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Design High-Efficiency Intelligent PID like Fuzzy Backstepping Controller for Three Dimension Motor

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***Abstract*—** The minimum rule base Proportional Integral Derivative (PID) Fuzzy backstepping Controller for three dimensions spherical motor is presented in this research. The popularity of PID Fuzzy backstepping 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 backstepping controller can be determined as an optimization task. Over the years, use of intelligent strategies for tuning of these controllers has been growing. PID methodology has three inputs 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. In this research the PID-like fuzzy controller can be constructed as a parallel structure of a PI-like controller and a PD-like fuzzy controller to have the minimum rule base. However backstepping controller is work based on cancelling decoupling and nonlinear terms of dynamic parameters of each dimension, this controller is work based on spherical motor dynamic model and this technique is highly sensitive to the knowledge of all parameters of nonlinear three dimension spherical motor's dynamic equation. This research is used to reduce or eliminate the backstepping controller problem based on minimum rule base fuzzy logic theory to control of spherical motor system and testing of the quality of process control in the simulation environment of MATLAB/SIMULINK Simulator.

***Index Terms*—** PID Like Fuzzy Control; Backstepping Controller; P+D Like Fuzzy Control; P+I Like Fuzzy Control; Three Dimension Spherical Motor

I. INTRODUCTION

Multi-degree-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 (control system) is a device which can sense information from linear or nonlinear system (e.g., three degrees of freedom spherical motor) to improve the systems performance and the immune system behavior [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.

Advanced control techniques such as integrator backstepping, feedback linearization, adaptive and robust have been applied to the control of numerous single -axis machines and robotic manipulators. Since available control techniques for continuum robot and robotic manipulators are so broad, the review in this research is restricted to some of the nonlinear control techniques for continuum robot. Most of the authors referenced on the nonlinear control techniques for continuum robot also do a significant amount of work on the control of robotic manipulators. Kokotovic [13] published one of the pioneering works on the backstepping control technique and Qu et al. [14] extended this technique and developed a robust backstepping-type controller for a one-link robot with the motor dynamics taken into consideration. Carroll et al. [15] also extended the work of Kokotovic [16] to design an embedded computed torque and output feedback controller for pennanent magnet brush de (BDC) motors. Hemati et al. [16] developed a robust feedback linearizing controller for a single-link robot actuated by a brushless de motor (BLOC). In [17], Carroll et al. also developed a robust tracking controller for a BLOC, which achieved globally bounded results for rotor position tracking error despite parametric uncertainties and additive bounded disturbances. In addition to DC machines, SR and PM stepper motors are also candidates for advanced nonlinear controllers. In [18], Die'-Spong et al. introduced a detailed nonlinear model and an electronic commutation strategy for the SR motor and applied a state feedback control algorithm which compensated for all the nonlinearities of the system. The work in [18] was then generalized to a direct-drive manipulator with SR actuation by Taylor et al. [19]. Carroll et al. [20] also used a backstepping technique to develop an adaptive tracking controller for the SR motor. Bodson [21] developed a model-based control law for the PM stepper motor using an exact linearization methodology while considering practical issues such as voltage saturation. Even though some of the above control techniques are not of the backstepping type controller, the backstepping-type controller developed in this thesis was somewhat inspired by them.

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[38-57]. 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 [57-60]. In project we can used 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 is based on design PID like fuzzy controller based on the minimum rule base and applied this controller to conventional backstepping controller to solve the robust challenge in backstepping 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, backstepping 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]:

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

Where τ is actuation torque, H (q) is a symmetric and positive define inertia matrix, B(q) is the matrix of coriolios 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]:

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

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:

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

Where $\Psi(.) \in R^n$ is a nonlinear vector function, $X = [X_1, X_2, \dots\dots, X_l]^T$ 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;

$$\boldsymbol{R}_i^{i-1} = \boldsymbol{U}_{i(\theta_i)}\boldsymbol{V}_{i(\alpha_i)} \quad (4)$$

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

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

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

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

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

$$\boldsymbol{R}_n^0 = (\boldsymbol{U}_1\boldsymbol{V}_1)(\boldsymbol{U}_2\boldsymbol{V}_2)\dots\dots\dots(\boldsymbol{U}_n\boldsymbol{V}_n) \quad (7)$$

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

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

Backstepping Controller: The three dimension spherical motor dynamics in (1) have the appropriate structure for the so-called backstepping controller design method. With the position error defined as $Z_1 = X_d - X_a$, all joints will track the desired specified state X_d if the error dynamics are given as follows:

$$\left(\dot{\mathbf{Z}}_1 + [\mathbf{K_p}]\mathbf{Z_1}\right) = \mathbf{0} \quad (9)$$

where $[\mathrm{K_p}]$ is a positive definite gain matrix. The error dynamics in (9) can be rewritten as:

$$\mathbf{X_2} = \dot{\mathbf{X}}_\mathbf{d} + [\mathbf{K_p}]\mathbf{Z_1} \quad (10)$$

Substitution of (10) into (1) makes the position error dynamics go to zero. Since the state vector $\mathrm{x_2}$ is not a control variable, (10) cannot be directly substituted into (1). The expression in (10) is therefore defined as a fictitious control input and is labeled expressed below as $\mathrm{X_{2_d}}$.

$$\mathbf{X_{2_d}} = \dot{\mathbf{X}}_{\mathbf{1_d}} + [\mathbf{K_p}](\boldsymbol{X_d} - \boldsymbol{X_a}) \quad (11)$$

The fictitious control input in (11) is selected as the specified velocity trajectory and hence the velocity error can be defined as $Z_2 = X_{2_d} - X_{2_a}$ With the following dynamics

$$\left(\dot{\mathbf{Z}}_2 + [\mathbf{K_p}]\mathbf{Z_2}\right) = \mathbf{0} \quad (12)$$

The joint position error will approach zero asymptotically, which will lead to the eventual asymptotic convergence of the joint position error. The error dynamics in (12) can be rewritten as:

$$\mathbf{X_2} = \dot{\mathbf{X_d}} + [\mathbf{K_p}]\mathbf{Z_2} \tag{13}$$

Substitution of (12) into (1) leads to the following expression as the desired stabilizing torque:

$$\boldsymbol{\tau} = [\mathbf{H}](\dot{\mathbf{X}}_{\mathbf{2_d}} + [\mathbf{K_p}]\mathbf{Z_2}) + \mathbf{C}(\mathbf{X_1}, \mathbf{X_2}) \tag{14}$$

The desired torque control input is a nonlinear compensator since it depends on the dynamics of the spherical motor. The time derivative of desired velocity vector is calculated using (12). In terms of the desired state trajectory, and its time derivatives and the position and velocity state variables, the desired torque can be rewritten in following form:

$$\boldsymbol{\tau} = [\mathbf{H}]\mathbf{y} + \mathbf{C}(\mathbf{X_1}, \mathbf{X_2}) \tag{15}$$

where

$$\mathbf{y} = \ddot{\mathbf{X}}_{\mathbf{1_d}} + \left([\mathbf{K_p}] + [\mathbf{K_d}]\right)\left(\dot{\mathbf{X}}_{\mathbf{1_d}} - \dot{\mathbf{X}}_{\mathbf{1}}\right) + ([\mathbf{K_p}][\mathbf{K_d}]\boldsymbol{X_d} - \boldsymbol{X_a} \tag{16}$$

The backstepping controller developed above is very similar to inverse dynamics control algorithm developed for spherical motor. The backstepping controller is ideal from a control point of view as the nonlinear dynamics of the spherical motor are cancelled and replaced by linear subsystems. The drawback of the backstepping controller is that it requires perfect cancellation of the nonlinear spherical motor dynamics. Accurate real time representations of the motor dynamics are difficulty due to uncertainties in the system dynamics resulting from imperfect knowledge of the motor mechanical parameters; existence of unmodeled dynamics and dynamic uncertainties due to payloads. The requirement for perfect dynamic cancellation raises sensitivity and robustness issues that are addressed in the design of a robust backstepping controller. Another drawback of the backstepping controller is felt during real-time implementation of the control algorithm. Implementation of the backstepping controller requires the computation of the exact three dimension motor dynamics at each sampling time.

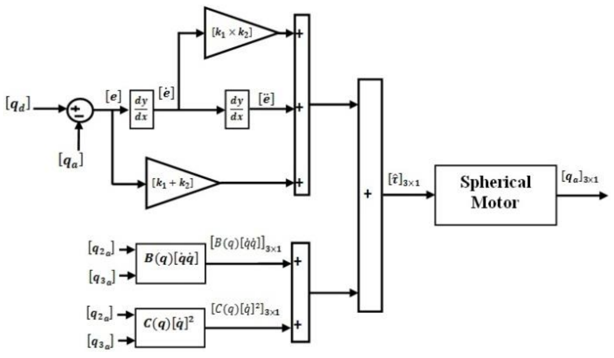

Fig. 1. Block diagram of robust backstepping controller

This computational burden has an effect on the performance of the control algorithm and imposes constraints on the hardware/software architecture of the control system. By only computing the dominant parts of the motor dynamics, this computational burden can be reduced. These drawbacks of the backstepping controller makes it necessary to consider control algorithms that compensate for both model uncertainties and for approximations made during the on-line computation of motor dynamics. Figure 1 shows the block diagram of backstepping controller

Robust Backstepping Control: When there are uncertainties in the spherical motor dynamics due to modeling inaccuracy and computational relaxation, robust controllers are ideal for ensuring system stability. When the system dynamics are completely known, the required torque control vector for the control of the spherical motor is given by (15) and (16). In the presence of modeling uncertainties, a reasonable approximation of the torque control input vector is given by

$$\boldsymbol{y} = \ddot{\boldsymbol{X}}_{\boldsymbol{1_d}} + \left([\boldsymbol{K_p}] + [\boldsymbol{K_d}]\right)\left(\dot{\boldsymbol{X}}_{\boldsymbol{1_d}} - \dot{\boldsymbol{X}}_{\boldsymbol{1}}\right) + ([\boldsymbol{K_p}][\boldsymbol{K_d}]\boldsymbol{X_d} - \boldsymbol{X_a} \tag{17}$$

$$\boldsymbol{T_d} = [\widehat{\boldsymbol{H}}]\boldsymbol{y} + \widehat{\boldsymbol{C}} \tag{18}$$

where $[\widehat{H}]$ and $\hat{C}$ are estimates of the inertia and coriolis terms in the spherical motor dynamics; and y is given by (16). The uncertainty on the estimates are expressed as

$$[\widetilde{\boldsymbol{H}}] = [\widehat{\boldsymbol{H}}] - [\boldsymbol{H}] \tag{19}$$

$$[\widetilde{\boldsymbol{C}}] = [\widehat{\boldsymbol{C}}] - [\boldsymbol{C}] \tag{20}$$

These uncertainties account for both imperfect modeling and intentional computational simplification. Application of the approximate control vector given by (18) leads to the following expression for the closed loop dynamics:

$$[\boldsymbol{H}]\dot{\boldsymbol{x}}_{\boldsymbol{2}} + \boldsymbol{C} = [\widehat{\boldsymbol{H}}]\boldsymbol{y} + \widehat{\boldsymbol{C}} \tag{21}$$

Since the inertia matrix [H] is symmetric and positive definite, the closed loop dynamics in (21) can be rewritten as

$$\ddot{\boldsymbol{x}}_{\boldsymbol{1}} = \boldsymbol{y} - \boldsymbol{\eta} \tag{22}$$

where

$$\boldsymbol{\eta} = \left([\boldsymbol{I}] - [\boldsymbol{H}]^{-1}[\widehat{\boldsymbol{H}}]\right)\boldsymbol{y} - [\boldsymbol{H}]^{-1}\widetilde{\boldsymbol{C}} \tag{23}$$

Substitution of (20) for $\boldsymbol{y}$ in (22) results in the following expression for the closed loop error dynamics.

$$\ddot{\widetilde{\boldsymbol{x}}}_{\boldsymbol{1}} + \left([\boldsymbol{K_p}] + [\boldsymbol{K_d}]\right)\dot{\widetilde{\boldsymbol{x}}}_{\boldsymbol{1}} + [\boldsymbol{K_p}][\boldsymbol{K_d}]\widetilde{\boldsymbol{x}}_{\boldsymbol{1}} = \boldsymbol{\eta} \tag{24}$$

Defining a new error state vector,

$$\boldsymbol{\xi} = \begin{bmatrix} \widetilde{\boldsymbol{x}}_{\boldsymbol{1}} \\ \dot{\widetilde{\boldsymbol{x}}}_{\boldsymbol{1}} \end{bmatrix} \tag{25}$$

The error dynamics in (24) can be expressed as

$$\dot{\xi} = [\boldsymbol{F}]\xi + [\boldsymbol{D}](\ddot{x}_{1d} - \boldsymbol{y} + \boldsymbol{\eta}) \tag{26}$$

Where $[\boldsymbol{F}] = \begin{bmatrix} [\mathbf{0}] & [\mathbf{1}] \\ [\mathbf{0}] & [\mathbf{0}] \end{bmatrix}$ and $[\boldsymbol{D}] = \begin{bmatrix} [\mathbf{0}] \\ [\mathbf{1}] \end{bmatrix}$ are block matrices of dimensions $R^{3\times3}$. Since $\boldsymbol{\eta}$ is a nonlinear function of the position and velocity state vectors, the system error dynamics in the above equation are nonlinear and coupled. The backstepping controller developed in the previous section cannot guarantee system stability. The Lyapunov direct method is, however, used to design an outer feedback loop on the error dynamics that compensates for the system uncertainty contributed by $\boldsymbol{\eta}$.

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 [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.

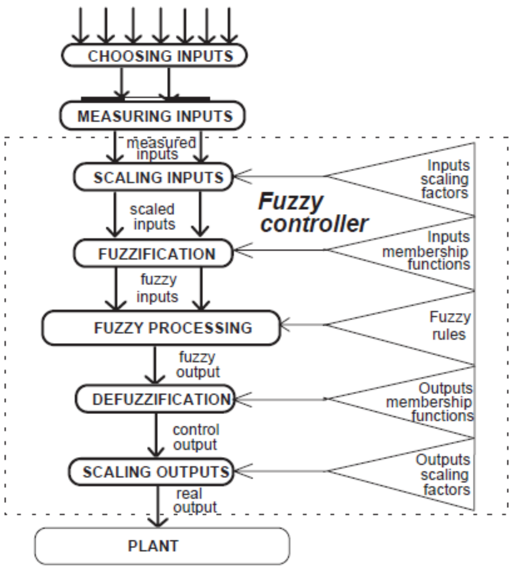

Fig. 2. Fuzzy Controller operation

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 use a singleton as a membership function of the rule consequent part. The following definition shows the Mamdani and Sugeno fuzzy rule base

$$\begin{aligned} &\boldsymbol{if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ C\ 'mamdani'} \\ &\boldsymbol{if\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ f(x,y)'sugeno'} \end{aligned} \tag{27}$$

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;

$$\begin{aligned} &\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U)} \\ &= \mathbf{max}\left\{\mathbf{min}_{i=1}^{r}\left[\boldsymbol{\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)}\right]\right\} \end{aligned} \tag{28}$$

The Sum-min aggregation defined as below

$$\begin{aligned} &\boldsymbol{\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U)} \\ &= \sum \mathbf{min}_{i=1}^{r}\left[\boldsymbol{\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U)}\right] \end{aligned} \tag{29}$$

where r is the number of fuzzy rules activated by x_k and y_k and also $\mu_{\cup_{i=1}^{r} FR^i}(x_k, y_k, U)$ 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

$$\boldsymbol{COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k, y_k, U_i)}} \tag{30}$$

and COA method used the following equation to calculate the defuzzification

$$\boldsymbol{COA(x_k, y_k) = \frac{\sum_i U_i \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \mu_U \cdot (x_k, y_k, U_i)}} \tag{31}$$

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, $\mu_U \cdot (x_k, y_k, U_i)$ 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 continuum robot manipulator [21-34].

$$e(t) = \theta_a(t) - \theta_d(t) \tag{32}$$

$$U_{PID} = K_{p_a}e + K_{V_a}\dot{e} + K_I \sum e \tag{33}$$

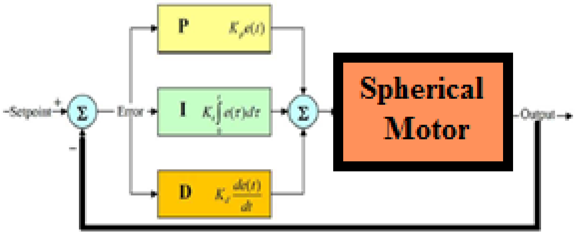

Fig. 3. Block diagram of linear PID method

The model-free control strategy is based on the assumption that the joints of the manipulators 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 manipulator. With the independent joint assumption, no a priori knowledge of robot manipulator 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 manipulator 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 robot joints, which cannot be compensated for by a standard robot controller such as PID [50], and hence model-based control becomes the alternative.

III. Methodology

Conversely pure backstepping controller is a high-quality nonlinear controller; it has an important problem; nonlinear equivalent dynamic formulation in uncertain dynamic parameter and partly uncertain system. Backstepping controller is a nonlinear controller but it has a challenge in stability and robustness in presence of uncertainty and external disturbance. Based on literature backstepping dynamic formulation is written by;

$$\tau = (\ddot{e} + (K_1 \times K_2)\dot{e} + (K_1 + K_2)e) + N(q, \dot{q}) \tag{34}$$

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 introduce. 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 × 7 × 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 plus change of error is the input, and if any input is described with seven linguistic values, and any rule has two conditions we will need 7 × 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 \ Δe	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

$\boldsymbol{\Delta e(t)}$ 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 ($\boldsymbol{e(t)}$ is **Positive Big**) and it is moving towards the set-point with a small step ($\boldsymbol{\Delta e(t)}$ is **Negative Small**) then the magnitude of this step has to be significantly increased ($\boldsymbol{U}$ is **Negative Medium**). However, when *actual input* is still much below the set-point ($\boldsymbol{e(t)}$ is **Positive Big**) but it is moving towards the set-point very fast ($\boldsymbol{\Delta e(t)}$ 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 ($\boldsymbol{e(t)}$ is **Positive Small, Zero, Negative Small**) or significantly above it (**Negative Medium, Negative Big**). At the same time, since $\boldsymbol{\Delta e(t)}$ 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 $\boldsymbol{e(t)}$ is **Negative Medium** or **Big,** which means that *actual input* is significantly below the set-point. At the same time, since $\boldsymbol{\Delta e(t)}$ 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 ($\boldsymbol{e(t)}$ is **Negative Big**) and it is moving towards the set-point with a somewhat large step ($\boldsymbol{\Delta e(t)}$ 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 $\boldsymbol{e(t)}$ 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 $\boldsymbol{\Delta e(t)}$ 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 PD like fuzzy controller shows in Figure 4.

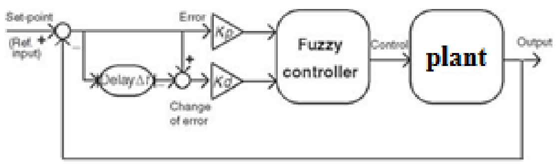

Fig. 4. Block diagram of PD like Fuzzy Controller

In PI controller error and integral of error are the inputs. We can move the integration from the part preceding to a fuzzy controller to the part following it. We can integrate the output of a controller, not the input. Then we may have the error and the change of error inputs and still realise the PI-control. Figure 5 shows the other form of PI like controller.

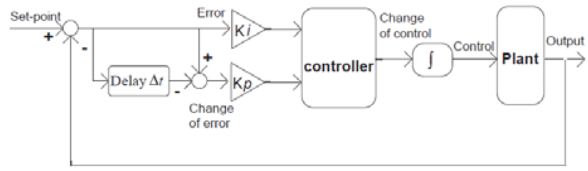

Fig. 5. Block diagram of New Type PI like Controller

Based on above discussion the PID-like fuzzy controller can be constructed as a parallel structure of a PD-like fuzzy controller and a PI-like controller (Fig. 6) with the output approximated as:

$$\boldsymbol{U_{PID}} = \left(\frac{\boldsymbol{K_{p_a}}}{\boldsymbol{2}}\boldsymbol{e} + \boldsymbol{K_{V_a}}\dot{\boldsymbol{e}}\right) + \left(\frac{\boldsymbol{K_{p_a}}}{\boldsymbol{2}}\boldsymbol{e} + \boldsymbol{K_I}\sum \boldsymbol{e}\right) \qquad \textbf{(35)}$$

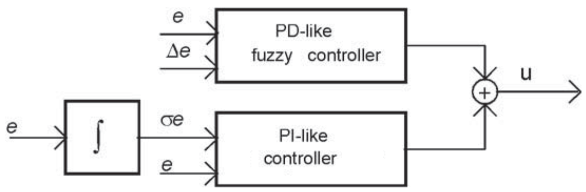

Fig. 6. The structure for a PID-like fuzzy controller

In this type of design, we have 49 rule bases for PD like fuzzy controller and PI like controller as well as. This PID like fuzzy controller applied to pure backstepping controller to remove the challenge in this conventional nonlinear controller. Figure 7 shows the block diagram of PID like fuzzy backstepping controller.

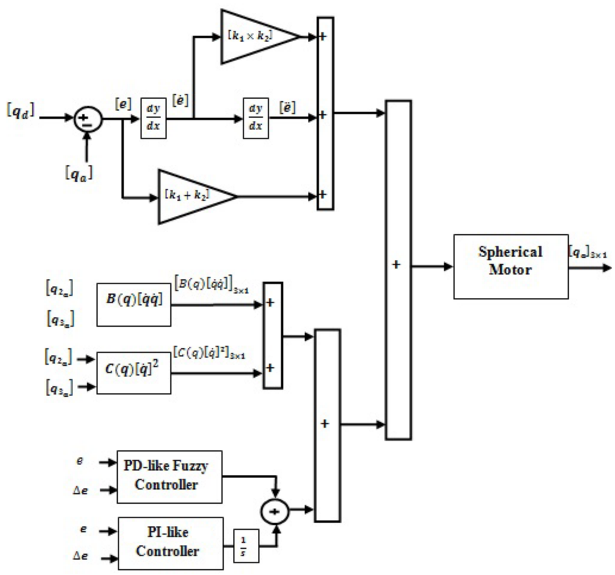

Fig. 7. Block diagram of PID like Fuzzy Backstepping Controller

IV. Results And Discussion

PID like fuzzy backstepping controller was tested to Step response trajectory. In this simulation is used to control position of 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 discussion PID like fuzzy backstepping controller and pure backstepping controller have the same performance in certain system. Based on Fig 8, pure backstepping controller has a slight transient oscillation, to solve this challenge the output gain updating factor of PID like fuzzy backstepping controller is decreased. In this design pure backstepping controller has about 5% overshoot but both of two controllers have the same rise time.

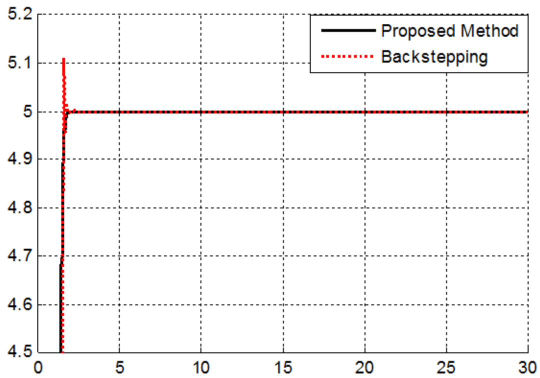

Fig. 8. Backstepping controller and proposed method

Disturbance rejection: Figure 9 shows the power disturbance elimination in proposed method and pure backstepping 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 backstepping controller has moderate fluctuation in presence of external disturbance and uncertainty.

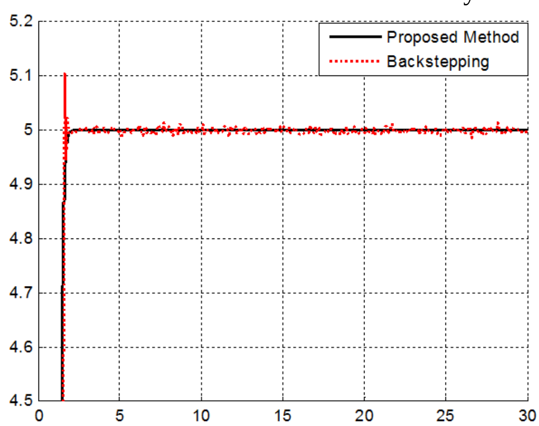

Fig. 9. Backstepping controller and proposed method in presence of external disturbance

Based on above graph, pure backstepping controller has many challenges in presence of external disturbance. To eliminate above challenge, this research is used the following methodology; decrease the output scaling factor of the PD-part, increase the scaling factor for an integral input compared to other inputs, apply the centre of gravity defuzzification method, reduce the width of the membership function for the zero class of the error signal and Redistribute the membership functions, increasing their concentration around the zero point.

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 backstepping controller has shown growing popularity in both industry and academia. To improve the optimality and robustness, we have proposed PD like fuzzy controller parallel with PI like controller based on 49 rule base for nonlinear systems with general performance criteria. Backstepping 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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