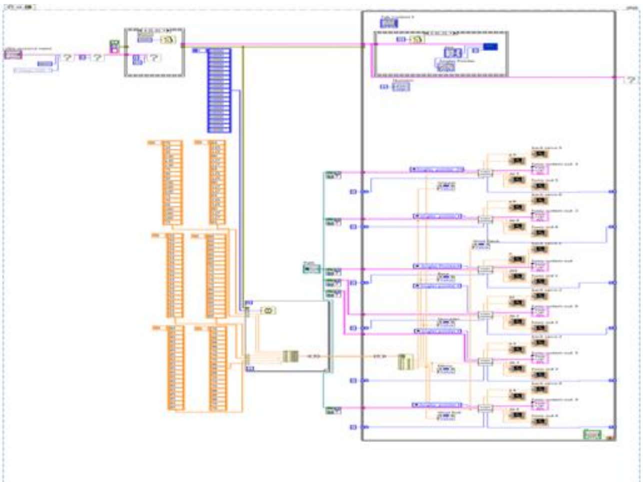
Fig. 14. Block diagram of AIRFC system.

The Front Panels of Fig. 15 and Fig. 16 show the results for the error (e), change of error (de), back servo real signal, Fuzzy 1 output and the FPGA signal for the base, shoulder joint angles respectively. Also, the same results are obtained for other joint angles. FPGA Signals Front Panel for the six angles are as shown in Fig. 17.

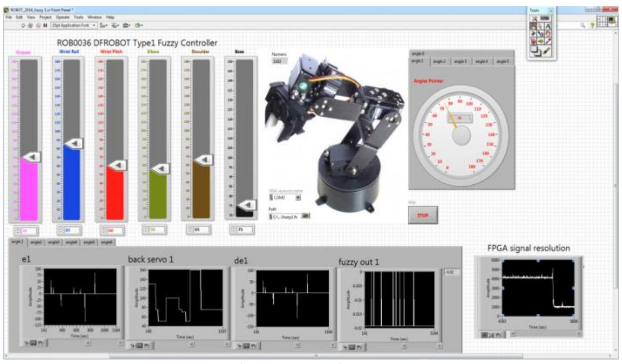

Fig. 15. The front panel for the base angle.

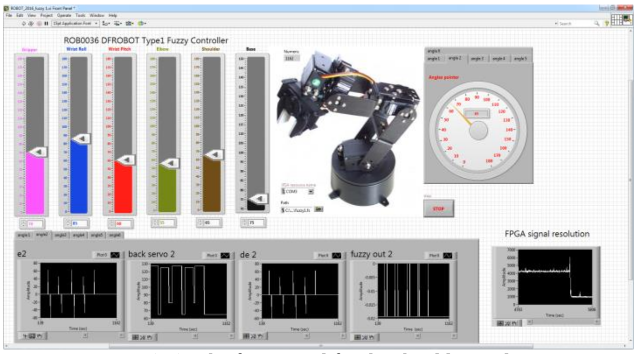

Fig. (16): The front panel for the shoulder angle.

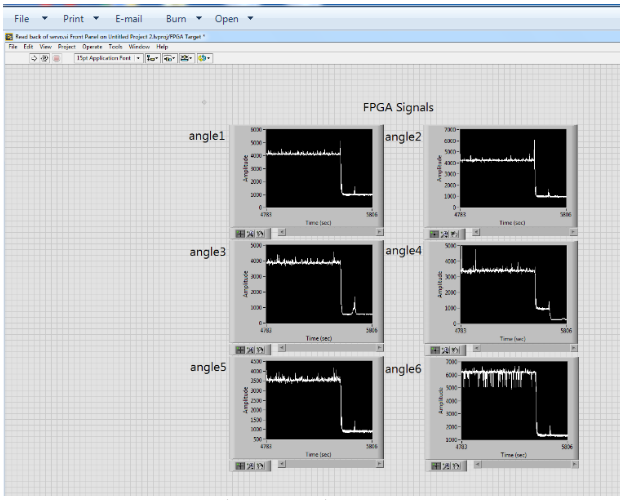

Fig. 17. The front panel for the FPGA signals.

The PCI 7833R FPGA board is connected by using the LabVIEW FPGA Model which extends the LabVIEW graphical development platform to target FPGAs on the NI reconfigurable I/O hardware, and gives the designers more efficient and effective ability to design complex systems by providing high integrated development area. So for software implementation it is necessary to install; LabVIEW 2016, FPGA Model 2016, Xilinx Compilation Tool for ISE 14.7 and also LabVIEW Real-Time Module to program the real time operating system. The Pictures related to the motors Signal are maximize to clearly notice the position response as shown in Fig. 18.

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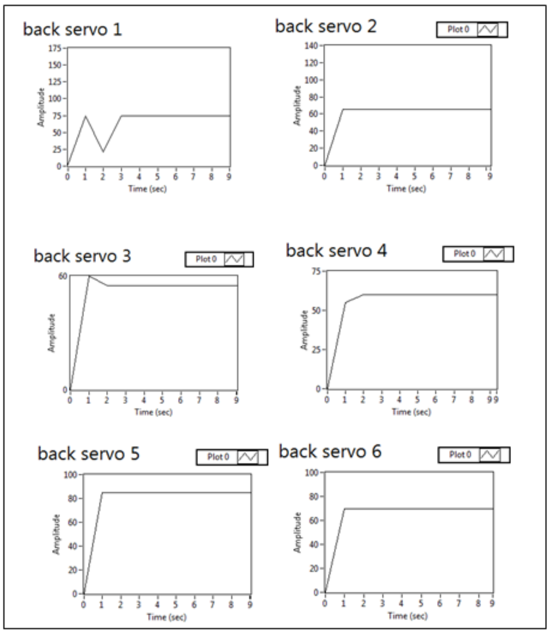

Fig. 18. T1FLC servo motors signals for the six angles.

The complete design of IT2FLC is implemented by using a Fuzzy Logic toolbox performed on MATLAB program, the surface viewer produced from the design is as shown in Fig. 19. Gaussian type MF shape is used in this model they are all implemented with real values of the input variables. Using the Takagi – Sugeno model it will be possible to decompose a system with complex circuits into simplest subsystems. The IT2FLC outputs from the inference engine must be converted to obtain a T1FLC, which then be defuzzified into a crisp output, this can be accomplished by using the type reducer which is implemented by using the KM algorithm.

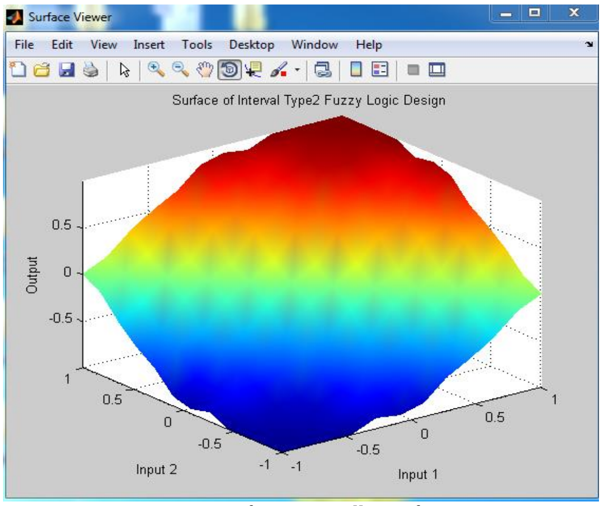

Fig. 19. Type2 fuzzy controller surface viewer.

The robot arm hardware connection is done by using LabVIEW program, some electronic parameters are not available in LabVIEW like the fuzzy type2 toolbox but it is found in MATLAB. So the benefits of the two programs can be considered and a newly designed program is performed by using Transmission Control Protocol- Internet Protocol (TCP-IP) that brings the already analysis or existing blocks in MATLAB to the working program in LabVIEW. Implementation of the IT2FLC for controlling the movements of the 6DOF Robotic arm joints can be achieved as in the front panel of Fig. 20 for the base angle. The performance of the controller with the same steps implemented previously with TIFLC help to reach the required task points to pick and place objects by following the selected path and can be achieved in this work with high uncertainty for detecting all the points within the space region of the manipulator arm movement.

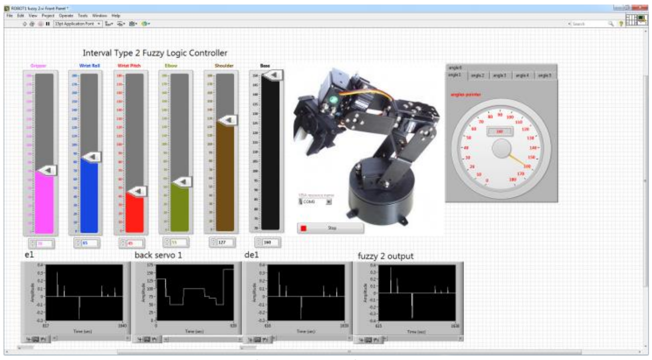

Fig. 20. The front panel for the base angle.

The Figures related to the back servo for the six angles are maximizing to show the motor responses as shown in Fig. 21.

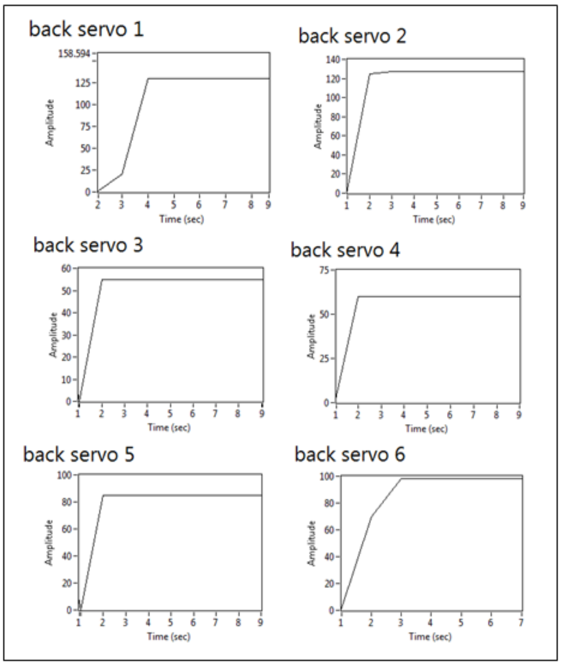

Fig. 21. The servo motors signals for the six angles.

The performance comparison of fuzzy logic type1 controller with triangular membership and Interval type2 fuzzy logic controller with Gaussian membership are shown in Table IV.

TABLE IV: PERFORMANCE COMPARISON BETWEEN T1FLC AND IT2FLC.

Type of Controller	Base Angle (θ_1)	Shoulder Angle (θ_2)	Elbow Angle (θ_3)	Wrist pitch Angle (θ_4)	Wrist Roll Angle (θ_5)	Gripper Angle (θ_6)

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Fuzzy Type1	t_r(sec)	1.45	0.65	0.7	0.7	0.8	2.5
With Triangular	t_s(sec)	4	2	2	2	22	3
MFs	MP%	0	0	13.2	0	0	0
Fuzzy Type2	t_r(sec)	22	0.6	0.85	1.4	0.6	0.65
With Gaussian	t_s(sec)	2,95	1	2	2	1	1
MFs	MP%	0	0	0	0	0	0

VIII. CONCLUSION

In this work, an efficient, effective and accurate tools have been used for applying the developed controllers on the real system robot arm with a perfect step to see the performance for achieving the required task of the manipulator arm trajectory. AIRFC system with T1FLC is applied on a PCI-7833R FPGA board from NI with a high processing facility. In this case, the desired input angle is the robot trajectory for a certain path.

A new developed Type2 fuzzy logic controller is applied by using Takagi-Sugeno fuzzy model which has much advantage; it reduces the number of rules required using the mamdani model, insure continuity of output surface and more suited to mathematical analysis. The IT2FLC performed on MATLAB using Gaussian MFs and Karnik Mendel algorithm for the type reducer, the controller shows an ability to eliminate persistent oscillations and handle the model uncertainty.

Very accurate results are obtained by applying the program of the TCP-IP server to transform the IT2FS to work with LabVIEW and then implement the controller to the robot arm joints. The comparison table shows that in case of type2 fuzzy logic the rise time is less than that of type1fuzzy logic for the shoulder, wrist roll and the gripper angles and it is higher for base, elbow and wrist pitch angles. The settling time is the same in elbow and wrist pitch angles and for the type2 fuzzy controller it is less for other angles.

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