

Design Intelligent PID like Fuzzy Sliding Mode Controller for Spherical Motor

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Abstract—The minimum rule base Proportional Integral Derivative (PID) Fuzzy Sliding Mode Controller (SMC) with application to spherical motor is presented in this research. The popularity of PID Fuzzy Sliding Mode Controller can be attributed to their robust performance in a wide range of operating conditions and partly to their functional simplicity. The process of setting of PID Fuzzy Sliding Mode Controller can be determined as an optimization task. Over the years, use of intelligent strategies for tuning of these controllers has been growing especially in nonlinear and uncertain systems. Proportional Integral Derivative methodology has three inputs and if any input is described with seven linguistic values, and any rule has three conditions, we will need 343 rules. It is too much work to write 343 rules and have lots of problem to design embedded control system e.g., Field Programmable Gate Array (FPGA). In this research the PID-like fuzzy controller can be constructed as a parallel structure of a PD-like fuzzy controller and a conventional PI controller to have the minimum rule base and good trajectory follow disturbance to control of spherical motor. However Sliding Mode Controller is work based on cancelling decoupling and nonlinear terms of dynamic parameters for each direction of three degree of freedom spherical motor, this controller is work based on motor dynamic model and this technique is highly sensitive to the knowledge of all parameters of nonlinear spherical motor's dynamic equation which caused to challenge in uncertain system. This research is used to reduce or eliminate the Sliding Mode Controller problem based on minimum rule base fuzzy logic theory to control of three degrees of freedom spherical motor system and testing of the quality of process control in the simulation environment of MATLAB/SIMULINK Simulator.

Index Term—PID like fuzzy control, Sliding Mode Controller, PD like fuzzy control, conventional PI control, three degrees of freedom spherical motor.

I. INTRODUCTION

Multi degrees-of-freedom (DOF) actuators are finding wide use in a number of Industries. Currently, a significant number of the existing robotic actuators that can realize multi-DOF motion are constructed using gear and linkages to connect several single-DOF motors in series and/or parallel. Not only do such actuators tend to

be large in size and mass, but they also have a decreased positioning accuracy due to mechanical deformation, friction and backlash of the gears and linkages. A number of these systems also exhibit singularities in their workspaces, which makes it virtually impossible to obtain uniform, high-speed, and high-precision motion. For high precession trajectory planning and control, it is necessary to replace the actuator system made up of several single-DOF motors connected in series and/or parallel with a single multi-DOF actuator. The need for such systems has motivated years of research in the development of unusual, yet high performance actuators that have the potential to realize multi-DOF motion in a single joint. One such actuator is the spherical motor. Compared to conventional robotic manipulators that offer the same motion capabilities, the spherical motor possesses several advantages. Not only can the motor combine 3-DOF motion in a single joint, it has a large range of motion with no singularities in its workspace. The spherical motor is much simpler and more compact in design than most multiple single-axis robotic manipulators. The motor is also relatively easy to manufacture. The spherical motor have potential contributions to a wide range of applications such as coordinate measuring, object tracking, material handling, automated assembling, welding, and laser cutting. All these applications require high precision motion and fast dynamic response, which the spherical motor is capable of delivering. Previous research efforts on the spherical motor have demonstrated most of these features. These, however, come with a number of challenges. The spherical motor exhibits coupled, nonlinear and very complex dynamics. The design and implementation of feedback controllers for the motor are complicated by these dynamics. The controller design is further complicated by the orientation-varying torque generated by the spherical motor. Some of these challenges have been the focus of previous and ongoing research [1-11].

Controller is a device to improve the system's performance [11-20]. In feedback control system considering that there are many disturbances and also variable dynamic parameters something that is really necessary is keeping plant variables close to the desired value. Feedback control system development is the most important thing in many different fields of safety engineering. The main targets in design control systems are safety stability, good disturbance rejection to reach

the best safety, and small tracking error[21-33]. At present, in some applications spherical motors are used in unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable safety performance (e.g., minimum error, good trajectory, disturbance rejection). According to the control theory, systems' controls are divided into two main groups: conventional control theory and soft computing control theory. Conventional control theories are work based on system dynamic model. This technique is highly sensitive to the knowledge of all parameters of nonlinear spherical motor's dynamic equation. Conventional control theory is divided into two main groups: linear control theory and nonlinear control theory. Soft computing (intelligent) control theory is free of some challenges associated to conventional control theory. This technique is worked based on intelligent control theory. This theory is divided into the following groups: fuzzy logic theory, neural network theory, genetic algorithm and neuro-fuzzy theory [21-34].

Sliding mode controller (SMC) is a powerful nonlinear controller which has been analyzed by many researchers especially in recent years. This theory was first proposed in the early 1950 by Emelyanov and several co-workers and has been extensively developed since then with the invention of high speed control devices [35-46]. The main reason to opt for this controller is its acceptable control performance in wide range and solves two most important challenging topics in control which names, stability and robustness [47-53]. Sliding mode controller is divided into two main sub controllers: discontinues controller (τ_{dis}) and equivalent controller (τ_{eq}). Discontinues controller causes an acceptable tracking performance at the expense of very fast switching. In the theory of infinity fast switching can provide a good tracking performance but it also can provide some problems (e.g., system instability and chattering phenomenon). After going toward the sliding surface by discontinues term, equivalent term help to the system dynamics match to the sliding surface[54-58]. However, this controller used in many applications but, pure sliding mode controller has following challenges: chattering phenomenon, and nonlinear equivalent dynamic formulation [59-68]. Chattering phenomenon can causes some problems such as saturation and heat the mechanical parts of spherical motor. To reduce or eliminate the chattering, various papers have been reported by many researchers which classified into two most important methods: boundary layer saturation method and estimated uncertainties method [60-68]. In boundary layer saturation method, the basic idea is the discontinuous method replacement by saturation (linear) method with small neighborhood of the switching surface. This replacement caused to increase the error performance against with the considerable chattering reduction. In recent years, artificial intelligence theory has been used in sliding mode control systems. Neural network, fuzzy logic and neuro-fuzzy are synergically combined with nonlinear classical controller and used in

nonlinear, time variant and uncertain plant (e.g., spherical motor) [34-68].

Although the fuzzy-logic control is not a new technique, its application in this current research is considered to be novel since it aimed for an automated dynamic-less response rather than for the traditional objective of uncertainties compensation[38-68]. The intelligent tracking control using the fuzzy-logic technique provides a cost-and-time efficient control implementation due to the automated dynamic-less input. This in turn would further inspire multi-uncertainties testing for continuum robot [57-68]. In project we can use fuzzy logic theory when a plant can be considered as a black box with outputs available for measurement and a possibility of changing inputs. The plant is supposed to be observable and controllable. Some information about the plant operation or plant control is available, which can or cannot be of a quantitative nature, but it can be formulated as a set of rules (maybe after some processing). An acceptable fuzzy control solution is possible, which should satisfy design specifications. It must not be optimal in regard to some criteria as it is hard to prove that a fuzzy control system is optimal and even stable. However, a fuzzy controller is able to provide a stable and 'good' solution.

This method design PID like fuzzy controller based on the minimum rule base and applied this controller to conventional sliding mode controller to solve the robust challenge in sliding mode controller and have a linear behavior based on the nonlinear control system.

This paper is organized as follows; section 2, is served as an introduction to the dynamic of three degrees of freedom spherical motor, sliding mode controller, design linear PID controller and fuzzy inference system. Part 3, introduces and describes the methodology algorithm. Section 4 presents the simulation results and discussion of this algorithm applied to three degrees of freedom spherical motor and the final section describe the conclusion.

II. THEORY

Dynamic and Kinematics Formulation of Spherical Motor: Dynamic modeling of spherical motors is used to describe the behavior of spherical motor such as linear or nonlinear dynamic behavior, design of model based controller such as pure sliding mode controller which design this controller is based on nonlinear dynamic equations, and for simulation. The dynamic modeling describes the relationship between motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (e.g., inertia, coriolios, centrifugal, and the other parameters) to behavior of system[1-10]. Spherical motor has nonlinear and uncertain dynamic parameters 3 degrees of freedom (DOF) motor.

The equation of a spherical motor governed by the following equation [1-10]:

$$H(q) \begin{bmatrix} \ddot{\alpha} \\ \ddot{\beta} \\ \ddot{\gamma} \end{bmatrix} + B(q) \begin{bmatrix} \dot{\alpha}\dot{\beta} \\ \dot{\alpha}\dot{\gamma} \\ \dot{\beta}\dot{\gamma} \end{bmatrix} + C(q) \begin{bmatrix} \dot{\alpha}^2 \\ \dot{\beta}^2 \\ \dot{\gamma}^2 \end{bmatrix} = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} \quad (1)$$

Where τ is actuation torque, $H(q)$ is a symmetric and positive definite inertia matrix, $B(q)$ is the matrix of coriolis torques, $C(q)$ is the matrix of centrifugal torques. This is a decoupled system with simple second order linear differential dynamics. In other words, the component \ddot{q} influences, with a double integrator relationship, only the variable q_i , independently of the motion of the other parts. Therefore, the angular acceleration is found as to be [1-11]:

$$\ddot{q} = H^{-1}(q) \cdot \{\tau - \{B + C\}\} \quad (2)$$

This technique is very attractive from a control point of view.

Study of spherical motor is classified into two main groups: kinematics and dynamics. Calculate the relationship between rigid bodies and final part without any forces is called Kinematics. Study of this part is pivotal to design with an acceptable performance controller, and in real situations and practical applications. As expected the study of kinematics is divided into two main parts: forward and inverse kinematics. Forward kinematics has been used to find the position and orientation of task frame when angles of joints are known. Inverse kinematics has been used to find possible joints variable (angles) when all position and orientation of task frame be active [1].

The main target in forward kinematics is calculating the following function:

$$\Psi(X, q) = 0 \quad (3)$$

Where $\Psi(.) \in R^n$ is a nonlinear vector function, $X = [X_1, X_2, \dots, X_l]^T$ is the vector of task space variables which generally task frame has three task space variables, three orientation, $q = [q_1, q_2, \dots, q_n]^T$ is a vector of angles or displacement, and finally n is the number of actuated joints. The Denavit-Hartenberg (D-H) convention is a method of drawing spherical motor free body diagrams. Denvit-Hartenberg (D-H) convention study is necessary to calculate forward kinematics in this motor.

A systematic Forward Kinematics solution is the main target of this part. The first step to compute Forward Kinematics (F.K) is finding the standard D-H parameters. The following steps show the systematic derivation of the standard D-H parameters.

1. Locate the spherical motor
2. Label joints
3. Determine joint rotation (θ)
4. Setup base coordinate frames.
5. Setup joints coordinate frames.
6. Determine α_i , that α_i , link twist, is the angle between Z_i and Z_{i+1} about an X_i .

7. Determine d_i and a_i , that a_i , link length, is the distance between Z_i and Z_{i+1} along X_i . d_i , offset, is the distance between X_{i-1} and X_i along Z_i axis.
8. Fill up the D-H parameters table. The second step to compute Forward kinematics is finding the rotation matrix (R_n^0). The rotation matrix from $\{F_i\}$ to $\{F_{i-1}\}$ is given by the following equation;

$$R_i^{i-1} = U_{i(\theta_i)} V_{i(\alpha_i)} \quad (4)$$

Where $U_{i(\theta_i)}$ is given by the following equation [1-11];

$$U_{i(\theta_i)} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 \\ \sin(\theta_i) & \cos(\theta_i) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

and $V_{i(\alpha_i)}$ is given by the following equation [1-11];

$$V_{i(\alpha_i)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha_i) & -\sin(\alpha_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) \end{bmatrix} \quad (6)$$

So (R_n^0) is given by [8]

$$R_n^0 = (U_1 V_1)(U_2 V_2) \dots \dots (U_n V_n) \quad (7)$$

The final step to compute the forward kinematics is calculate the transformation ${}^0_n T$ by the following formulation [3]

$${}^0_n T = {}^0_1 T \cdot {}^1_2 T \cdot {}^2_3 T \dots \dots \cdot {}^{n-1}_n T = \begin{bmatrix} R_n^0 & 0 \\ 0 & 1 \end{bmatrix} \quad (8)$$

SLIDING MODE CONTROLLER: One of the significant challenges in control algorithms is a linear behavior controller design for nonlinear systems. When system works with various parameters and hard nonlinearities this technique is very useful in order to be implemented easily but it has some limitations such as working near the system operating point[12]. Some of nonlinear systems which work in industrial processes are controlled by linear PID controllers, but the design of linear controller for spherical motors are extremely difficult because they are nonlinear, uncertain and MIMO[33-57]. To reduce above challenges the nonlinear robust controllers is used to systems control. One of the powerful nonlinear robust controllers is sliding mode controller (SMC), although this controller has been analyzed by many researchers but the first proposed was in the 1950 [12-33]. This controller is used in wide range areas such as in robotics, in control process, in aerospace applications and in power converters because it has an acceptable control performance and solve some main challenging topics in control such as resistivity to the external disturbance. The lyapunov formulation can be written as follows,

$$V = \frac{1}{2} S^T \cdot H \cdot S \quad (9)$$

The derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S^T \cdot \dot{H} \cdot S + S^T H \dot{S} \quad (10)$$

The dynamic equation of spherical motor can be written based on the sliding surface as

$$H \dot{S} = -VS + H \dot{S} + VS - \tau \quad (11)$$

It is assumed that

$$S^T (\dot{H} - 2V) S = 0 \quad (12)$$

by substituting (11) in (10)

$$\dot{V} = \frac{1}{2} S^T \dot{H} S - S^T VS + S^T (H \dot{S} + VS - \tau) = S^T (H \dot{S} + VS - \tau) \quad (13)$$

Suppose the control input is written as follows

$$\hat{\tau} = \hat{\tau}_{eq} + \hat{\tau}_{dis} = [\hat{H}^{-1}(\hat{V}) + \hat{S}] \hat{H} + K_v \cdot sgn(S) + K_v S \quad (14)$$

By replacing the equation (14) in (13)

$$\dot{V} = S^T (H \dot{S} + VS - \hat{H} \dot{S} - \hat{V} S - K_v S - K_v sgn(S)) = S^T (H \dot{S} + \tilde{V} S - K_v S - K_v sgn(S)) \quad (15)$$

It is obvious that

$$|\hat{H} \dot{S} + \tilde{V} S - K_v S| \leq |\hat{H} \dot{S}| + |\tilde{V} S| + |K_v S| \quad (16)$$

The Lemma equation in spherical motor system can be written as follows

$$K_u = [|\hat{H} \dot{S}| + |VS| + |K_v S| + \eta]_i, \quad i = 1, 2, 3, 4, \dots \quad (17)$$

The equation (12) can be written as

$$K_u \geq |[H \dot{S} + VS - K_v S]_i| + \eta_i \quad (18)$$

Therefore, it can be shown that

$$\dot{V} \leq -\sum_{i=1}^n \eta_i |S_i| \quad (19)$$

Based on above discussion, the control law for spherical motor is written as:

$$U = U_{eq} + U_{switch} \quad (20)$$

Where, the model-based component U_{eq} is the nominal dynamics of systems and U_{eq} can calculate as follows:

$$U_{eq} = [H^{-1}(B + C) + \dot{S}] H \quad (21)$$

U_{switch} is computed as;

$$U_{switch} = K \cdot \text{SGN}(\lambda e + \dot{e}) \quad (22)$$

by replace the formulation (22) in (20) the control output can be written as;

$$U = U_{eq} + K \cdot \text{SGN}(S) \quad (23)$$

By (23) and (21) the sliding mode control of spherical motor is calculated as;

$$U = [H^{-1}(B + C) + \dot{S}] H + K \cdot \text{SGN}(S) \quad (24)$$

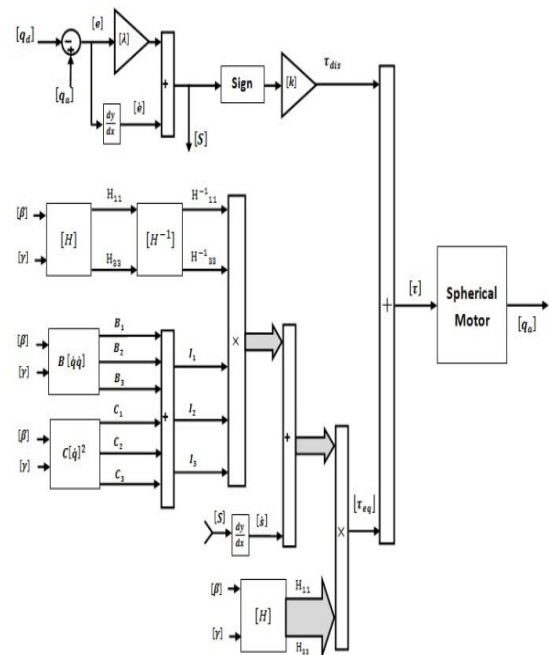


Fig 1: Sliding Mode Control: 3 DOF spherical motor

Fuzzy Logic Controller: Based on foundation of fuzzy logic methodology; fuzzy logic controller has played important rule to design nonlinear controller for nonlinear and uncertain systems [19-33]. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of; Input fuzzification (binary-to-fuzzy [B/F] conversion), Fuzzy rule base (knowledge base), Inference engine and Output defuzzification (fuzzy-to-binary [F/B] conversion). Figure 2 shows fuzzy controller operation.

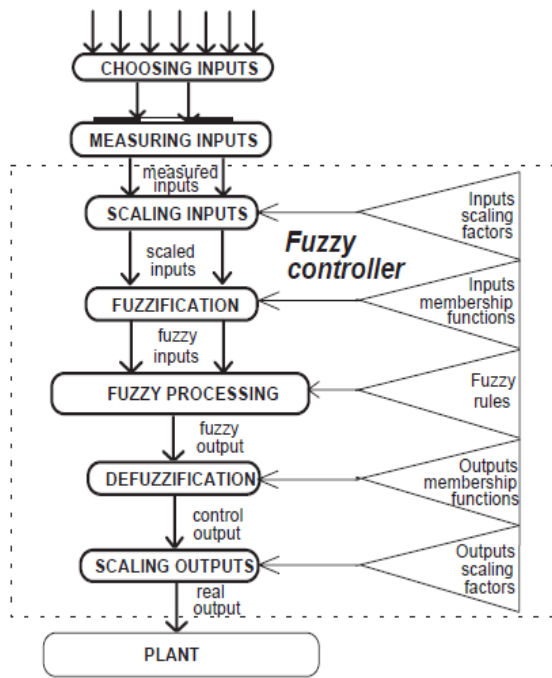


Fig 2: Fuzzy Controller operation

The fuzzy inference engine offers a mechanism for transferring the rule base in fuzzy set which it is divided into two most important methods, namely, Mamdani method and Sugeno method. Mamdani method is one of the common fuzzy inference systems and he designed one of the first fuzzy controllers to control of system engine. Mamdani’s fuzzy inference system is divided into four major steps: fuzzification, rule evaluation, aggregation of the rule outputs and defuzzification. Michio Sugeno uses a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base

$$\begin{aligned} & \text{if } x \text{ is } A \text{ and } y \text{ is } B \text{ then } z \text{ is } C \text{ 'mamdani'} \\ & \text{if } x \text{ is } A \text{ and } y \text{ is } B \text{ then } z \text{ is } f(x,y) \text{'sugeno'} \end{aligned} \quad (25)$$

When x and y have crisp values fuzzification calculates the membership degrees for antecedent part. Rule evaluation focuses on fuzzy operation (AND/OR) in the antecedent of the fuzzy rules. The aggregation is used to calculate the output fuzzy set and several methodologies can be used in fuzzy logic controller aggregation, namely, Max-Min aggregation, Sum-Min aggregation, Max-bounded product, Max-drastic product, Max-bounded sum, Max-algebraic sum and Min-max. Two most common methods that used in fuzzy logic controllers are Max-min aggregation and Sum-min aggregation. Max-min aggregation defined as below;

$$\begin{aligned} \mu_U(x_k, y_k, U) &= \mu_{U_{i=1}^r FR^i}(x_k, y_k, U) \\ &= \max \left\{ \min_{i=1}^r \left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U) \right] \right\} \end{aligned} \quad (26)$$

The Sum-min aggregation defined as below

$$\begin{aligned} \mu_U(x_k, y_k, U) &= \mu_{U_{i=1}^r FR^i}(x_k, y_k, U) \\ &= \sum \min_{i=1}^r \left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U) \right] \end{aligned} \quad (27)$$

where r is the number of fuzzy rules activated by x_k and y_k and also $\mu_{U_{i=1}^r FR^i}(x_k, y_k, U)$ is a fuzzy interpretation of i – th rule. Defuzzification is the last step in the fuzzy inference system which it is used to transform fuzzy set to crisp set. Consequently defuzzification’s input is the aggregate output and the defuzzification’s output is a crisp number. Centre of gravity method (COG) and Centre of area method (COA) are two most common defuzzification methods, which COG method used the following equation to calculate the defuzzification

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^r \mu_{u_i}(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^r \mu_{u_i}(x_k, y_k, U_i)} \quad (28)$$

and COA method used the following equation to calculate the defuzzification

$$COA(x_k, y_k) = \frac{\sum_i U_i \mu_{u_i}(x_k, y_k, U_i)}{\sum_i \mu_{u_i}(x_k, y_k, U_i)} \quad (29)$$

Where $COG(x_k, y_k)$ and $COA(x_k, y_k)$ illustrates the crisp value of defuzzification output, $U_i \in U$ is discrete element of an output of the fuzzy set, $\mu_{u_i}(x_k, y_k, U_i)$ is the fuzzy set membership function, and r is the number of fuzzy rules.

Design PID Controller: Design of a linear methodology to control of continuum robot manipulator was very straight forward. Since there was an output from the torque model, this means that there would be two inputs into the PID controller. Similarly, the outputs of the controller result from the two control inputs of the torque signal. In a typical PID method, the controller corrects the error between the desired input value and the measured value. Since the actual position is the measured signal. Figure 3 shows linear PID methodology, applied to spherical motor [21-34].

$$e(t) = \theta_a(t) - \theta_d(t) \quad (30)$$

$$U_{PID} = K_{p_a} e + K_{V_a} \dot{e} + K_I \int e \quad (31)$$

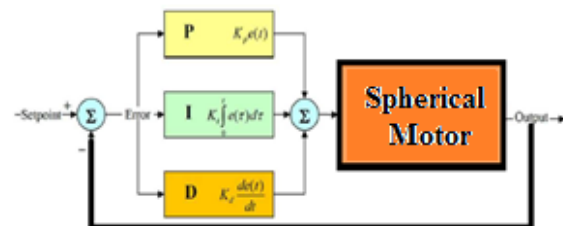


Fig 3: Block diagram of linear PID method

The model-free control strategy is based on the assumption that the joints of the motors are all independent and the system can be decoupled into a group of single-axis control systems [18-23]. Therefore, the kinematic control method always results in a group of

individual controllers, each for an active joint of the motor. With the independent joint assumption, no a priori knowledge of spherical motor dynamics is needed in the kinematic controller design, so the complex computation of its dynamics can be avoided and the controller design can be greatly simplified. This is suitable for real-time control applications when powerful processors, which can execute complex algorithms rapidly, are not accessible. However, since joints coupling is neglected, control performance degrades as operating speed increases and a motor controlled in this way is only appropriate for relatively slow motion [44, 46]. The fast motion requirement results in even higher dynamic coupling between the various spherical motor joints, which cannot be compensated for by a standard motor controller such as PID [50], and hence model-based control becomes the alternative.

III. METHODOLOGY

Conversely pure sliding mode controller is a high-quality nonlinear controller; it has two important problems; nonlinear equivalent dynamic formulation in uncertain dynamic parameter and chattering phenomenon. To reduce the chattering phenomenon and equivalent dynamic problems, this research is focused on applied parallel fuzzy logic theorem and modified linear methodology in sliding mode controller as a compensator. In a typical PD method, the controller corrects the error between the desired input value and the measured value. Since the actual position is the measured signal. The derivative part of PD methodology is worked based on change of error and the derivative coefficient. In this research the modified PD is used based on boundary derivative part. Based on the SMC controller;

$$\begin{aligned} \tau_{new-dis} &= K \cdot \text{sgn}(S) + K \times S, \\ S &= \lambda e + \dot{e} \end{aligned} \tag{32}$$

$$\dot{e}(t) \triangleq \left(\frac{s}{0.1s+1} \right) \times e(t) \tag{33}$$

$$U_{PD} = \lambda e + \dot{e} \tag{34}$$

This is suitable for real-time control applications when powerful processors, which can execute complex algorithms rapidly, are not accessible. The result of modified PD method shows the power of disturbance rejection in this methodology.

Based on literature SMC formulation is written by;

$$\tau = [H^{-1}(B + C) + \dot{S}]H + K \cdot \text{SGN}(S) \tag{35}$$

The main challenge in this research is the role of nonlinearity term in presence of uncertainty. To solve this main challenge artificial intelligence based controller is introduced. This type of controller is intelligent therefore design a dynamic of system based on experience knowledge is done by this method. One of the main artificial intelligence techniques is fuzzy logic theory. In

this theory the behavior and dynamic of controller is defined by rule base. However defined and number of rule base play important role to design high quality controller but system has limitation to the number of rule base to implementation and the speed of response. Based on literature PID controller can reduce or eliminate the steady state error and design stable controller. But this type of controller has three types of inputs; proportional part, integral part and derivative part. To design PID like fuzzy controller and if any input is described with seven linguistic values, and any rule has three conditions we will need $7 \times 7 \times 7 = 343$ rules. It is too much work to write 343 rules, the speed of system is too low and design embedded controller based on FPGA or CPLD is very difficult. Based on (9) the PID controller has three inputs and three coefficients. In PD like fuzzy controller error and change of error are the inputs and if any input is described with seven linguistic values, and any rule has two conditions we will need $7 \times 7 = 49$ rules. Table 1 shows the rule table of PD like fuzzy controller based on seven linguistic variables for each input and totally 49 rules.

Table 1: Rule Table of PD like Fuzzy Controller

$e \backslash \Delta e$	PB	PM	PS	Z	NS	NM	NB
PB	NB	NB	NB	NB	NM	NS	Z
PM	NB	NB	NB	NM	NS	Z	PS
PS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
NS	NM	NS	Z	PS	PM	PB	PB
NM	NS	Z	PS	PM	PB	PB	PB
NB	Z	PS	PM	PB	PB	PB	PB

This table includes 49 rules. We are taking into account now not just the error but the change-of-error as well. It allows describing the dynamics of the controller. To explain how this rules set works and how to choose the rules, let us divide the set of all rules into the following five groups:

Group 1: In this group of rules both e and Δe are (positive or negative) small or zero. This means that the current value of the process output variable has deviated from the desired level (the set-point) but is still close to it. Because of this closeness the control signal should be zero or small in magnitude and is intended to correct small deviations from the set-point. Therefore, the rules in this group are related to the steady-state behavior of the process. The change-of-error, when it is Negative Small or Positive Small, shifts the output to negative or positive region, because in this case, for example, when $e(t)$ and $\Delta e(t)$ are both Negative Small the error is already negative and, due to the negative change-of-error, tends to become more negative. To prevent this trend, one needs to increase the magnitude of the control output.

Group 2: For this group of rules $e(t)$ is Positive Big or Medium which implies that actual input is significantly above the set point. At the same time since $\Delta e(t)$ is

negative, this means that actual input is moving towards the set-point. The control signal is intended to either speed up or slow down the approach to the set-point. For example, if actual input is much below the set-point ($e(t)$ is Positive Big) and it is moving towards the set-point with a small step ($\Delta e(t)$ is Negative Small) then the magnitude of this step has to be significantly increased (U is Negative Medium). However, when actual input is still much below the set-point ($e(t)$ is Positive Big) but it is moving towards the set-point very fast ($\Delta e(t)$ is Negative Big) no control action can be recommended because the error will be compensated due to the current trend.

Group 3: For this group of rules actual output is either close to the set-point ($e(t)$ is Positive Small, Zero, Negative Small) or significantly above it (Negative Medium, Negative Big). At the same time, since $\Delta e(t)$ is negative, actual input is moving away from the set-point. The control here is intended to reverse this trend and make actual input, instead of moving away from the set-point, start moving towards it. So here the main reason for the control action choice is not just the current error but the trend in its change.

Group 4: For this group of rules $e(t)$ is Negative Medium or Big, which means that actual input is significantly below the set-point. At the same time, since $\Delta e(t)$ is positive, actual input is moving towards the set-point. The control is intended to either speed up or slow down the approach to the set-point. For example, if actual input is much above the set-point ($e(t)$ is Negative Big) and it is moving towards the set-point with a somewhat large step ($\Delta e(t)$ is Positive Medium), then the magnitude of this step has to be only slightly enlarged (output is Negative Small).

Group 5: The situation here is similar to the Group 3 in some sense. For this group of rules $e(t)$ is either close to the set-point (Positive Small, Zero, Negative Small) or significantly above it (Positive Medium, Positive Big). At the same time since $\Delta e(t)$ is positive actual input is moving away from the set-point. This control signal is intended to reverse this trend and make actual input instead of moving away from the set-point start moving towards it.

The PID-like fuzzy controller can be constructed as a parallel structure of a PD-like fuzzy controller and a conventional PI controller with the output approximated as:

$$U_{PID} = \left(\frac{K_{pa}}{2} e + K_{va} \dot{e}\right) + \left(\frac{K_{pa}}{2} e + K_I \sum e\right) \quad (36)$$

In this type of design, we have 49 rule bases for PD like fuzzy controller. This PID like fuzzy controller applied to pure sliding mode controller to remove the challenge in this conventional nonlinear controller. Figure 4 shows the block diagram of PID like fuzzy sliding mode controller.

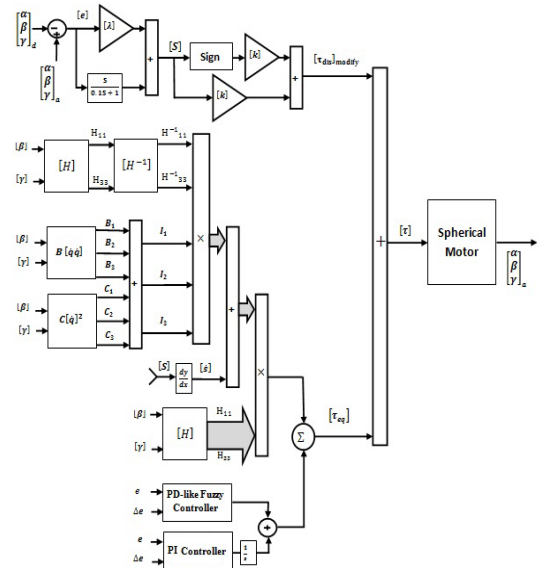


Fig 4: Block diagram of PID like Fuzzy Computed Torque Controller

IV. RESULTS AND DISCUSSION

PID like fuzzy sliding mode controller was tested to step response trajectory. This simulation is used to control position of three degrees of freedom spherical motor without and with external disturbance. The simulation was implemented in MATLAB/SIMULINK environment. These systems are tested by band limited white noise with a predefined 40% of relative to the input signal amplitude. This type of noise is used to external disturbance in continuous and hybrid systems and applied to nonlinear dynamic of these controllers.

Tracking performances: In proposed controller; the performance is depended on two important parameters; nonlinear equivalent part and PID like fuzzy controller. According to above however discussion PID like fuzzy sliding mode controller have accept performance in certain parameters but pure sliding mode controller have overshoot about 1% and steady state error is about 0.05. Based on Fig 5, pure sliding mode controller can eliminate the chattering but it has steady state error. To solve this challenge the output gain updating factor of PID like fuzzy sliding mode controller is decreased. In this design rise time in pure sliding mode controller is lower than proposed method.

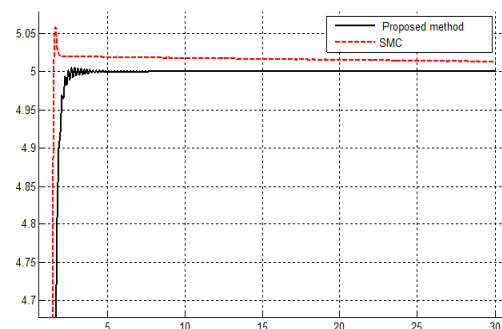


Fig 5: Sliding Mode controller and proposed method

Disturbance rejection: Figure 6 shows the power disturbance elimination in proposed method and pure sliding mode controller in presence of external disturbance and uncertainty parameters. The disturbance rejection is used to test and analyzed the robustness comparisons of these controllers for step trajectory. A band limited white noise with predefined of 40% the power of input signal value is applied to the step trajectory. According to the following graph, pure sliding mode controller has moderate fluctuation in presence of external disturbance and uncertainty.

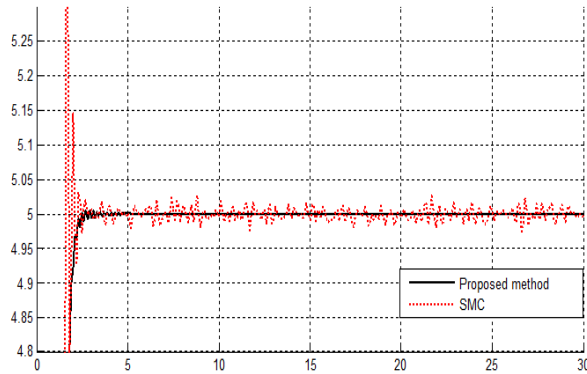


Fig 6: Sliding Mode controller and proposed method in presence of external disturbance

Based on above graph, pure sliding mode controller has many challenges in presence of external disturbance.

V. CONCLUSION

The central issues and challenges of non linear control and estimation problems are to satisfy the desired performance objectives in the presence of noises, disturbances, parameter perturbations, un-modeled dynamics, sensor failures, actuator failures and time delays. Evaluation algorithm PID like fuzzy sliding mode controller has shown growing popularity in both industry and academia. In this research chattering phenomenon is eliminated based on applied parallel linear methodology and artificial intelligence theory. To improve the optimality and robustness, we have proposed PD like fuzzy controller parallel with conventional PI controller based on 49 rule base with general performance criteria. Sliding mode controller provides us an effective tool to control nonlinear systems through the dynamic formulation of nonlinear system. Fuzzy logic controller is used to estimate highly nonlinear dynamic parameters. Mixed performance criteria have been used to design the controller and the relative weighting matrices of these criteria can be achieved by choosing different coefficient matrices. The simulation studies show that the proposed method provides a satisfactory alternative to the existing nonlinear control approaches.

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