Design Adaptive Artificial Inverse Dynamic Controller: Design Sliding Mode Fuzzy Adaptive New Inverse Dynamic Fuzzy Controller

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Abstract

In this research, a model free sliding mode fuzzy adaptive inverse dynamic fuzzy controller (SMFIDFC) is designed for a robot manipulator to rich the best performance. Inverse dynamic controller is considered because of its high performance in certain system. Fuzzy methodology has been included in inverse dynamic to keep away from design nonlinear controller based on dynamic model. Sliding mode fuzzy adaptive methodology is applied to model free controller to have better result in presence of structure and unstructured uncertainties. Besides, this control method can be applied to non-linear systems easily. Today, strong mathematical tools are used in new control methodologies to design adaptive nonlinear controller with satisfactory output results (e.g., minimum error, good trajectory, disturbance rejection).

Keywords: Inverse Dynamic Controller, Fuzzy Logic Methodology, Inverse Dynamic Fuzzy Controller, Adaptive Methodology, Sliding Mode Fuzzy Adaptive Inverse Dynamic Fuzzy Methodology.

1. INTRODUCTION, BACKGROUND AND MOTIVATION

Robot manipulators have many applications in aerospace, manufacturing, automotive, medicine and other industries. Robot manipulators consist of three main parts: mechanical, electrical, and control. In the mechanical point of view, robot manipulators are collection of serial or parallel links which have connected by revolute and/or prismatic joints between base and end-effector frame. A serial link robot is a sequence of joints and links which begins with a base frame and ends with an end-effector. This type of robot manipulators, comparing with the load capacitance is more weightily because each link must be supported the weights of all next links and actuators between the present link and end-effector[6]. Serial robot manipulators have been used in automotive industry, medical application, and also in research laboratories. In 1978 the serial link PUMA (Programmable Universal Machine for Assembly) was introduced and it was quickly used in research laboratories and industries. Dynamic equation is the study of motion with regard to forces. Dynamic modeling is vital for control, mechanical design, and simulation. It is used to describe dynamic parameters and also to describe the relationship between displacement, velocity and acceleration to force acting on robot manipulator [1-2].

Inverse dynamics control (IDC) is based on cancelling decoupling and nonlinear terms of dynamics of each link. Inverse dynamics control is a powerful nonlinear controller which it widely used in control robot manipulator. It is based on Feed-back linearization and computes the required arm torques using the nonlinear feedback control law. This controller works very well when all dynamic and physical parameters are known but when the robot manipulator has variation in dynamic parameters, the controller has no acceptable performance[14]. In practice, most of physical systems (e.g., robot manipulators) parameters are unknown or time variant, therefore, Inverse dynamics fuzzy control used to compensate dynamic equation of robot manipulator[1-2]. Research on Inverse dynamics control is significantly growing on robot manipulator application which has been reported in [1-2, 4, 7-8, 9, 18, 29]. Vivas and Mosquera [7]have proposed a predictive functional controller and compare to computed torque controller for tracking response in uncertain environment. However both controllers have been used in Feed-back linearization, but predictive strategy gives better result as a performance. An Inverse dynamics control with non parametric regression models have been presented for a robot arm[7]. This controller also has been problem in uncertain dynamic models. Based on [1-2]and [7-9] Inverse dynamics control is a significant nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known the controller works fantastically; practically a large amount of systems have uncertainties and sliding mode controller decrease this kind of challenge. Piltan et al. [21] have proposed a simple adaptive fuzzy gain scheduling for robot manipulator. An independent joint position and stiffness adaptive control computed torque control has been presented for a robot arm [4]. Soltani and Piltan [46] have addressed the problem of output feedback tracking control of a robot arm which by computed torque like controller.

Application of fuzzy logic to automatic control was first reported in [10], where, based on Zadeh's proposition, Mamdani buit a controller for a steam engine and boiler combination by synthesizing a set of linguistic expressions in the form of IF-THEN rules as follows: IF (system state) THEN (control action), which will be referred to as "Mamdani controller' hereafter. In Mamdani's controller the knowledge of the system state (the IF part) and the set of actions (the THEN part) are obtained from the experienced human operators [11]. Fuzzy control has gradually been recognized as the most significant and fruitful application for fuzzy logic. In the past three decades, more diversified application domains for fuzzy logic controllers have been created, which range from water cleaning process, home appliances such as air conditioning systems and online recognition of handwritten symbols [10-15, 20, 36].

Many dynamic systems to be controlled have unknown or varying uncertain parameters. For instance, robot manipulators may carry large objects with unknown inertial parameters. Generally, the basic objective of adaptive control is to maintain performance of the closed-loop system in the presence of uncertainty (e.g., variation in parameters of a robot manipulator). The above objective can be achieved by estimating the uncertain parameters (or equivalently, the corresponding controller parameters) on-line, and based on the measured system signals. The estimated parameters are used in the computation of the control input. An adaptive system can thus be regarded as a control system with on-line parameter estimation [3, 16-29]. In conventional nonlinear adaptive controllers, the controller attempts to learn the uncertain parameters of particular structured dynamics, and can achieve fine control and compensate for the structure uncertainties and bounded disturbances. On the other hand, adaptive control techniques are restricted to the parameterization of known functional dependency but of unknown Constance. Consequently, these factors affect the existing nonlinear adaptive controllers in cases with a poorly known dynamic model or when the fast real-time control is required. Adaptive control methodologies and their applications to the robot manipulators have widely been studied and discussed in the following references [4-5, 16-45].

In this research we will highlight the SISO sliding mode fuzzy adaptive algorithm to on line tuning inverse dynamic fuzzy controller with estimates the nonlinear dynamic part derived in the Lyapunov sense. This algorithm will be analyzed and evaluated on robotic manipulators. Section 2, is served as a problem statements, objectives, robot manipulator dynamics and introduction to the classical inverse dynamic control and its application to robot manipulator. Part 3, introduces and describes the methodology algorithms, introduced sliding mode controller to design adaptive part and proves Lyapunov stability. Section 4 presents the simulation results of this algorithm applied to a 3 degree-of-freedom robot manipulator and the final section is describe the conclusion.

2. ROBOT MANIPULATOR DYNAMICS, OBJECTIVES, PROBLEM STATEMENTS and FEEDBACK LINEARIZATION FORMULATION

Robot Manipulator Dynamic Formulation: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 3, 16-28, 30, 3840]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \quad (1)$$

Where τ is actuation torque, M (q) is a symmetric and positive define inertia matrix, $N(q,\dot{q})$ is the vector of nonlinearity term. This robot manipulator dynamic equation can also be written in a following form:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \quad (2)$$

Where B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques, and G(q) is the vector of gravity force. The dynamic terms in equation (2) are only manipulator position. 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 joint variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [3, 16-28]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \quad (3)$$

Inverse Dynamic Control: This technique is very attractive from a control point of view. The central idea of inverse dynamic controller (IDC) is feedback linearization so, originally this algorithm is called inverse dynamic controller. It has assumed that the desired motion trajectory for the manipulator $q_d(t)$, as determined, by a path planner. Defines the tracking error as [4-9, 18, 21, 31]:

$$e(t) = q_d(t) - q_a(t) \quad (4)$$

Where e(t) is error of the plant, $q_d(t)$ is desired input variable, that in our system is desired displacement, $q_a(t)$ is actual displacement. If an alternative linear state-space equation in the form $\dot{x} = Ax + BU$ can be defined as

$$\dot{x} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ I \end{bmatrix} U \quad (5)$$

With $U = -M^{-1}(q).N(q,\dot{q}) + M^{-1}(q).\tau$ and this is known as the Brunousky canonical form. By equation (4) and (5) the Brunousky canonical form can be written in terms of the state $x = [e^T\ \dot{e}^T]^T$ as [1]:

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}.\begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} U \quad (6)$$

With

$$U = \ddot{q}_d + M^{-1}(q).\{N(q.\dot{q}) - \tau\} \quad \textbf{(7)}$$

Then compute the required arm torques using inverse of equation (7), is;

$$\tau = M(q)(\ddot{q}_d - U) + N(\dot{q}, q) \quad \textbf{(8)}$$

This is a nonlinear feedback control law that guarantees tracking of desired trajectory. Selecting proportional-plus-derivative (PD) feedback for U(t) results in the PD-computed torque controller [4, 6-9];

$$\tau = M(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q, \dot{q}) \quad \textbf{(9)}$$

and the resulting linear error dynamics are

$$\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) = 0 \quad \textbf{(10)}$$

According to the linear system theory, convergence of the tracking error to zero is guaranteed [6]. Where K_p and K_v are the controller gains. The result schemes is shown in Figure 1, in which two feedback loops, namely, inner loop and outer loop, which an inner loop is a compensate loop and an outer loop is a tracking error loop. However, mostly parameter $N(q, \dot{q})$ is all unknown. So the control cannot be implementation because non linear parameters cannot be determined. In the following section computed torque like controller will be introduced to overcome the problems.

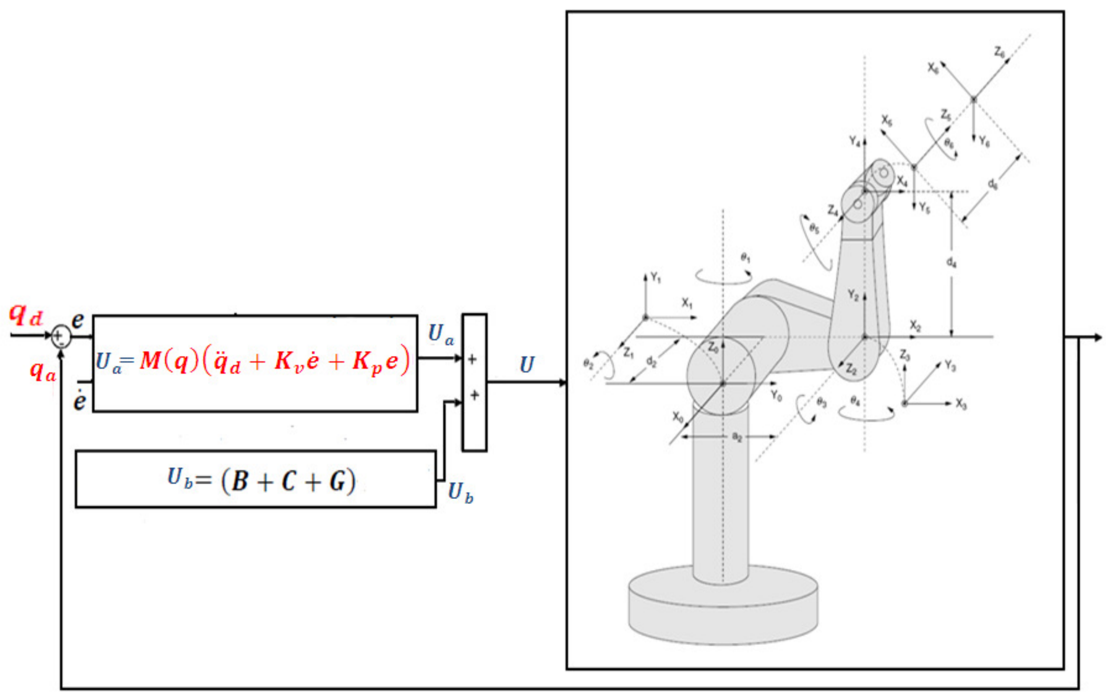

FIGURE 1: Block diagram of PD-inverse dynamic controller (PD-IDC)

The application of proportional-plus-derivative (PD) IDC to control of robot manipulator introduced in this part. PUMA 560 robot manipulator is a nonlinear and uncertain system which needs to have powerful nonlinear robust controller such as inverse dynamic controller. Suppose that in (9) the nonlinearity term defined by the following term

$$N(q, \dot{q}) = B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q) = \quad \textbf{(11)}$$

$$\begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\,2} + C_{13}\dot{q}_3^{\,2} \\ C_{21}\dot{q}_1^{\,2} + C_{23}\dot{q}_3^{\,2} \\ C_{31}\dot{q}_1^{\,2} + C_{32}\dot{q}_2^{\,2} \\ 0 \\ C_{51}\dot{q}_1^{\,2} + C_{52}\dot{q}_2^{\,2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

Therefore the equation of PD-IDC for control of PUMA 560 robot manipulator is written as the equation of (12);

$$\begin{bmatrix} \hat{\tau}_1 \\ \hat{\tau}_2 \\ \hat{\tau}_3 \\ \hat{\tau}_4 \\ \hat{\tau}_5 \\ \hat{\tau}_6 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \begin{bmatrix} \ddot{q}_{d1} + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ \ddot{q}_{d2} + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ \ddot{q}_{d3} + K_{v3}\dot{e}_3 + K_{p3}e_3 \\ \ddot{q}_{d4} + K_{v4}\dot{e}_4 + K_{p4}e_4 \\ \ddot{q}_{d5} + K_{v5}\dot{e}_5 + K_{p5}e_5 \\ \ddot{q}_{d6} + K_{v6}\dot{e}_6 + K_{p6}e_6 \end{bmatrix} \quad \textbf{(12)}$$

$$+ \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\,2} + C_{13}\dot{q}_3^{\,2} \\ C_{21}\dot{q}_1^{\,2} + C_{23}\dot{q}_3^{\,2} \\ C_{31}\dot{q}_1^{\,2} + C_{32}\dot{q}_2^{\,2} \\ 0 \\ C_{51}\dot{q}_1^{\,2} + C_{52}\dot{q}_2^{\,2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

The controller based on a formulation (12) is related to robot dynamics therefore it has problems in uncertain conditions.

Problem Statement: inverse dynamic 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. Even though, this controller is used in wide range areas but, pure inverse dynamic controller has the disadvantage that the main potential difficulty encountered in implementation of the inverse dynamic control methodology described above is that the dynamic model of the robot manipulator to be controlled is often not known accuratly.
Pure fuzzy logic controller (FLC) works in many areas, but it cannot guarantee the basic requirement of stability and acceptable performance[8]. Although both inverse dynamic controller and fuzzy logic controller have been applied successfully in many applications but they also have some limitations. Proposed method focuses on substitution fuzzy logic system applied to main controller to compensate the uncertainty in nonlinear dynamic equation to implement easily and avoid mathematical model base controller. To reduce the effect of uncertainty in proposed method, sliding mode adaptive method is applied in feedback linearization fuzzy controller in robot manipulator.

Objectives: The main goal in this original paper is to design a new adaptive position controller for robot manipulator with acceptable performances (e.g., trajectory performance, torque performance, disturbance rejection, steady state error and RMS error). Robot manipulator has nonlinear and uncertain dynamic parameters consequently; following objectives have been pursuit in the mentioned study.

- To design and implement a position inverse dynamic fuzzy controller in order to solve the uncertainty in nonlinear parameters problems in the pure inverse dynamic control.
- To develop a position sliding mode fuzzy adaptive inverse dynamic fuzzy controller in order to solve the disturbance rejection.

3. METHODOLOGY: DESIGN A NOVEL SLIDING MODE FUZZY ADAPTIVE INVERSE DYNAMIC FUZZY ESTIMATION CONTROLLER

First Step, Design Inverse Dynamic Fuzzy Controller: In recent years, artificial intelligence theory has been used in robotic systems. Neural network, fuzzy logic, and neuro-fuzzy are combined with nonlinear methods and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). This controller can be used to control of nonlinear, uncertain, and noisy systems. This method is free of some model-based techniques that used in classical controllers. The main reasons to use fuzzy logic technology are able to give approximate recommended solution for unclear and complicated systems to easy understanding and flexible. Fuzzy logic provides a method which is able to model a controller for nonlinear plant with a set of IF-THEN rules, or it can identify the control actions and describe them by using fuzzy rules. Besides applying fuzzy logic in the main controller of a control loop, it can be used to design adaptive control, tuning parameters, working in a parallel with the classical and non classical control method. However the application area for fuzzy control is really wide, the basic form for all command types of controllers consists of [10-15, 20, 36];

- Input fuzzification (binary-to-fuzzy[B/F]conversion)
- Fuzzy rule base (knowledge base)
- Inference engine
- Output defuzzification (fuzzy-to-binary[F/B]conversion).

As a summary the design of fuzzy logic controller based on Mamdani's fuzzy inference method has four steps, namely, fuzzification, fuzzy rule base and rule evaluation, aggregation of the rule output (fuzzy inference system), and deffuzzification.

Fuzzification: the first step in fuzzification is determine inputs and outputs which, it has one input (U_α) and one output (U_{fuzzy}). The input is U_α which measures the summation of linear loop and nonlinear loop in main controller. The second step is chosen an appropriate membership function for inputs and output which, for simplicity in implementation and also to have an acceptable performance the researcher is selected the triangular membership function. The third step is chosen the correct labels for each fuzzy set which, in this research namely as linguistic variable. The linguistic variables for input (U_α) are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and it is quantized in to thirteen levels represented by: -1, -0.83, -0.66, -0.5, -0.33, -0.16, 0, 0.16, 0.33, 0.5, 0.66, 0.83, 1 and the linguistic variables to find the output are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR) and it is quantized in to thirteen levels represented by: -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6.

Fuzzy Rule Base and Rule Evaluation: the first step in rule base and evaluation is provide a least structured method to derive the fuzzy rule base which, expert experience and control engineering knowledge is used because this method is the least structure of the other one and the researcher derivation the fuzzy rule base from the knowledge of system operate and/or the classical controller. Design the rule base of fuzzy inference system can play important role to design the best performance of fuzzy sliding mode controller, that to calculate the fuzzy rule base the researcher is used to heuristic method which, it is based on the behavior of the control of robot manipulator suppose that the fuzzy rules in this controller is [36];

F.R^1: *IF U_α is NB, THEN U_{fuzzy} is LL.* **(13)**

The complete rule base for this controller is shown in Table 1. Rule evaluation focuses on operation in the antecedent of the fuzzy rules in fuzzy sliding mode controller. This part is used AND/OR fuzzy operation in antecedent part which AND operation is used.

Aggregation of the Rule Output (Fuzzy Inference): Max-Min aggregation is used to this work which the calculation is defined as follows;

$$\mu_U(x_k,y_k,U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k,y_k,U) = max\left\{min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k,y_k),\mu_{p_m}(U)\right]\right\} \quad (14)$$

Deffuzzification: The last step to design fuzzy inference in our fuzzy sliding mode controller is defuzzification. This part is used to transform fuzzy set to crisp set, therefore the input for defuzzification is the aggregate output and the output of it is a crisp number. In this design the Center of gravity method (COG) is used and calculated by the following equation [36];

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^{r} \mu_u(x_k, y_k, U_i)} \quad \textbf{(15)}$$

This table has 7 cells, and used to describe the dynamics behavior of fuzzy controller.

U_α	NB	NM	NS	Z	PS	PM	PB
U_{fuzzy}	LL	ML	SL	Z	SR	MR	LR

TABLE 1: Rule table

Figure 2 is shown the feedback linearization fuzzy controller based on fuzzy logic controller and minimum rule base.

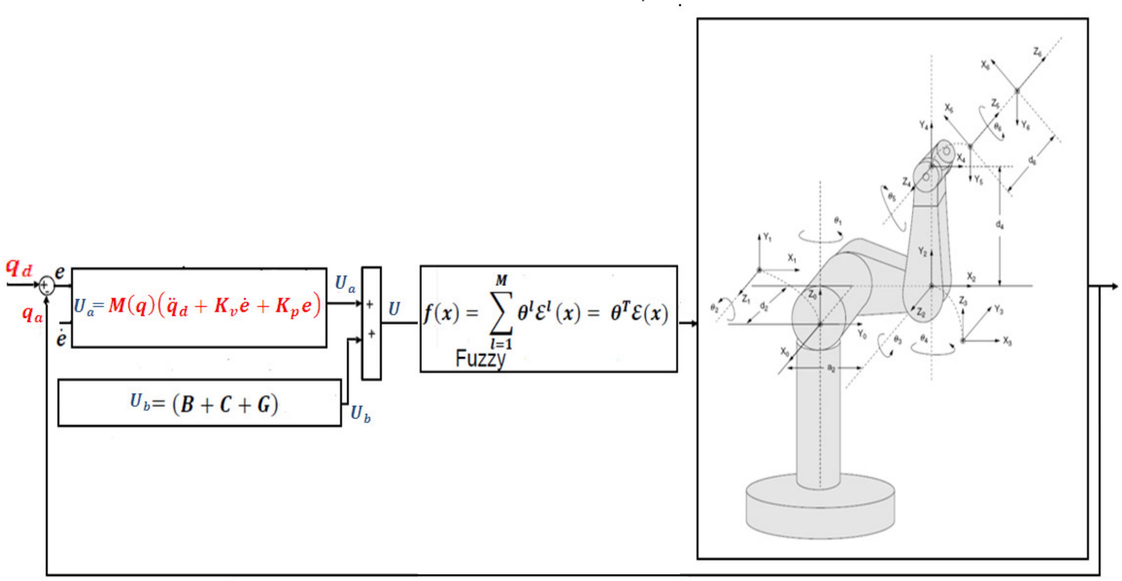

FIGURE2: Block Diagram of inverse dynamic Fuzzy Controller with Minimum Rule Base

Second Step; Design Sliding Mode Fuzzy Adaptive Inverse Dynamic Fuzzy Controller With Minimum Rules: All conventional controller have common difficulty, they need to find several parameters. Tuning feedback linearization fuzzy method can tune automatically the scale parameters using artificial intelligence method. To keep the structure of the controller as simple as possible and to avoid heavy computation, a one input Mamdani sliding mode fuzzy supervisor tuner is selected. In this method the tuneable controller tunes the PD coefficient inverse dynamic controller using gain updating factors.

However proposed inverse dynamic fuzzy controller has satisfactory performance but calculates the main controller coefficient by try and error or experience knowledge is very difficult, particularly when system has uncertainties; sliding mode fuzzy adaptive inverse dynamic fuzzy controller is recommended. The lyapunov formulation is defined by:

$$V = \frac{1}{2} S^T M S + \frac{1}{2} \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi^T . \phi_j \quad \textbf{(16)}$$

Where γ_{sj} is positive coefficient, $\phi = \theta^* - \theta;\ \theta^*\ is\ minimum\ error\ \&\ \theta\ is\ adjustable\ parameter$

Since $\dot{M} - 2V$ is skew-symetric matrix, we can get

$$S^T M\dot{S} + \frac{1}{2}S^T \dot{M}S = S^T(M\dot{S} + VS) \quad (17)$$

From following two functions:

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \quad (18)$$

And

$$\tau = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \quad (19)$$

We can get:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \quad (20)$$

Since; $\dot{q}_r = \dot{q} - S$ & $\ddot{q}_r = \ddot{q} - \dot{S}$ then

$$M\dot{S} + (V + A)S = \Delta f - K \quad (21)$$
$$M\dot{S} = \Delta f - K - VS - AS$$

The derivative of V defined by;

$$\dot{V} = S^T M\dot{S} + \frac{1}{2}S^T \dot{M}S + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j \quad (22)$$

$$\dot{V} = S^T(M\dot{S} + VS) + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j$$

$$\dot{V} = S^T(\Delta f - K - VS - AS + VS) + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j$$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - K_j)] - \vec{S^T AS} + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j$$

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M}\theta_j^l[\mu_A(S_j)]}{\sum_{l=1}^{M}[\mu_A(S_j)]} = \theta_j^T\zeta_j(S_j) \quad (23)$$

Where $\zeta_j(S_j) = [\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots\ldots, \zeta_j^M(S_j)]^T$ and $\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)}$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - \theta^T\zeta(S_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j \quad (24)$$

Based on $\phi = \theta^* - \theta \to \theta = \theta^* - \phi$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - \theta^{*T}\zeta(S_j) + \phi^T\zeta(S_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\dot{\phi}_j \quad (25)$$

$$\dot{V} = \sum_{j=1}^{M}[S_j(\Delta f_j - (\theta^*)^T\zeta(S_j)] - S^T AS + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi_j^T[\gamma_{sj}.S_j.\zeta_j(S_j) + \dot{\phi}_j])$$

where $\dot{\theta}_j = \gamma_{sj}S_j\zeta_j(S_j)$ is adaption law, $\dot{\phi}_j = -\dot{\theta}_j = -\gamma_{sj}S_j\zeta_j(S_j)$

consequently $\dot{V}$ can be considered by

$$\dot{V} = \sum_{j=1}^{m}[S_j\,\Delta f_j - \left((\theta_j^*)^T\zeta_j(S_j)\right)] - S^T AS \quad (26)$$

If the minimum error can be defined by

$$e_{mj} = \Delta f_j - \left((\theta_j^*)^T\zeta_j(S_j)\right) \quad (27)$$

$\dot{V}$ is intended as follows

$$\dot{V} = \sum_{j=1}^{m} [S_j \, e_{mj}] - S^T AS \qquad (28)$$
$$\leq \sum_{j=1}^{m} |S_j||e_{mj}| - S^T AS$$
$$= \sum_{j=1}^{m} |S_j||e_{mj}| - a_j S_j^{\,2}$$
$$= \sum_{j=1}^{m} |S_j|(|e_{mj}| - a_j S_j)$$

For continuous function $g(x)$, and suppose $\varepsilon > 0$ it is defined the fuzzy logic system in form of $Sup_{x\in U}|f(x) - g(x)| < \epsilon$

the minimum approximation error (e_{mj}) is very small.
$if \;\; a_j = \alpha \quad that \quad \alpha|S_j| > e_{mj} \; (S_j \neq 0) \qquad then \quad \dot{V} < 0 \; for \; (S_j \neq 0)$

Figure 3 is shown the block diagram of proposed fuzzy adaptive applied to feedback linearization fuzzy controller.

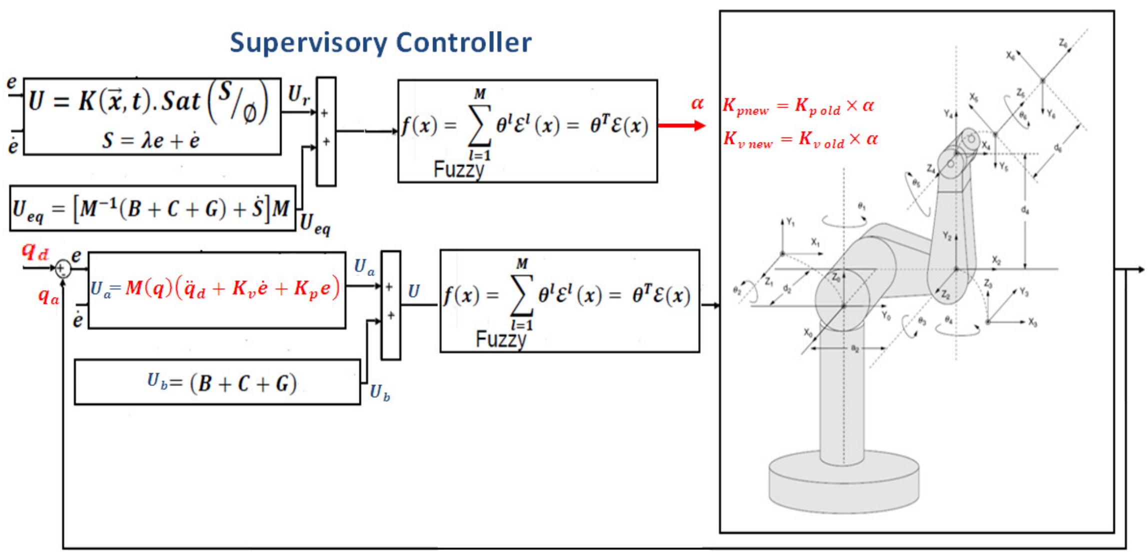

FIGURE 3: Design sliding mode fuzzy adaptive inverse dynamic fuzzy controller

4 SIMULATION RESULTS

Pure inverse dynamic controller (IDC) and sliding mode fuzzy adaptive inverse dynamic fuzzy controller (SMFIDFC) are implemented in Matlab/Simulink environment. Tracking performance and disturbance rejection is compared.

Tracking Performances: From the simulation for first, second and third trajectory without any disturbance, it was seen that IDC and SMFIDFC have the same performance because this system is worked on certain environment. The SMFIDFC gives significant trajectory good following when compared to pure fuzzy logic controller. Figure 4 shows tracking performance without any disturbance for IDC and SMFIDFC.

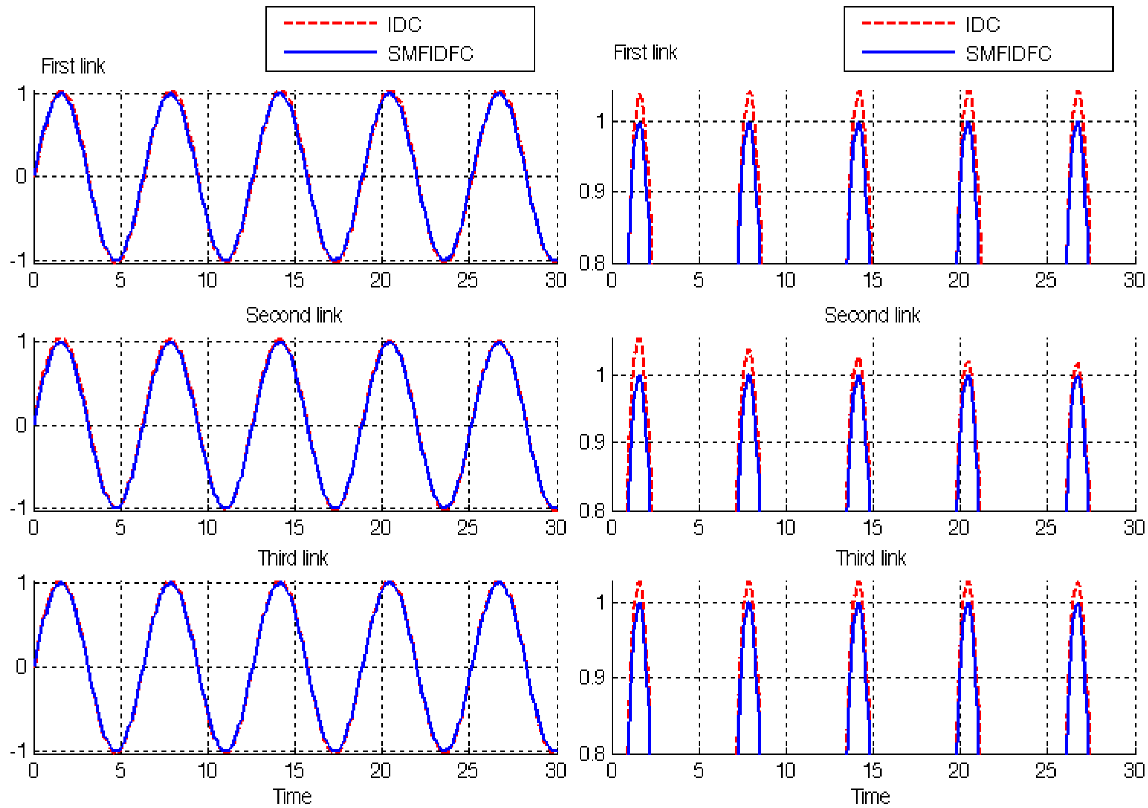

FIGURE 4 : IDC Vs. SMFIDFC: applied to 3DOF's robot manipulator

By comparing sinus response trajectory without disturbance in IDC and SMFIDFC, it is found that the SMFIDFC's overshoot **(0%)** is lower than IDC's **(3%)** and the rise time in FAFLIFC's **(0.8 sec)** and FLIC's **(0.8 sec)**.

Disturbance Rejection: Figure 5 has shown the power disturbance elimination in IDC and SMFIDFC. The main targets in these controllers are disturbance rejection as well as the other responses. A band limited white noise with predefined of 40% the power of input signal is applied to the IDC and SMFIDFC. It found fairly fluctuations in IDC trajectory responses.

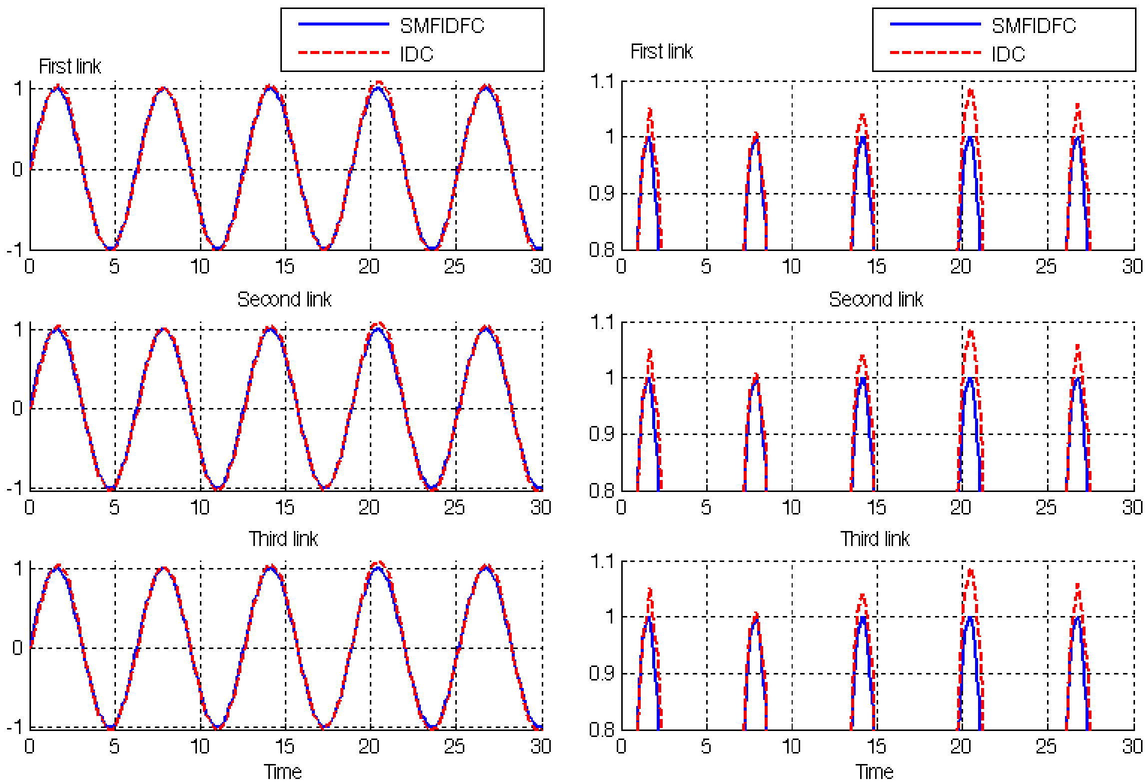

FIGURE 5: IDC Vs. SMFIDFC: applied to robot manipulator.

Among above graph relating to trajectory following with external disturbance, IDC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the SMFIDFC's overshoot **(0%)** is lower than IDC's **(10%)**, although both of them have about the same rise time**.**

5 CONCLUSIONS

In this research, sliding mode fuzzy Lyapunov based tuning inverse dynamic fuzzy methodology to outline learns of this adaption gain is recommended. The study of stability for robot manipulator with regard to applied artificial intelligence in robust classical method and adaptive sliding mode fuzzy law in practice is considered to be a subject in this work. The system performance in inverse dynamic controller and inverse dynamic fuzzy controller are sensitive to the main controller coefficient. Compute the finest value of main controller coefficient for a system is the main important challenge work. This problem has solved by adjusting main controller coefficient of the inverse dynamic controller continuously on-line. Therefore, the overall system performance has improved with respect to the pure inverse dynamic controller and inverse dynamic fuzzy controller. As mentioned in previous, this controller solved external disturbance as well as mathematical nonlinear equivalent part by applied sliding mode fuzzy supervisory controller in inverse dynamic fuzzy controller. By comparing between sliding mode fuzzy adaptive inverse dynamic fuzzy controller and inverse dynamic fuzzy controller, it found that sliding mode fuzzy adaptive inverse dynamic fuzzy controller has steadily stabilised in response although inverse dynamic fuzzy controller has small oscillation in the presence of structure and unstructured uncertainties.

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