Fuzzy logic Controller Design for gun-turret system

M. Galal*, N. G. Mikhail*, G. Elnashar*

Abstract: High precision control is desirable for future weapon systems. In this paper, several control design methodologies are applied to a weapon system to assess the applicability of each control design method and to characterize the achievable performance of the gun-turret system in precision control. The design objective of the gun-turret control system is to achieve a rapid and precise tracking response with respect to the turret motor command from the fire control system under the influences of disturbances, nonlinearities, and modeling uncertainties. A fuzzy scheme is proposed for control of multi-body, multi-input and multi-output nonlinear systems with joints represented by a gun turret-barrel model which consists of two subsystems: two motors driving two loads (turret and barrel) coupled by nonlinear dynamics. Fuzzy control schemes are employed for compensation and nonlinear feedback control laws are used for control of nonlinear dynamics. Fuzzy logic control (FLC) provides an effective means of capturing the approximate, inexact nature of the real world, and to address unexpected parameter variations and anomalies. Viewed in this perspective, the essential part of the FLC is a set of linguistic control rules related by the dual concepts of fuzzy implication and the compositional rule of inference. In essence, the FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Accordingly, the design must be robust, adaptive, and, hopefully, intelligent in order to accommodate these uncertainties. Simulation results verify the desired system tracking performance.

Keywords: Multivariable nonlinear systems; weapon gun turret system; fuzzy logic control.

1. Introduction

Dc motors used in many applications such as steel rolling mills, electric trains, and robotic manipulators require speed controllers to perform tasks. Major problems in applying a conventional control algorithm as a speed controller are the effects of the nonlinearity in the system to be controlled. The nonlinear characteristics of the Dc motor such as saturation and friction could degrade the performance of the conventional controllers [1-3]. Many advanced model-based control methods such as variable-structure control [4] and model reference adaptive control [5] have been developed to reduce these effects. However, the performance of these methods depends on the accuracy of the system models and parameters. Generally, an accurate nonlinear model of an actual Dc motor is difficult to find, and parameter values obtained from system identification may be only approximated values.

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* Egyptian Armed Forces

Emerging intelligent techniques have been developed and extensively used to improve or to replace conventional control techniques because these techniques do not require a precise model. One of intelligent techniques, fuzzy logic developed by Zadeh [6, 7] is applied for controller design in many applications [8, 9]. A fuzzy logic controller (FLC) was proved analytically to be equivalent to a nonlinear PI controller when a nonlinear defuzzification method is used [10]. Also, the results from the comparison of conventional and fuzzy logic control techniques in the form of FLC [11, 12] and fuzzy compensator [13, 14] showed fuzzy logic can reduce the effects of nonlinearity in a DC motor and improve the performance of a controller. A FLC has been implemented on many platforms such as digital signal processor (DSP) [15], PC [16], or off-the-shelf microcontroller [17]. These platforms have different advantages and disadvantages. The FLC developed on DSP or PC can quickly process fuzzy computation to generate control efforts, but the physical size of the system may be too big and quite expensive for a small DC motor applications. On the other hands, using an off-the –shelf microcontroller to implement a FLC is inexpensive and the physical size of the system is small, but the FLC requires longer processing time. One way to improve the response time in microcontroller implementation approach is to use a look up table, but this method needs much more memory to store a table.

An alternative method to implement a FLC is using a fuzzy logic chip. The fuzzy logic chip is first developed in 1985 by Togai and Watanable [18]. It has been developed and improved continuously to be a commercial fuzzy logic microcontroller by many companies. The main feature of this chip is its capability in hardware level to execute fuzzy computation. Fuzzy rules and member ship functions are defined and stored in RAM or ROM by specific formats that make a designer's job easier. This feature could reduce developing time and bypass the need of a high speed yet expensive system to develop a FLC. The designer can also utilize other features included in a fuzzy logic microcontroller to reduce the size and to improve the system performance.

In this paper, a FLC is implemented for a position control of a Turntable and an Arm fixed on it each is derived by a DC motor. Heuristic knowledge is applied to define fuzzy membership functions and rules. The membership functions and rules are modified after initially borrowing the knowledge from a PI controller developed from a simple linear model [11, 14].

2. System Description

The gun-turret system shown in Fig. 1 consists of two revolute joints with two electric DC motors. The arm of length "L" is attached to the motor number "2".

According to Dinavit_Hartinberg convention the coordinate frames are considered and rearranged as shown in figure. The joint parameters and the transformation matrices can be defined as shown in Table 1.

Table 1   Joint Parameters

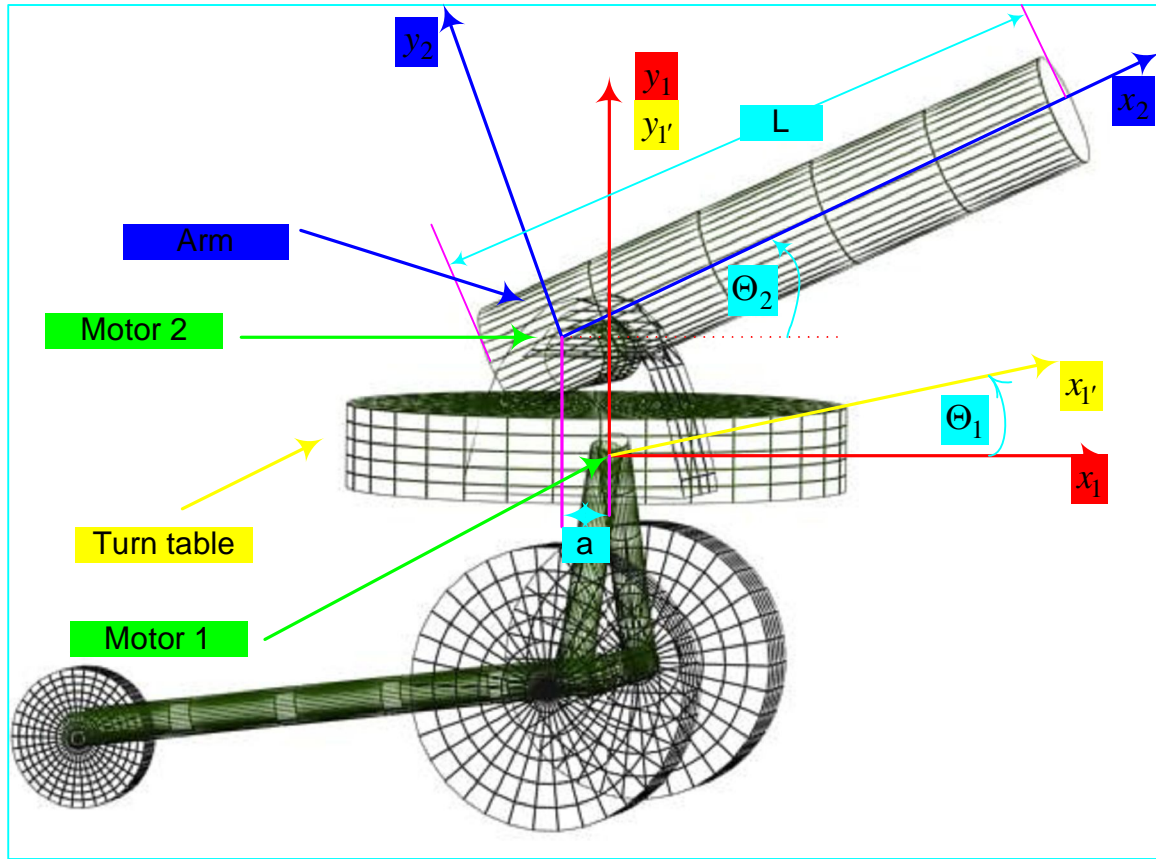| Joint	Θ	d	a	α
1	Θ_1	0	0	90
1'	0	0	a	0
2	Θ_2	0	L	0

Fig. 1 The gun-turret system

Where the joint parameters Θ, d, a, and α are defined earlier with DH convention using the transformation matrix.

Lagrange's equation of motion (equation (1)) is applied to give two equations of motion, one to describe the turntable motion by angular coordinate Θ_1 equation (11) and the second one to describe the motion of the arm by angular coordinate Θ_2 equation (12).

$$F = C_F P_c A_t$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i \tag{1}$$

where:

T   ……   Total kinetic energy of the system.
V   …...   Total potential energy of the system.
D   …..   Dissipation function due to damping.
Q_i ….   Generalized force corresponding to i-coordinate.

Then, the total kinetic energy, potential energy, dissipation function (if we have damping) and the virtual work of the system must be obtained to apply Lagrangian dynamic modeling.

Kinetic Energy

The total kinetic energy of the system consists of four main terms, the kinetic energy of the arm T_A, the kinetic energy of the two rotors of the motors T_{R_1} and T_{R_2}, and the kinetic energy of the payload at the end effector of the arm T_p.

$$T = T_A + T_{R_1} + T_{R_2} + T_p \tag{2}$$

The kinetic energy of the arm is due to the distribution of its mass along the length "L" is defined by:

$$T_A = \frac{1}{2} (\rho \, AL) \frac{L^2}{3} \dot{\Theta}_2^{\,2} + \frac{1}{2} (\rho \, AL) (\frac{L^2}{3} c_2^2 + a\,L\,c_2 + a^2) \dot{\Theta}_1^{\,2} \tag{3}$$

where

A   ....   Cross-section area.
ρ ....   Density of the arm material

$$T_{R_1} = \frac{1}{2} I_{R_1} \dot{\Theta}_1^2 \tag{4}$$

where

T_{R_1} ....   Kinetic energy of rotor "1".

I_{R_1} ....   Mass moment of inertia of rotor "1".

$$T_{R_2} = \frac{1}{2} I_{R_2} \dot{\Theta}_2^{\,2} + \frac{1}{2} (I_{R_2} + m_{R_2} a^2) \dot{\Theta}_1^2 $$

where

T_{R_2} ....   Kinetic energy of rotor "2".

I_{R2} ....   Mass moment of inertia of rotor "2".

m_{R_2} ....   Mass of rotor "2".

$$T_p = \frac{1}{2} m_p (LC_2 + a)^2 \dot{\Theta}_1^2 + \frac{1}{2} m_p L^2 \dot{\Theta}_2^{\,2} \tag{5}$$

where

m_p .... Mass of the payload.

Potential Energy

The potential energy due to gravity of the arm, the payload and motor "2" represent the total potential energy of the system as the strain energy of the arm is neglected due to it is considered as a rigid body.

- Gravitational potential energy of the arm

$$V_A = \int_{Arm} r_2^T \, g \, dm$$

$$V_A = -9.81 \, \rho A \, \frac{L^2}{2} \, S_2 \tag{7}$$

- Gravitational potential energy of the payload

$$V_p = m_p \, \underline{r}_p^T \, \underline{g}$$

$$V_p = -9.81 m_p \, LS_2 \tag{8}$$

From equations (7) and (8), the total potential energy is defined as,

$$V = V_A + V_p$$

$$V = -9.81 \, \rho A \, \frac{L^2}{2} \, S_2 - 9.81 m_p \, LS_2 \tag{9}$$

For a system without any external applied force at the end effector, the generalized force can be obtained from the virtual work of the system,

$$\delta W = \delta \underline{q}^T \, \underline{Q}$$

The virtual work of the considered system is given by:

$$\delta W = M_1 \, \delta \Theta_1 + M_2 \, \delta \Theta_2$$

Then,

$$\underline{Q} = \begin{pmatrix} M_1 \\ M_2 \end{pmatrix} \tag{10}$$

where
Q ……… the generalized force.
M_1 ……… applied torque at motor "1".
M_2 ……… applied torque at motor "2".

Turntable's Equation of Motion
Driving each term of the Lagrange's equation of motion we get that:

$$[(\frac{\rho AL^3}{3} + m_p \, L^2) \, C_2^2 + (\rho AL^2 a + 2 m_p \, L \, a) \, C_2$$

$$+ (\rho A \, La^2 + I_{R_1} + I_{R_2} + m_{R_2} \, a^2 + m_p \, a^2)] \, \ddot{\Theta}_1$$

$$- [2(\frac{\rho AL^3}{3} + m_p \, L^2) \, C_2 \, S_2 + (\rho AL^2 a + 2 m_p \, L \, a) \, S_2] \dot{\Theta}_2 \, \dot{\Theta}_1 = M_1 \tag{11}$$

Arm's Equation of Motion

$$(\frac{\rho AL^3}{3} + I_{R_2} + m_p L^2)\ \ddot{\Theta}_2$$

$$+ (\frac{\rho AL^3}{3}\ C_2 S_2 + m_p L^2 C_2 S_2 + \frac{\rho AL^2 a}{2}\ S_2 + m_p LaS_2)\ \dot{\Theta}_1^2$$

$$- 9.81\ (\frac{\rho AL^2}{2} + m_p L)\ C_2 = M_2 \qquad (12)$$

where:

Θ_1 , Θ_2 ... angular position of motor "1" and motor "2" respectively.

c_1, s_1 ... $\cos \Theta_1$ and $\sin \Theta_1$ respectively.

c_2, s_2 ... $\cos \Theta_2$ and $\sin \Theta_2$ respectively.

L ... the arm length.

a ... the distance between the two motors in the x_1 direction.

3. Controller Design

While conventional controllers depend on the accuracy of the system model and parameters, FLCs use a different approach to control the system. Instead of using system model, the operation of a FLC is based in heuristic knowledge and linguistic descriptions to perform a task. The effects from inaccurate parameters and models are reduced because a FLC does not require a system model. However, building a FLC from the ground-up may not provide good result than a conventional controller if there is not enough knowledge of the system. Therefore, in this paper, the FLC is initially constructed as a-priori knowledge in the process. The performance of the FLC is then improved by adjusting the results and membership functions. These design procedure are described as follows.

Procedure 1: Defining inputs, outputs, and universe of discourse

To apply heuristic knowledge in the FLC, inputs, outputs, and universe of discourse are defined first. The inputs are the error (E) between the reference position (Θ_r) and the actual position (Θ_a), and the change in error (CE). The output is the change in armature voltage (CU). The inputs and output illustrated in Fig. 2 are described by:

$$E = e\ (k) = \Theta_r\ (k) - \Theta_a\ (k)$$

$$CE = e\ (k) - e\ (k\text{-}1)$$

$$CU = u\ (k) - u\ (k\text{-}1)$$
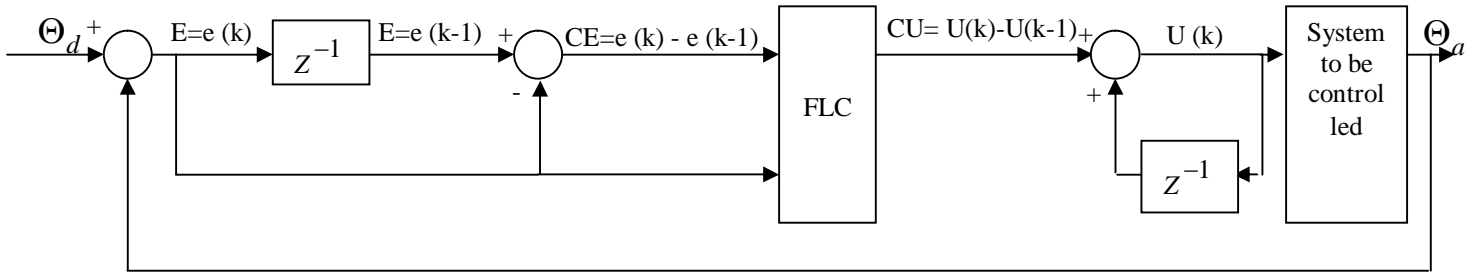
where
K ... is the time index.

Fig. 2   Block diagram of the FLC

The maximum range of the system angular position is +/-60°. The possible error in the range is between -120° to +120°. Therefore, the universe of discourse of E is defined to span between -120° to +120°. The universe of discourse of the change in error is based on the experiment data from the PI controller design included in procedure 2, which gives the range of error change, is +/- 5.5°. For the change in armature voltage, the minimum and maximum defined value are -1.5V and +1.5V respectively.

Procedure 2: Defining fuzzy membership functions and rules
To perform fuzzy computation, the inputs and output must be converted from numerical or "crisp" value into linguistic forms. The terms such as "Small" and "Big" are used to quantize the inputs and output values to linguistic terms that used to represent the input and output values are defined by seven fuzzy variables as shown in table 2.

Table 2   Fuzzy linguistic terms

Term	PB	PM	PS	ZE	NS	NM	NB
Definition	Positive Big	Positive Medium	Positive Small	Zero	Negative Small	Negative Medium	Negative Big

Fuzzy membership functions are used as tools to convert crisp values to linguistic terms forms. A fuzzy membership function can contain several fuzzy sets depending on how many linguistic terms. In this paper, seven fuzzy sets are obtained by applying the seven linguistic terms. The number for indicating how much a crisp value can be a member in each fuzzy set is called a degree of membership. One crisp value can be converted to be partly in many fuzzy sets, but the membership degree in each fuzzy set may be different.

In order to define fuzzy membership function, designers can choose many different shapes based on their preference or experience. The popular shapes are triangular and trapezoidal because these shapes are easy to represent designer's ideas and require low computation time. For performing fine-tuning to improve the efficient of the controller, the adjacent of each fuzzy set value should overlap about 25% [19]. The initial membership functions are illustrated in Fig. 3.

In equations (2, 3), we see that the equations of motion are in a nonlinear form. We ought to use FLC to overcome this nonlinearity of the equation of motion of the system to be controlled.

Instead of using mathematical formulas, a FLC uses fuzzy rules to make a decision and generate the control effort. The rules are in the form of IF-THEN statements. For example, IF the error (E) is equal to Positive Big (PB) and the change in error (CE) is equal to Positive Medium (PM) THEN the change in armature voltage (CU) is equal to Negative Medium (NM). The matters in defining rules are how many rules should be used and how to determine the relation in IF-THEN statements. Actually, the solutions are based on the experience of a designer or the previous knowledge of the system. The critical point is if there is not sufficient knowledge applied in the design, the result could be drastically bad.

The initial rules are constructed as shown in Table 3. The efficiency can be improved by adjusting the membership functions and rules in procedure 3.
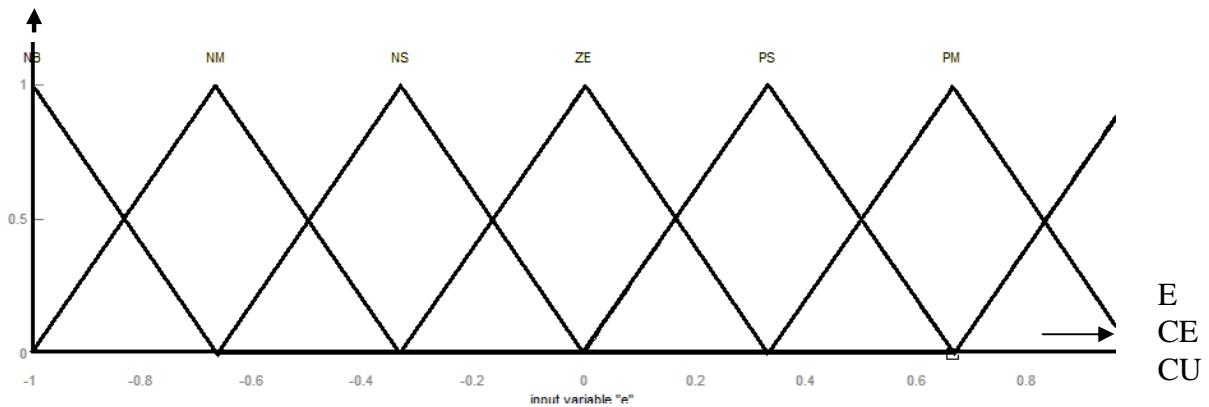

Fig. 3   Initial membership functions.

Table 3   Initial rules

e \ ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

To send out the armature voltage output, the output in the form of fuzzy sets must be converted to a crisp value. This process is called defuzzification. In this paper, the center of gravity method is chosen. The formula of this method is

$$Z = \frac{\sum\limits_{i=1}^{n} S_i F_i}{\sum\limits_{i=1}^{n} F_i}$$

where Z is the output from defuzzification, S_i is the specific position at the ith is the fuzzy set, and F_i is the membership degree at that position.

Procedure 3: Adjusting fuzzy membership functions and rules

In order to improve the performance of the FLC, the rules and membership functions are adjusted by making the area of membership functions near ZE region narrower to produce finer control resolution. On the other hands, making the area far from ZE region wider gives faster control response. Also, the performance can be improved by changing the severity of the rules [11]. After adjusting the rules and membership functions, the final rules and membership functions are obtained as shown in, Table 4 and Fig. 4 respectively.

Table 4   Modified rules

ce \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	ZE	PM	PM
NM	NB	NB	NB	NM	PS	PM	PB
NS	NB	NB	NM	NS	PM	PM	PB
ZE	NB	NM	NS	ZE	PB	PB	PB
PS	NM	NS	ZE	PS	PB	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Observing the performance of the system after applying the modified rules we get that there are some unused rules and in order to reduce memory size and have a faster performance we ought to eliminate the unused rules, so we get only 33 rules, table (5) shows the reduced modified rules.

Table 5   Reduced Modified Rules

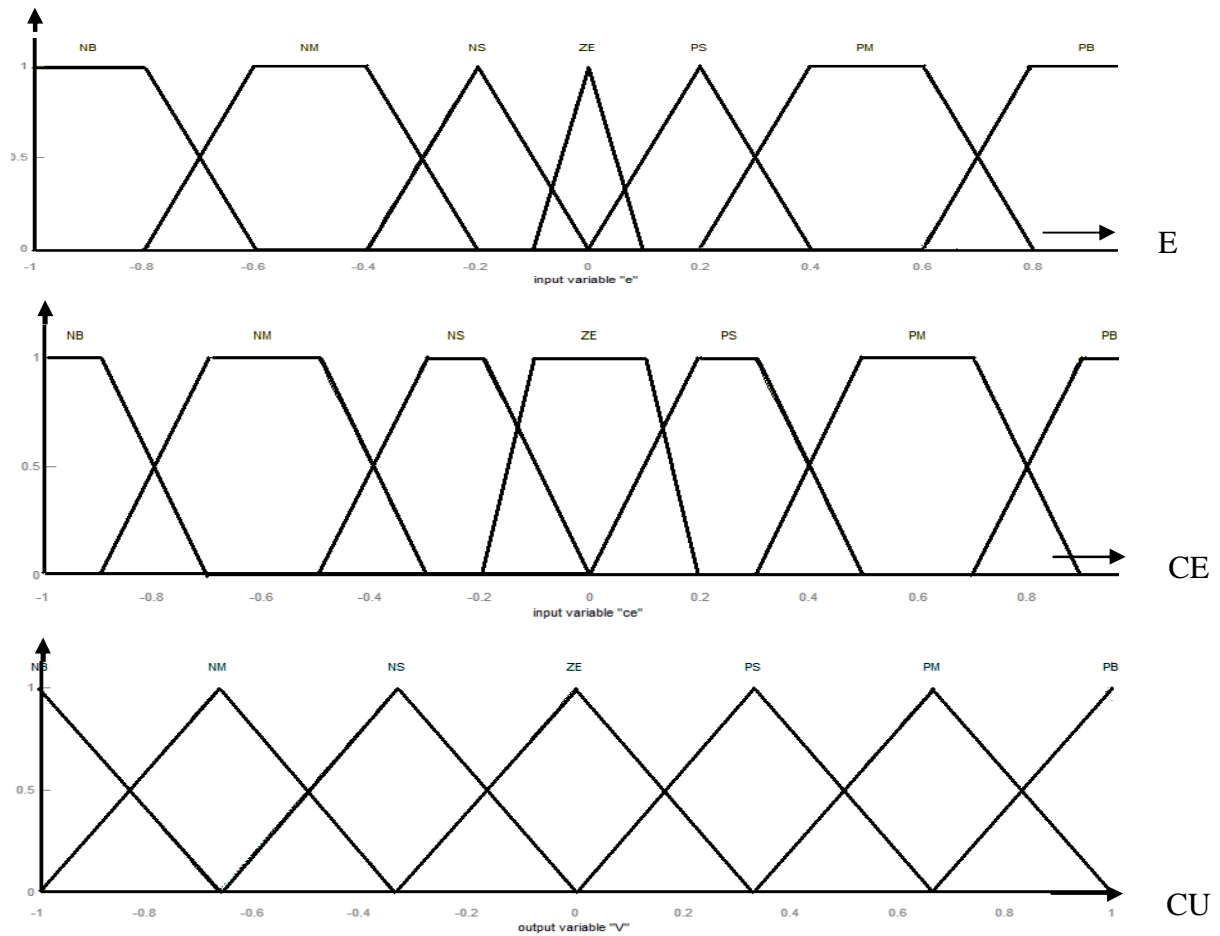| ce \ e	NB	NM	NS	ZE	PS
NB	NB	NB	NB	NB	ZE
NM	NB	NB	NB	NM	PS
NS	NB	NB	NM	NS	PM
ZE	NB	NM	NS	ZE	PB
PS	NM	NS	ZE	PS	PB
PM	NS	ZE	PS	PM	--
PB	ZE	PS	PM	PB	--

Fig. 4   Modified membership functions

4. Simulation Results

Matlab / Simulink software is used to simulate the Gun equation of motion and to make a good comparison between performances of FLC with 49 rules before and after adjusting the fuzzy membership functions and rules, step and half wave sinus signals were applied to the system as a control inputs. Both the controllers' step responses of the system were given in Fig. 5.a. For this work, rising times and overshot according to the modified FLC are better than in original the one which it's performance is out of the control aim.

5. Conclusions

This paper developed a solution to control of a two motor load system using fuzzy logic control. The implementation procedure of advanced control algorithms in the MATLAB/ SIMULINK software environment is presented to execute the control of the gun turret control system; and the results have shown that the developed control system is valid for advanced weapon control. Also, the designed control system can be applied to other complex controlled plants. The level of performance for each control algorithm is based on how well each they measure up to the criteria developed from the system. Simulation results show that modifying FLC responds with less overshot and minimum settling time. The modified controller showed a good position tracking performance.

6. References

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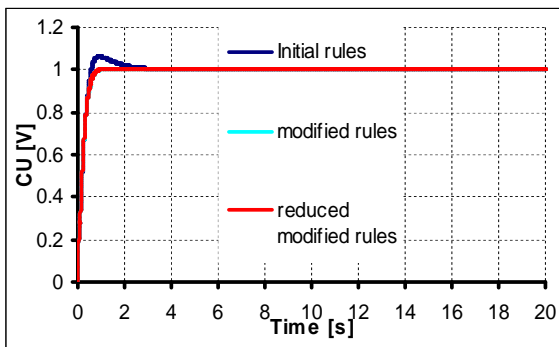[19]   B. Kosko, Neural networks and fuzzy systems, Prentice Hall, 1991.

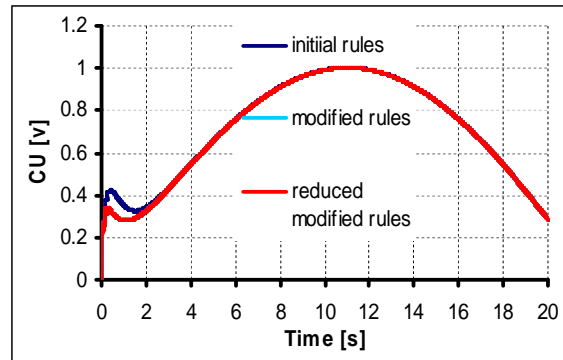**Fig. 5.a**   **Step responses of the Arm under different controllers**

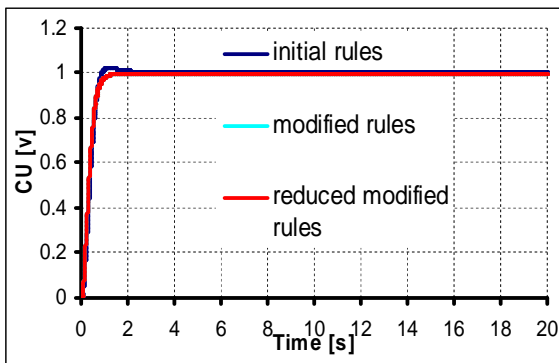**Fig. 5.b**   **Sinus responses of the Arm under different controllers**

Fig. 5.c   **Step responses of the turntable under different controllers**
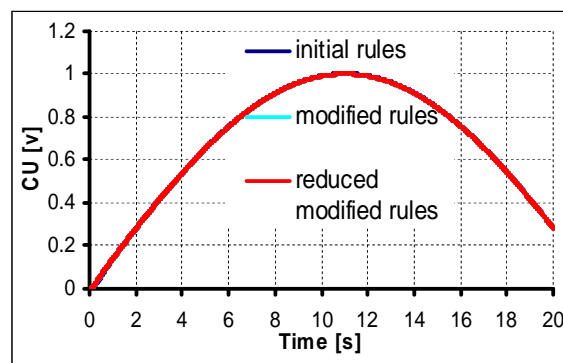
Fig. 5.d   **Sinus responses of the turntable under different controllers**

Fig. 5   **Step and Sinus System's responses under different controllers**