Volume 3 ▪ Issue 1 ▪ January / February 2012

INTERNATIONAL JOURNAL OF

ROBOTICS AND AUTOMATION (IJRA)

ISSN : 2180-1312
Publication Frequency: 6 Issues / Year

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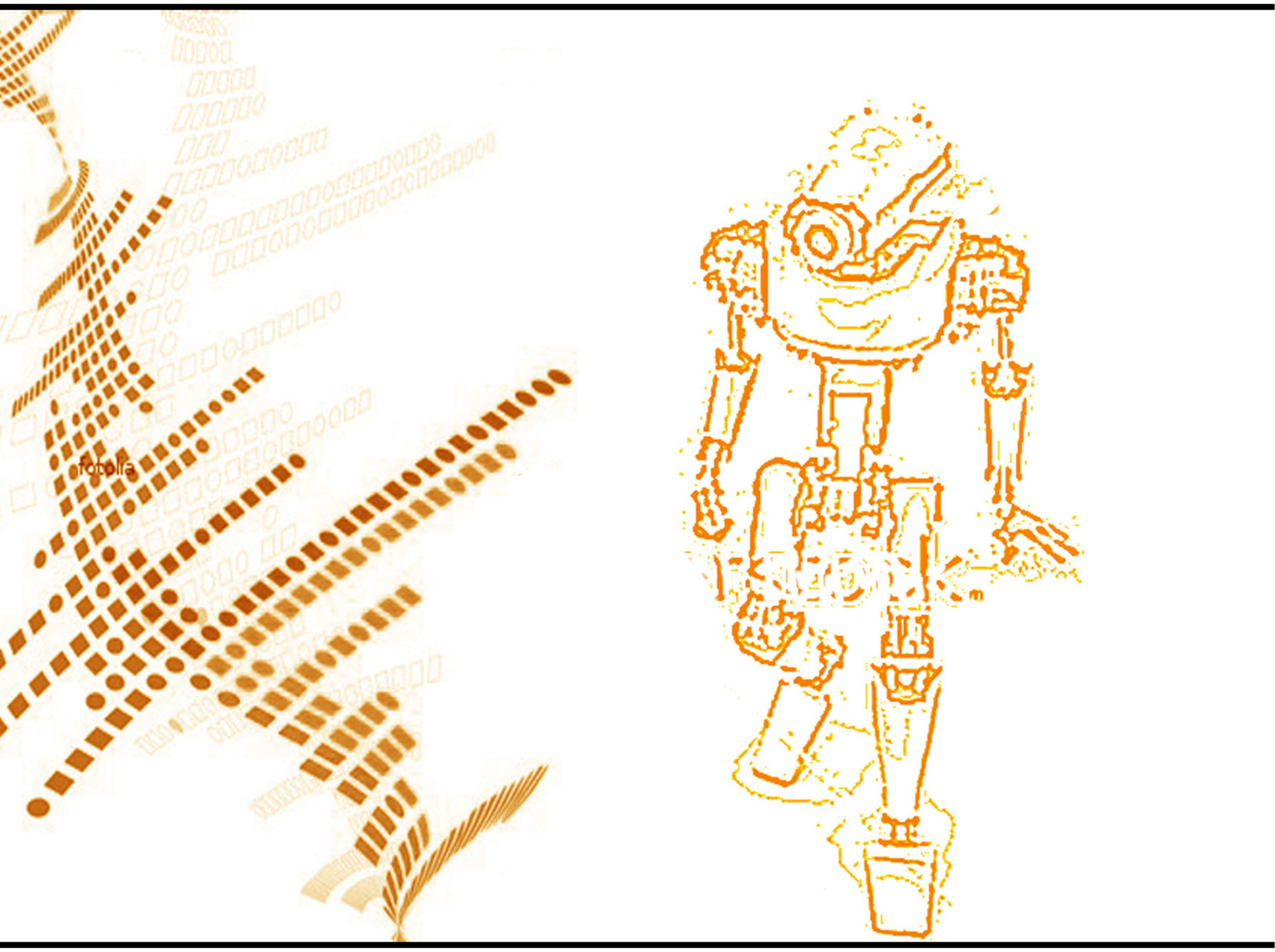

INTERNATIONAL JOURNAL OF ROBOTICS AND AUTOMATION (IJRA)

VOLUME 3, ISSUE 1, 2012

EDITED BY
DR. NABEEL TAHIR

ISSN (Online): 2180-1312

I International Journal of Robotics and Automation (IJRA) is published both in traditional paper form and in Internet. This journal is published at the website http://www.cscjournals.org, maintained by Computer Science Journals (CSC Journals), Malaysia.

IJRA Journal is a part of CSC Publishers
Computer Science Journals
http://www.cscjournals.org

INTERNATIONAL JOURNAL OF ROBOTICS AND AUTOMATION (IJRA)

Book: Volume 3, Issue 1, January / February 2012
Publishing Date: 21-02- 2012
ISSN (Online): 2180-1312

IJRA Journal is a part of CSC Publishers
http://www.cscjournals.org

Published in Malaysia

Typesetting: Camera-ready by author, data conversation by CSC Publishing Services – CSC Journals, Malaysia

CSC Publishers, 2012

EDITORIAL PREFACE

Robots are becoming part of people's everyday social lives - and will increasingly become so. In future years, robots may become caretaking assistants for the elderly or academic tutors for our children, or medical assistants, day care assistants, or psychological counselors. Robots may become our co-workers in factories and offices, or maids in our homes. It is the *First* Issue of Volume *Three* of International Journal of Robotics and Automation (IJRA). IJRA published six times in a year and it is being peer reviewed to very high International standards.

The initial efforts helped to shape the editorial policy and to sharpen the focus of the journal. Started with Volume 3, 2012, IJRA appears with more focused issues. Besides normal publications, IJRA intends to organize special issues on more focused topics. Each special issue will have a designated editor (editors) – either member of the editorial board or another recognized specialist in the respective field.

IJRA looks to the different aspects like sensors in robot, control systems, manipulators, power supplies and software. IJRA is aiming to push the frontier of robotics into a new dimension, in which motion and intelligence play equally important roles. IJRA scope includes systems, dynamics, control, simulation, automation engineering, robotics programming, software and hardware designing for robots, artificial intelligence in robotics and automation, industrial robots, automation, manufacturing, and social implications etc. IJRA cover the all aspect relating to the robots and automation.

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TABLE OF CONTENTS

Volume 3, Issue 1, January / February 2012

Pages

1 - 12 Design Novel Nonlinear Controller Applied to Robot Manipulator: Design New Feedback Linearization Fuzzy Controller With Minimum Rule Base Tuning Method
Farzin Piltan , Mohammad Keshavarz, Ali Badri, Arash Zargari

13 - 26 Design Adaptive Artificial Inverse Dynamic Controller: Design Sliding Mode Fuzzy Adaptive New Inverse Dynamic Fuzzy Controller
Farzin Piltan, Mohammad A. Bairami, Farid Aghayari, Sadeq Allahdadi

27 - 44 Design Auto Adjust Sliding Surface Slope: Applied to Robot Manipulator
Farzin Piltan, Sadeq Allahdadi, Mohammad A. Bairami, Hajar Nasiri

45 - 60 A New Estimate Sliding Mode Fuzzy Controller for Robotic Manipulator
Farzin Piltan, Farid Aghayari, Mohammad Reza Rashidian, Mohammad Shamsodini

Design Novel Nonlinear Controller Applied to Robot Manipulator: Design New Feedback Linearization Fuzzy Controller With Minimum Rule Base Tuning Method

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Abstract

In this paper, fuzzy adaptive base tuning feedback linearization fuzzy methodology to adaption gain is introduced. The system performance in feedback linearization controller and feedback linearization fuzzy controller are sensitive to the main controller coefficient. Therefore, compute the optimum value of main controller coefficient for a system is the main important challenge work. This problem has solved by adjusting main fuzzy controller continuously in real-time. In this way, the overall system performance has improved with respect to the classical feedback linearization controller and feedback linearization fuzzy controller. Adaptive feedback linearization fuzzy controller solved external disturbance as well as mathematical nonlinear equivalent part by applied fuzzy supervisory method in feedback linearization fuzzy controller. The addition of an adaptive law to a feedback linearization fuzzy controller to online tune the parameters of the fuzzy rules in use will ensure a moderate computational load. Refer to this research; tuning methodology can online adjust coefficient parts of the fuzzy rules. Since this algorithm for is specifically applied to a robot manipulator.

Keywords: Feedback Linearization Controller, Fuzzy Logic Methodology, Feedback Linearization Fuzzy Controller, Adaptive Methodology, Fuzzy Adaptive Feedback Linearization Fuzzy Methodology.

1. INTRODUCTION, BACKGROUND AND MOTIVATION

One of the important challenges in control algorithms is a linear behavior controller design for nonlinear systems. When system works with different 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[2]. Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but the design of linear controller for robot manipulators is extremely difficult because they are nonlinear, uncertain and MIMO[1, 6]. To reduce above challenges the nonlinear robust controllers is used to systems control. One of the powerful nonlinear robust controllers is feedback linearization controller (FLIC), this controller has been analyzed by many researchers [7].This controller is used in wide range areas such as in robotics, in control process, in aerospace applications and in power converters. Even though, this controller is used in wide range areas but, pure FLIC has challenged in uncertain (structured and unstructured) system. A multitude of nonlinear control laws have been developed called "computed-torque" or "inverse dynamic" controller in the robotics literature [1-3]. These controllers incorporate the inverse dynamic model of robot manipulators to construct. The computed-torque controllers have their root in feedback linearization control methodology [4, 9]. The idea is to design a nonlinear feedback (maybe calculated using the inverse dynamic model of the robot manipulator to be controlled) which cancels the nonlinearities of an actual robot manipulator. In this manner the closed-loop system becomes exactly linear or partly linear depending on the accuracy of the dynamic model, and then a linear controller such as PD and PID can be applied to control the robot manipulator. The main potential difficulty encountered in implementation of the computed-torque control methodology described above is that the dynamic model of the robot manipulator to be controlled is often not known accuratly. For instance, then the ideal performance (i.e., the exact linearization) of the computed-torque control has been proposed in [18, 23]. In the adaptive computed-torque contol methodology, it is assumed that the structure of the robot manipulator dynamics is perrfectly known but physcical parameters such as links mass, links inertia and friction coefficient are unknown. Therefore, the liearity in the parameters property of robot manipulator dynamic model presented in next part are exploited either to identify unnown parameters or modify the partially known parameters in order to account for the model uncertainty. The two important requirements of adaptive FLIC methodology are: the parameters must be updated such that the estimated inertia matrix remains positive definite and bounded at all times, which means the lower and upper bounds of ineritia parameters must be known a priori; and the measurment of acceleration is need in order to realize the update law [7]. Furthermore, due to the fact that parameters errors are not the sole source of imperfect decoupling and linearization of the robot manipulator dynamics, thus this control methodology cannot provie robustness against external disturbances and unstructured uncertainties [8]. Another difficulty that may be encountered in the implementation of FLIC is that the entire dynamic model (the inertia matrix and the vector of Coriolis, centrifugal, and gravitational terms) of the robot manipulator, i.e., all terms of equation in robot manipulator, must be computed on-line and in the control law, since control is now based on the nonlinear feedback of the current system state. For a robot manipulator with many joints and links, for example for a 6-DOF serial robot manipulator (Stewart-Gough platform) these computations can be complicated and time consuming. The problem of computation burden can even be increased when the adaptive FLIC is used. This is due to extra computation needed to update the parameters in each sample time. Two methods can be found in the literature to deal with the problem of computation burden described above. One method to deal with the problem of computation burden is to use feedforward computed-torque control in which the tourqe vector is computed on the basis of the desired trajectory of the joints (i.e., desired joints positions, velocities and accelerations) and FLIC the nonlinear coupling effects. As opposed to feedback FLIC, in the feedforward method it is possible to pre-compute all the terms of the dynamic model off-line and reduce the computation burden to a large extent [3-9]. The second method to deal with the problem of heavy computation burden in the FLIC is to develop a computationally efficient dynamic model. The feedback linearization-based (computed-torqe/inverse dynamic) control methodologies rely on the knowledge of the robot manipulator dynamic model and its parameters. In the case of imperfect dynamic model the closed-loop dynamics will no longer be decoupled and linearized, for detailed information the reader is referred to [4, 18, 23]. Furthermore, in the feedback linearization-based control methodology, the control law may cancel some beneficial nonlinearity such as friction [18, 23].

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, 15-29]:

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

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:

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

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, 10-29]:

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

Feedback Linearization Control: This technique is very attractive from a control point of view. The central idea of FLIC is feedback linearization so, originally this algorithm is called feedback linearization 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:

$$e(t) = q_d(t) - q_a(t) \tag{4}$$

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

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

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]:

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

With

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

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

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

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 [7-9, 18-23];

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

and the resulting linear error dynamics are

$$(\ddot{q}_d + K_v\dot{e} + K_p e) = 0 \tag{10}$$

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.

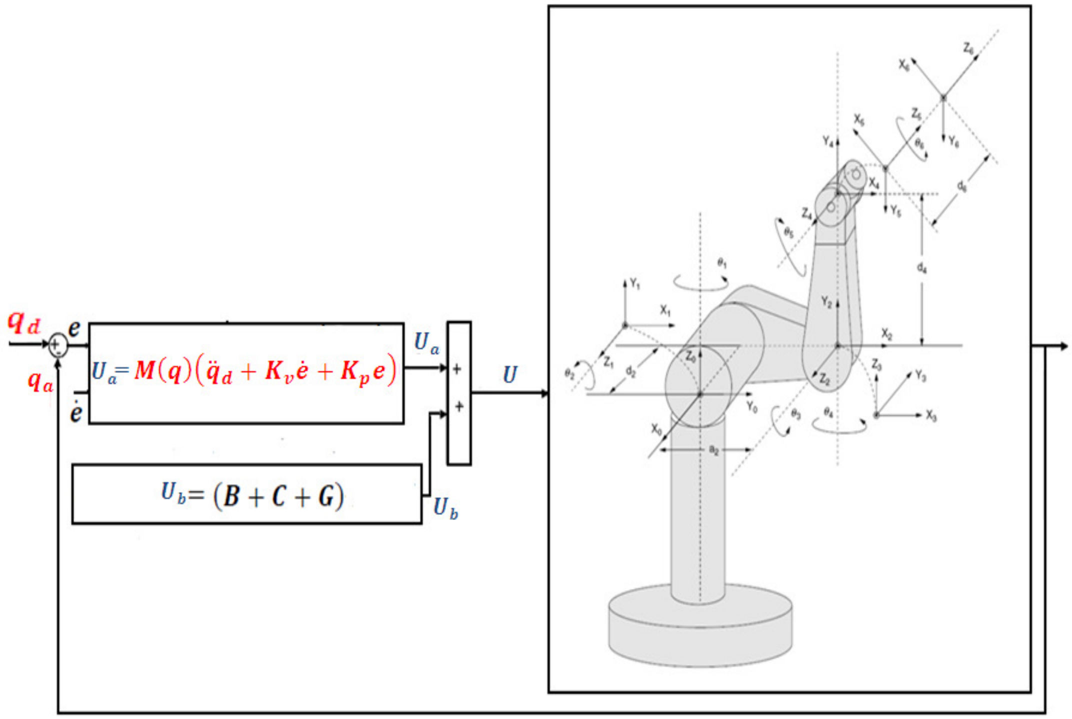

FIGURE 1: Block diagram of PD-computed torque controller (PD-CTC)

The application of proportional-plus-derivative (PD) FLIC to control of PUMA 560 robot manipulator introduced in this part. PUMA 56o robot manipulator is a nonlinear and uncertain system which needs to have powerful nonlinear robust controller such as computed torque controller.

Suppose that in (9) the nonlinearity term defined by the following term

$$N(q,\dot{q}) = B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q) = \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2{}^2 + C_{13}\dot{q}_3{}^2 \\ C_{21}\dot{q}_1{}^2 + C_{23}\dot{q}_3{}^2 \\ C_{31}\dot{q}_1{}^2 + C_{32}\dot{q}_2{}^2 \\ 0 \\ C_{51}\dot{q}_1{}^2 + C_{52}\dot{q}_2{}^2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix} \quad \textbf{(11)}$$

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

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \\ \widehat{\tau_4} \\ \widehat{\tau_5} \\ \widehat{\tau_6} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \begin{bmatrix} \ddot{q}_{d1} + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ \ddot{q}_{d2} + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ \ddot{q}_{d3} + K_{v3}\dot{e}_3 + K_{p3}e_3 \\ \ddot{q}_{d4} + K_{v4}\dot{e}_4 + K_{p4}e_4 \\ \ddot{q}_{d5} + K_{v5}\dot{e}_5 + K_{p5}e_5 \\ \ddot{q}_{d6} + K_{v6}\dot{e}_6 + K_{p6}e_6 \end{bmatrix} \quad \textbf{(12)}$$

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

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

Problem Statement: feedback linearization 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 FLIC has the following disadvantage: the main potential difficulty encountered in implementation of the computed-torque control methodology described above is that the dynamic model of the robot manipulator to be controlled is often not known accuratly. On the other hand, pure fuzzy logic controller (FLC) works in many areas, it cannot guarantee the basic requirement of stability and acceptable performance[8]. Although both FLIC and FLC 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 equivalent equation to implement easily and avoid mathematical model base controller. To reduce the effect of uncertainty in proposed method, adaptive method is applied in feedback linearization fuzzy controller in robot manipulator.

Objectives: The main goal is to design a 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 dynamic and uncertain parameters consequently; following objectives have been pursuit in the mentioned study.

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

3. METHODOLOGY: DESIGN A NOVEL ADAPTIVE FEEDBACK LINEARIZATION FUZZY ESTIMATION CONTROLLER

First step, Design feedback linearization 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;

- 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 [10-15, 29].

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;

$$\textbf{F.R}^1\textbf{:}\ \textit{IF}\ U_\alpha\ \textit{is NB, THEN}\ U_{fuzzy}\ \textit{is LL.} \quad \textbf{(13)}$$

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;

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

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;

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

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.

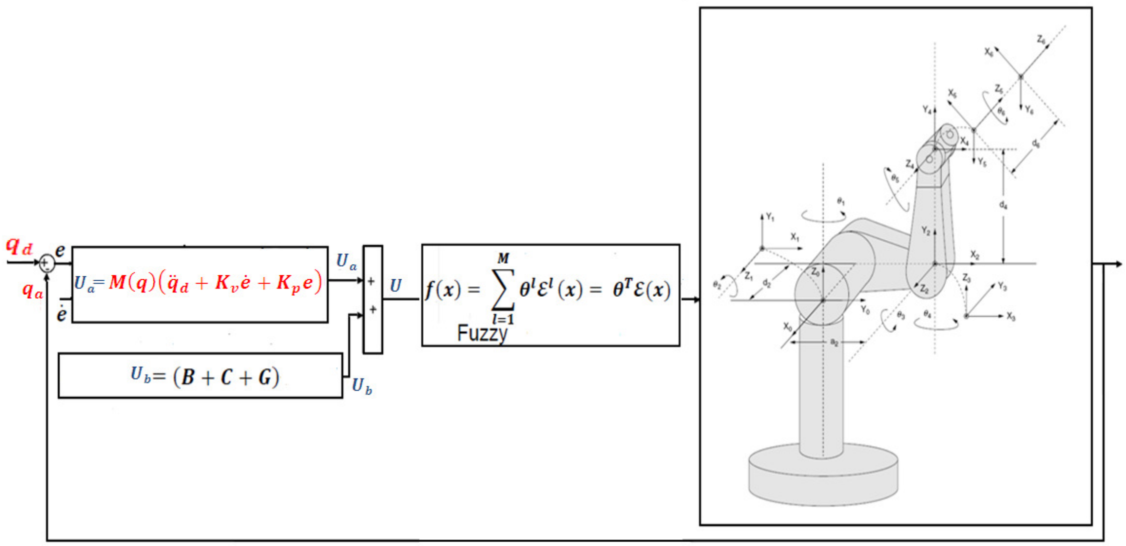

FIGURE2: Block Diagram of Feedback Linearization Fuzzy Controller with Minimum Rule Base

Second Step; Design Fuzzy Adaptive Feedback Linearization 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 two inputs Mamdani fuzzy supervisor tuner is selected. In this method the tuneable controller tunes the PD coefficient feedback linearization controller using gain updating factors.

However proposed feedback linearization fuzzy controller has satisfactory performance but calculate the main controller coefficient by try and error or experience knowledge is very difficult, particularly when system has uncertainties; fuzzy adaptive feedback linearization fuzzy controller is recommended.
The adaption low is defined as

$$\dot{\theta}_j = \gamma_{sj}\alpha_j\zeta_j(\alpha_j) \quad \textbf{(16)}$$

where the $\gamma_{sj}$is the positive constant and $\zeta_j(\alpha_j) = [\zeta_j^1(\alpha_j), \zeta_j^2(\alpha_j), \zeta_j^3(\alpha_j), \dots\dots, \zeta_j^M(\alpha_j)]^T$

$$\zeta_j^1(\alpha_j) = \frac{\mu_{(A)}{}_j^l(\alpha_j)}{\sum_i \mu_{(A)}{}_j^l(\alpha_j)} \quad \textbf{(17)}$$

As a result proposed method is very stable with a good performance. Figure 3 is shown the block diagram of proposed fuzzy adaptive applied to feedback linearization fuzzy controller. The fuzzy system can be defined as below

$$f(x) = \tau_{fuzzy} = \sum_{l=1}^{M} \theta^T \zeta(x) = \psi(e, \dot{e}) \quad \textbf{(18)}$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots\dots, \theta^M)^T, \zeta(x) = (\zeta^1(x), \zeta^2(x), \zeta^3(x), \dots\dots, \zeta^M(x))^T$

$$\zeta^1(x) = \frac{\sum_i \mu_{(xi)x_i}}{\sum_i \mu_{(xi)}} \quad \textbf{(19)}$$

where $\theta = (\theta^1, \theta^2, \theta^3, \dots\dots, \theta^M)$ is adjustable parameter in (18) and $\mu_{(xi)}$ is membership function.
error base fuzzy controller can be defined as

$$\alpha_{fuzzy} = \psi(e, \dot{e}) \quad \textbf{(20)}$$

the fuzzy division can be reached the best state when $\lim_{e\to\infty} e = 0$ and the error is minimum by the following formulation

$$\theta^* = \arg\min \left[Sup_{x \in U} \left| \sum_{l=1}^{M} \theta^T \zeta(x) - U_{equ} \right| \right] \tag{21}$$

Where $\theta^*$is the minimum error, $sup_{x \in U} \left| \sum_{l=1}^{M} \theta^T \zeta(x) - U_{equ} \right|$ is the minimum approximation error. The adaptive controller is used to find the minimum errors of $\theta - \theta^*$.

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l [\mu_A(\alpha_j)]}{\sum_{l=1}^{M} [\mu_A(\alpha_j)]} = \theta_j^T \zeta_j(\alpha_j) \tag{22}$$

Where $\zeta_j(\alpha_j) = [\zeta_j^1(\alpha_j), \zeta_j^2(\alpha_j), \zeta_j^3(\alpha_j), \ldots\ldots, \zeta_j^M(\alpha_j)]^T$

$$\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(\alpha_j)}{\sum_i \mu_{(A)}{}_j^l(\alpha_j)} \tag{23}$$

the adaption low is defined as

$$\dot{\theta}_j = \gamma_{sj} \alpha_j \zeta_j(\alpha_j) \tag{24}$$

where the $\gamma_{sj}$is the positive constant.

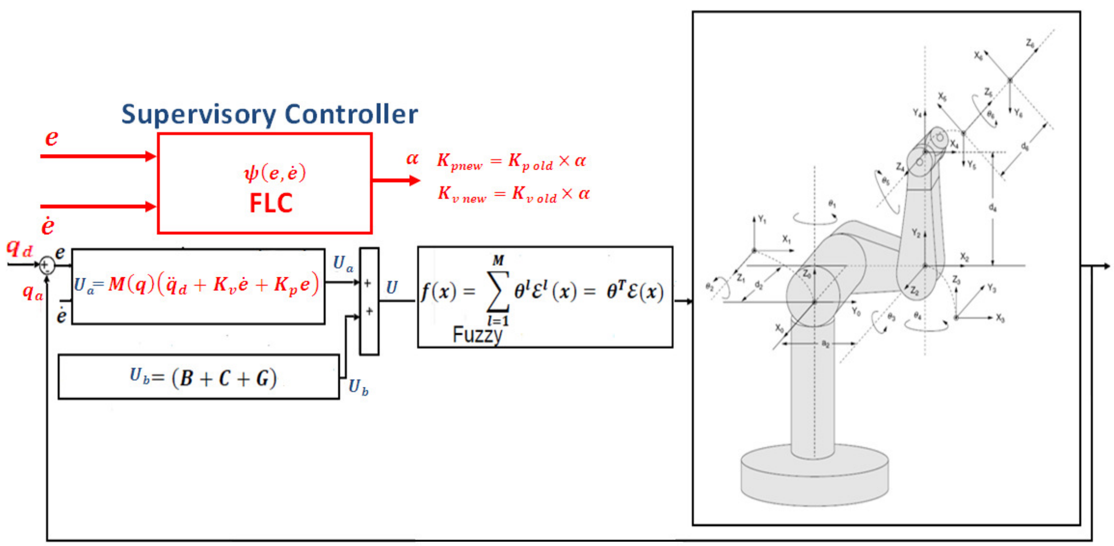

FIGURE 3: Design fuzzy adaptive feedback linearization fuzzy controllers

4 SIMULATION RESULTS

Pure feedback linearization controller (FLIC) and fuzzy adaptive feedback linearization fuzzy controller (FAFLIFC) are implemented in Matlab/Simulink environment. Tracking performance and disturbance rejection are compared.

Tracking Performances

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

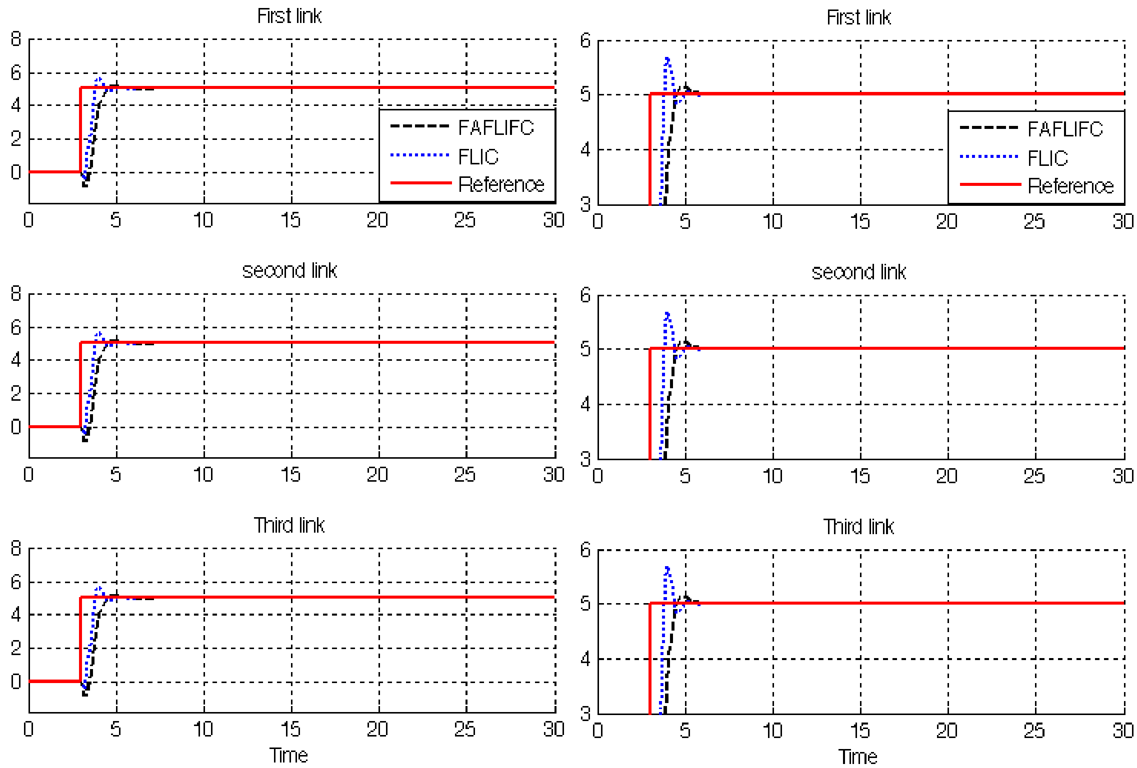

FIGURE 4: FLIC Vs. FAFLIFC: applied to 3DOF's robot manipulator

By comparing step response trajectory without disturbance in FLIC and FAFLIFC, it is found that the FAFLIFC's overshoot **(2.4%)** is lower than FLIC's **(14%)** and the rise time in FAFLIFC's **(1.2 sec)** and FLIC's **(0.8 sec)**.

Disturbance Rejection

Figure 5 has shown the power disturbance elimination in FLIC and FAFLIFC. 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 FLIC and FAFLIFC. It found fairly fluctuations in FLIC trajectory responses.

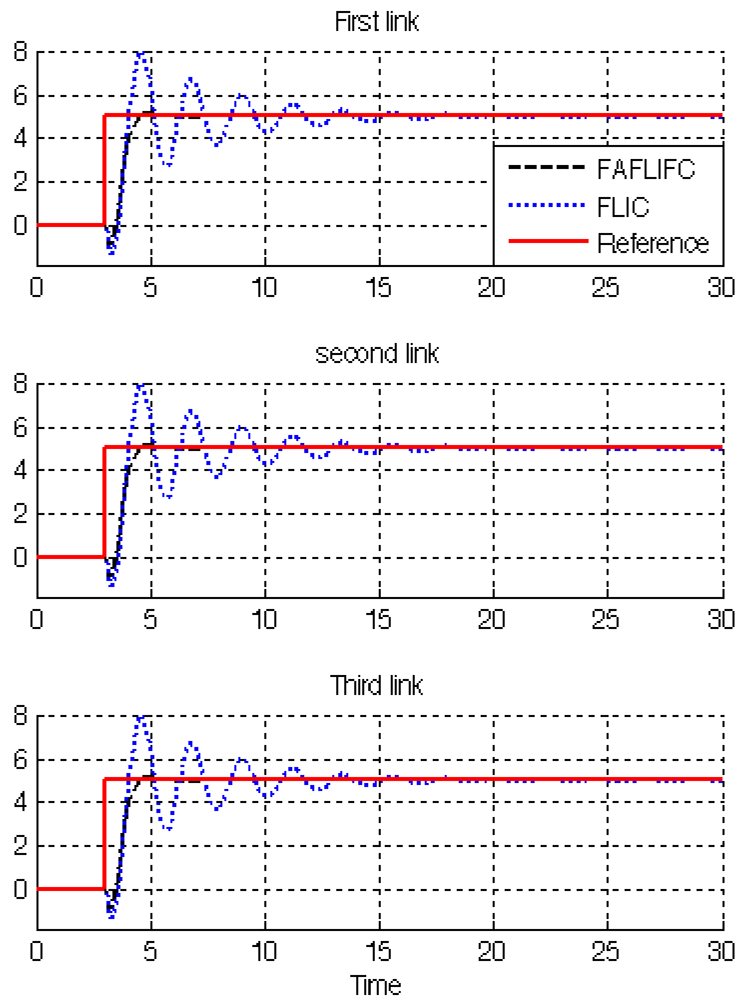

FIGURE 5: FLIC Vs. FAFLIFC: applied to robot manipulator.

Among above graph relating to trajectory following with external disturbance, FLIC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the FAFLIFC's overshoot **(2.4%)** is lower than FLIC's **(60%)**, although both of them have about the same rise time**.**

5 CONCLUSIONS

In this research, fuzzy adaptive base tuning feedback linearization fuzzy methodology to outline learns of this adaption gain is recommended. Since proof of stability is an important factor in practice does not hold, the study of stability for robot manipulator with regard to applied artificial intelligence in robust classical method and adaptive low in practice is considered to be a subject in this work. The system performance in feedback linearization controller and feedback linearization fuzzy controller are sensitive to the main controller coefficient. Therefore, compute the optimum 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 feedback linearization controller continuously in real-time. In this way, the overall system performance has improved with respect to the classical feedback linearization controller. As mentioned in previous, this controller solved external disturbance as well as mathematical nonlinear equivalent part by applied fuzzy supervisory method in feedback linearization fuzzy controller. By comparing between fuzzy adaptive feedback linearization fuzzy controller and feedback linearization fuzzy controller, found that fuzzy adaptive feedback linearization fuzzy controller has steadily stabilised in output response but feedback linearization fuzzy controller has slight oscillation in the presence of uncertainties.

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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]:

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

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:

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

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]:

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

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]:

$$e(t) = q_d(t) - q_a(t) \tag{4}$$

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

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

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]:

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

With

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

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

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

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];

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

and the resulting linear error dynamics are

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

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.

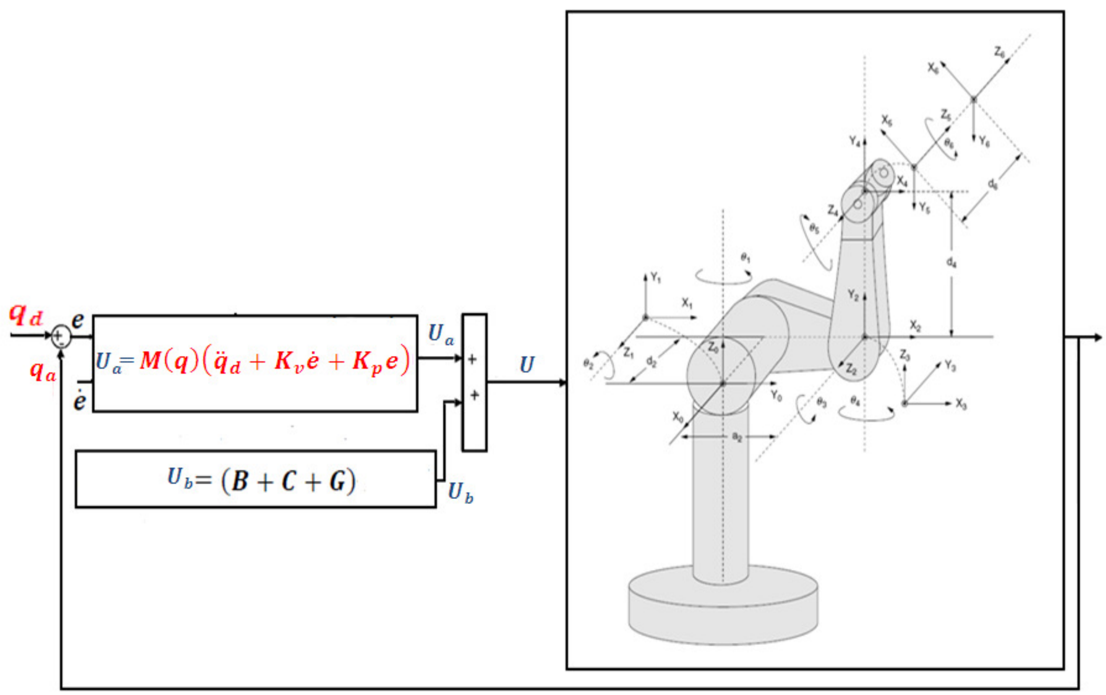

FIGURE 1: Block diagram of PD-inverse dynamic controller (PD-IDC)

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

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

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

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

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \\ \widehat{\tau_4} \\ \widehat{\tau_5} \\ \widehat{\tau_6} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \begin{bmatrix} \ddot{q}_{d1} + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ \ddot{q}_{d2} + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ \ddot{q}_{d3} + K_{v3}\dot{e}_3 + K_{p3}e_3 \\ \ddot{q}_{d4} + K_{v4}\dot{e}_4 + K_{p4}e_4 \\ \ddot{q}_{d5} + K_{v5}\dot{e}_5 + K_{p5}e_5 \\ \ddot{q}_{d6} + K_{v6}\dot{e}_6 + K_{p6}e_6 \end{bmatrix} \tag{12}$$

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

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.

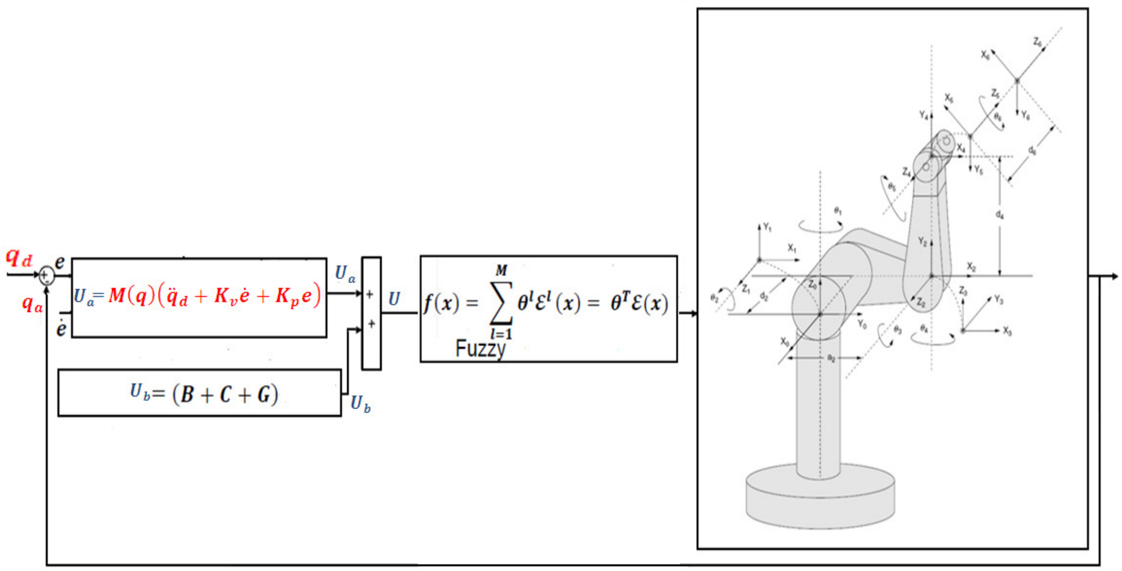

FIGURE2: Block Diagram of inverse dynamic Fuzzy Controller with Minimum Rule Base

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;

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

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

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

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

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 $\phi = \theta^* - \theta \rightarrow \theta = \theta^* - \phi$

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

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

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

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

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.
$if \;\; a_j = \alpha \quad that \quad \alpha|S_j| > e_{mj} \; (S_j \ne 0) \quad then \quad \dot{V} < 0 \; for \; (S_j \ne 0)$

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

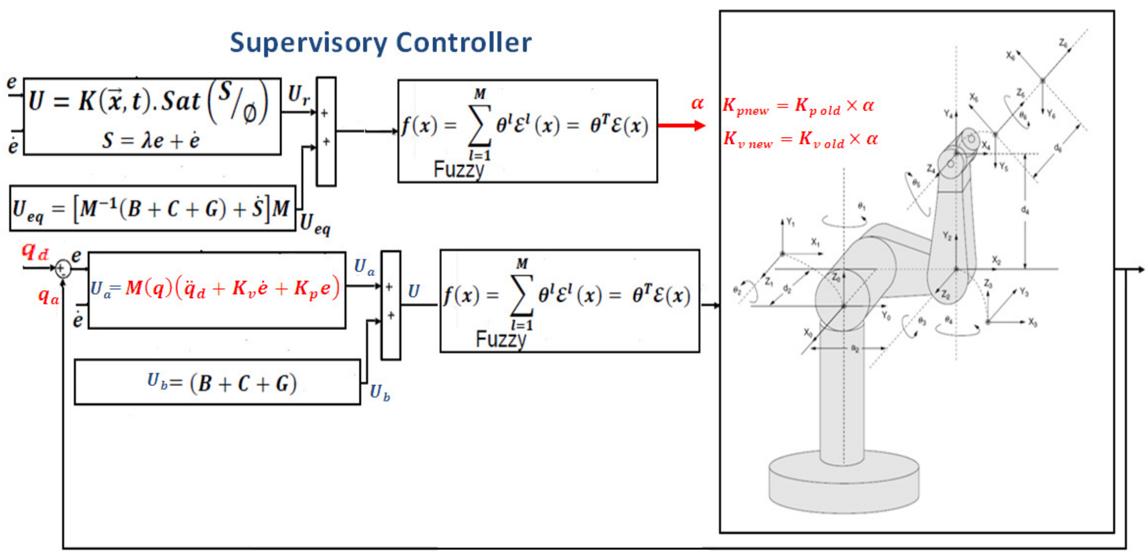

FIGURE 3: Design sliding mode fuzzy adaptive inverse dynamic fuzzy controller

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.

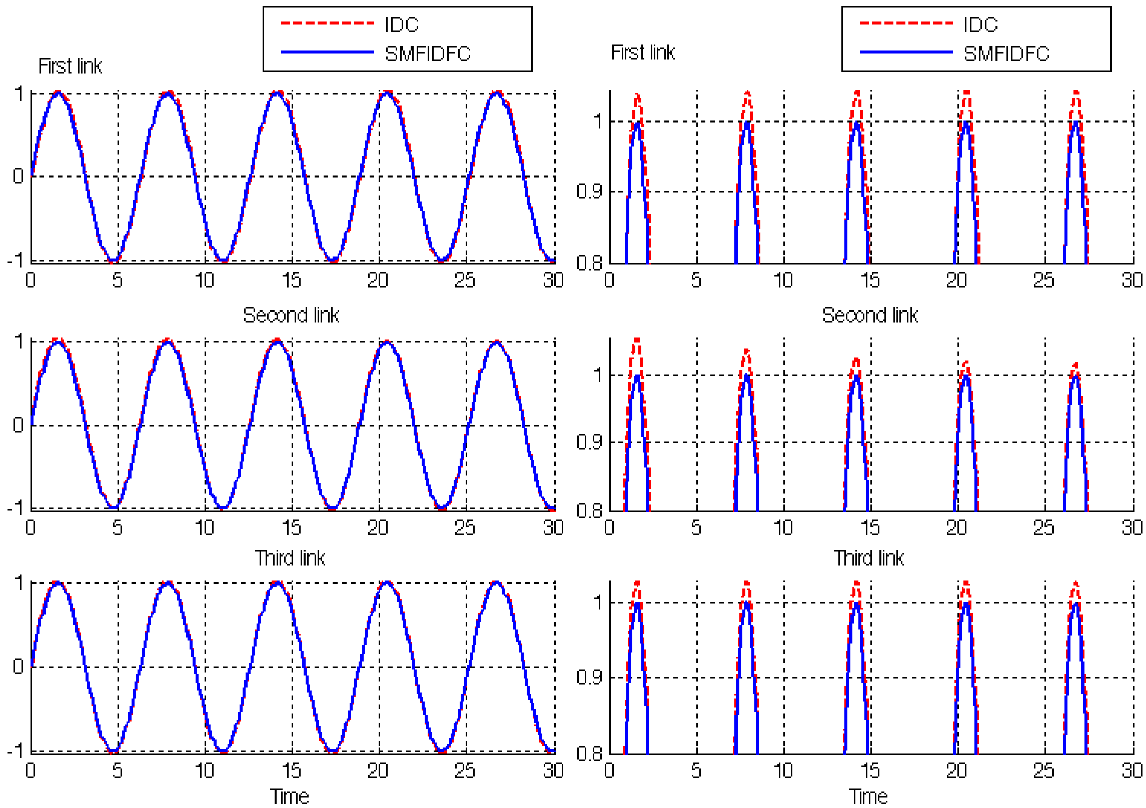

FIGURE 4 : IDC Vs. SMFIDFC: applied to 3DOF's robot manipulator

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.

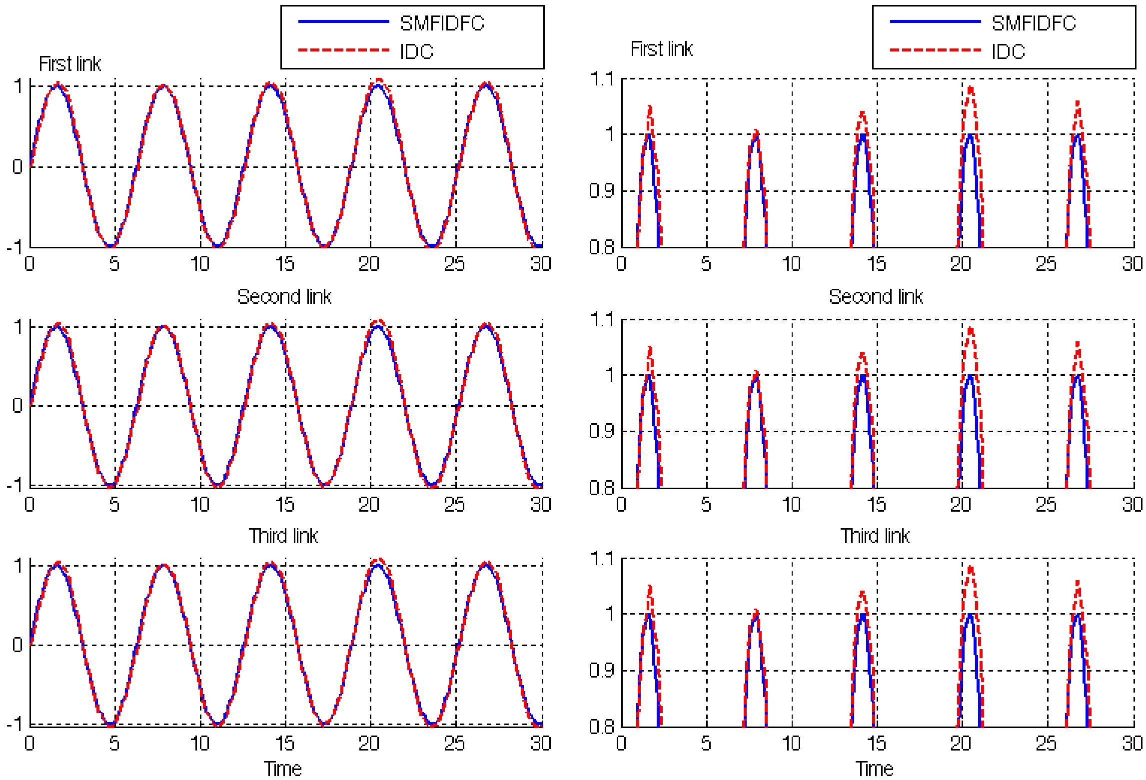

FIGURE 5: IDC Vs. SMFIDFC: applied to robot manipulator.

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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Design Auto Adjust Sliding Surface Slope: Applied to Robot Manipulator

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Abstract

The main target in this paper is to present the nonlinear methods in order to control the robot manipulators and also the related results. Also the important role of sliding surface slope in sliding mode fuzzy control of robot manipulator should be considered. Sliding mode controller (SMC) is a significant nonlinear controller in certain and uncertain dynamic parameters systems. To solve the chattering phenomenon, this paper complicated two methods to each other; boundary layer method and applied fuzzy logic in sliding mode methodology. To remove the chattering sliding surface slope also played important role so this paper focused on the auto tuning this important coefficient to have the best results by applied mathematical model free methodology. Auto tuning methodology has acceptable performance in presence of uncertainty (e.g., overshoot=0%, rise time=0.8 s, steady state error = 1e-9 and RMS error=0.0001632).

Keywords: Sliding Mode Controller, Fuzzy Logic Methodology, Sliding Mode Fuzzy Methodology, Robotic Manipulator, Auto Tuning Sliding Mode Fuzzy Controller.

1. INTRODUCTION, BACKGROUND and MOTIVATION

A robot system without any controllers does not to have any benefits, because controller is the main part in this sophisticated system. The main objectives to control of robot manipulators are stability, and robustness. Lots of researchers work on design the controller for robotic manipulators to have the best performance. Control of any systems divided in two main groups: linear and nonlinear controller [1-2, 4, 6-7, 9].

However, one of the important challenging in control algorithms is design linear behavior controller to easier implementation for nonlinear systems but these algorithms have some limitation such as controller working area must to be near the system operating point and this adjustment is very difficult specially when the dynamic system parameters have large variations, and when the system has hard nonlinearities [1-4]. Most of robot manipulators which work in industry are usually controlled by linear PID controllers. But the robot manipulator dynamic functions are, nonlinear with strong coupling between joints (low gear ratio), structure and unstructured uncertainty, and multi- inputs multi-outputs (MIMO) which, design linear controller is very difficult especially if the velocity and acceleration of robot manipulator be high and also when the ratio between joints gear be small [1-2]. To eliminate above problems in physical systems most of control researcher go toward to select nonlinear robust controller [1-4].

One of the most important powerful nonlinear robust controllers is sliding mode controller (SMC) [1-4, 7-9]. However Sliding mode control methodology was first proposed in the 1950 but this controller has been analyzed by many researchers in recent years [16, 18-19]. The main reason to select this controller in wide range area is have an acceptable control performance and solve some main challenging topics in control such as resistivity to the external disturbance and stability. Sliding mode controller is divided into two main sub controllers: discontinues controller(τ_{dis}) and equivalent controller(τ_{eq}) $[24, 28, 30, 38-44]$. 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[1, 6]. When all dynamic and physical parameters are known or limitation unknown the controller works superbly and output responses are good quality; practically a large amount of systems have unlimited or highly uncertainties and sliding mode controller with estimator methodology reduce this kind of limitation. However, this controller has above advantages but, pure sliding mode controller has following disadvantages i.e.chattering problem, sensitivity, and equivalent dynamic formulation [3]. Chattering phenomenon can causes some problems such as saturation and heat the mechanical parts of robot manipulators or drivers. 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 [1]. 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. Slotine and Sastry have introduced boundary layer method instead of discontinuous method to reduce the chattering[2]. Slotine has presented sliding mode with boundary layer to improve the industry application [2]. Estimated uncertainty method used in term of uncertainty estimator to compensation of the system uncertainties. It has been used to solve the chattering phenomenon and also nonlinear equivalent dynamic. If estimator has an acceptable performance to compensate the uncertainties, the chattering is reduced. Research on estimated uncertainty to reduce the chattering is significantly growing as their applications such as industrial automation and robot manipulator. For instance, the applications of artificial intelligence, neural networks and fuzzy logic on estimated uncertainty method have been reported in [10-15, 20, 36]. Wang et al. [5] have proposed a simple fuzzy estimator controller beside the discontinuous and equivalent control terms to reduce the chattering. Their design had three main parts i.e. equivalent, discontinuous and fuzzy estimator tuning part which has reduced the chattering very well. After the invention of fuzzy logic theory in 1965 by Zadeh (Zadeh, 1997), this theory was used in wide range area because Fuzzy logic controller (FLC) is one of the most important applications of fuzzy logic theory. 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]. This controller can be used to control of nonlinear, uncertain, and noisy systems. However pure FLC works in many engineering applications but, it cannot guarantee two most important challenges in control, namely, stability and acceptable performance [4]. 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]. Some researchers applied fuzzy logic methodology in sliding mode controllers (FSMC) to reduce the chattering and solve the nonlinear dynamic equivalent problems in pure sliding mode controller and the other researchers applied sliding mode methodology in fuzzy logic controller (SMFC) to improve the stability of systems, therefore FSMC is a controller based on SMC but SMFC works based on FLC [17, 21-44].

Adaptive control used in systems whose dynamic parameters are varying and/or have unstructured disturbance and need to be training on line. Adaptive fuzzy inference system provide a good knowledge tools for adjust a complex uncertain nonlinear system with changing dynamics to have an acceptable performance. Combined adaptive method to artificial sliding mode controllers can help to controllers to have a better performance by online tuning the nonlinear and time variant parameters [21-44]. 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 [17, 21-30]. 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 [19-44]. The combined adaptive sliding mode controllers (robust adaptive controllers) have been studied by Slotine and Coetsee [3], Piltan et al. [4, 9], and Wang [5], as a method to overcome the unmodelled dynamics and external disturbances. However, the combined adaptive controllers need a linearly parameterized model of the system under investigation and a priori knowledge of the bounds of uncertainties. Furthermore, the large number of parameters and adaptation gain (i.e., design parameter) corresponding to each unknown parameter introduces more complexity. The problem of application time and computation burden can lead to severe stability and robustness problem (e.g., when the fast real-time control is required). In addition to the above mentioned issued that need to be addressed, there is another issue which makes it necessary to develop a new uncertainty estimation method. That is because, currently, the control theory uses powerful tools which no longer rely on the parameterized dynamic model of the system, such as fuzzy modeling, neural networks and neuro-fuzzy modeling [16-44].

In this research we will highlight a new auto adjust sliding surface slope derived in the Lyapunov sense. This algorithm will be analyzed and evaluated on robotic manipulators. Section 2, is served as a problem statements, robot manipulator dynamics and introduction to the pure sliding mode controller with proof of stability and its application to robot manipulator. Part 3, introduces and describes the methodology algorithms 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, PROBLEM STATEMENTS AND SLIDING MODE CONTROLLER FORMULATION

Robot Manipulator Dynamic Formulation: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 3, 16-28, 30, 38-40]:

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

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:

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

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]:

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

Sliding Mode Control: This technique is very attractive from a control point of view. The central idea of sliding mode control (SMC) is based on nonlinear dynamic equivalent. 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, 31-44]:

$$e(t) = q_d(t) - q_a(t) \tag{4}$$

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. Consider a nonlinear single input dynamic system of the form [6]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{5}$$

Where u is the vector of control input, $x^{(n)}$ is the n^{th} derivation of$x$, $x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T$ is the state vector, $f(x)$ is unknown or uncertainty, and $b(x)$ is of known *sign* function. The control problem is truck to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and have an acceptable error which is given by:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \tag{6}$$

A time-varying sliding surface $s(x,t)$ is given by the following equation:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\tilde{x} = 0 \tag{7}$$

where λ is the positive constant. To further penalize tracking error integral part can be used in sliding surface part as follows:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\left(\int_0^t \tilde{x}\,dt\right) = 0 \tag{8}$$

The main target in this methodology is kept the sliding surface slope $s(x,t)$ near to the zero. Therefore, one of the common strategies is to find input U outside of $s(x,t)$.

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)| \tag{9}$$

where ζ is positive constant.

$$\textbf{If } S(0)>0 \rightarrow \frac{d}{dt}S(t) \le -\zeta \tag{10}$$

To eliminate the derivative term, it is used an integral term from t=0 to t=t_{reach}

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt}S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \tag{11}$$

Where t_{reach} is the time that trajectories reach to the sliding surface so, suppose $S(t_{reach}=0)$ defined as

$$0 - S(0) \le -\eta(t_{reach}) \to t_{reach} \le \frac{S(0)}{\zeta} \tag{12}$$

and

$$if\ S(0) < 0 \to 0 - S(0) \le -\eta(t_{reach}) \to S(0) \le -\zeta(t_{reach}) \to t_{reach} \le \frac{|S(0)|}{\eta} \tag{13}$$

Equation (13) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \to error(x - x_d) = 0 \tag{14}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda)\ \ \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{15}$$

The derivation of S, namely, $\dot{S}$ can be calculated as the following;

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{16}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \ \to \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \tag{17}$$

Where f is the dynamic uncertain, and also since $S = 0\ and\ \dot{S} = 0$, to have the best approximation ,$\hat{U}$ is defined as

$$\hat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{18}$$

A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = \hat{U} - K(\vec{x},t) \cdot \mathrm{sgn}(s) \tag{19}$$

where the switching function $\mathrm{sgn}(S)$ is defined as

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{20}$$

and the $K(\vec{x},t)$ is the positive constant. Suppose by (20) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) = \dot{S} \cdot S = [f - \hat{f} - K\mathrm{sgn}(s)] \cdot S = (f - \hat{f}) \cdot S - K|S| \tag{21}$$

and if the equation (13) instead of (12) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{22}$$

in this method the approximation of U is computed as

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{23}$$

Based on above discussion, the control law for a multi degrees of freedom robot manipulator is written as:

$$\tau = \tau_{eq} + \tau_{dis} \tag{24}$$

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

$$\tau_{eq} = [M^{-1}(B + C + G) + \dot{S}]M \tag{25}$$

Where [15-44]

$$\tau_{eq} = \begin{bmatrix} \tau_{eq1} \\ \tau_{eq2} \\ \tau_{eq3} \\ \tau_{eq4} \\ \tau_{eq5} \\ \tau_{eq6} \end{bmatrix},\ M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

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

$$\dot{S}=\begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \\ \dot{S}_3 \\ \dot{S}_4 \\ \dot{S}_5 \\ \dot{S}_6 \end{bmatrix} \text{ and } M=\begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}$$

and τ_{dis} is computed as;

$$\tau_{dis}=K\cdot \operatorname{sgn}(S) \qquad \textbf{(26)}$$

where

$$\tau_{dis}=\begin{bmatrix} \tau_{dis1} \\ \tau_{dis2} \\ \tau_{dis3} \\ \tau_{dis4} \\ \tau_{dis5} \\ \tau_{dis6} \end{bmatrix}, K=\begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \end{bmatrix}, (S)=\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} \; and \;\; S=\lambda e+\dot{e}$$

The result scheme is shown in Figure 1.

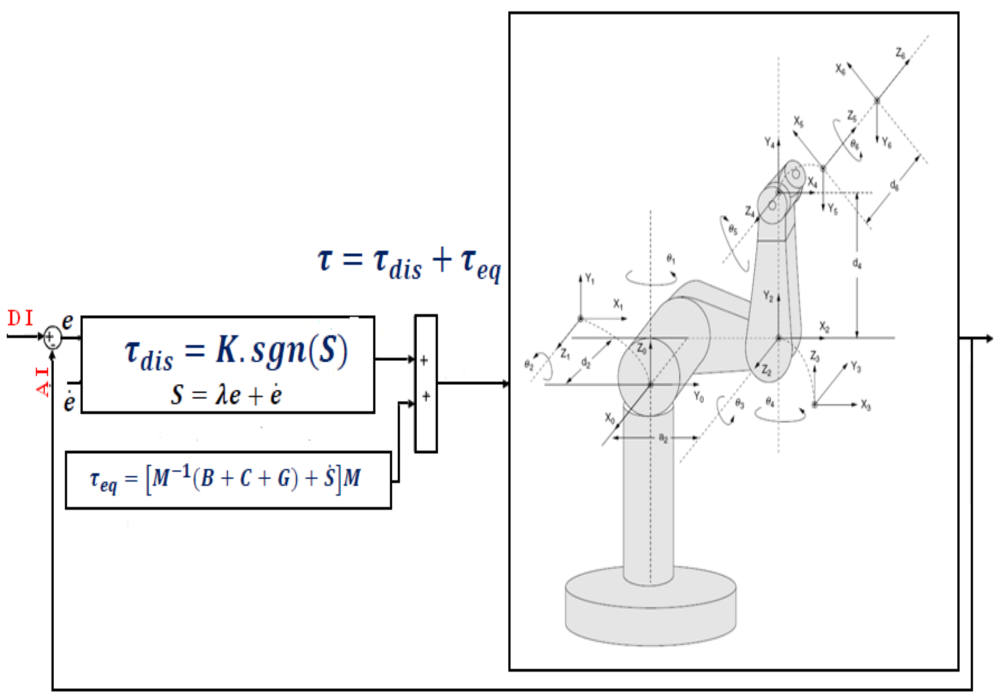

FIGURE :1 Block diagram of Sliding Mode Controller (SMC)

Problem Statement: Even though, SMC is used in wide range areas but, pure SMC has the chattering phenomenon disadvantages to reduce or eliminate the chattering this paper focouses on applied fuzzy logic methodology in sliding mode controller with minimum rule base after that sliding surface slope which has play important role in remove the chattering is auto adjusted.

Proof of Stability: The proof of Lyapunov function can be determined by the following equations. The dynamic formulation of robot manipulate can be written by the following equation

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \tag{27}$$

the lyapunov formulation can be written as follows,

$$V = \frac{1}{2}S^T.M.S \tag{28}$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2}S^T.\dot{M}.S + S^T M\dot{S} \tag{29}$$

the dynamic equation of robot manipulator can be written based on the sliding surface as

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \tag{30}$$

it is assumed that

$$S^T(\dot{M} - 2V)S = 0 \tag{31}$$

by substituting (30) in (29)

$$\dot{V} = \frac{1}{2}S^T\dot{M}S - S^TVS + S^T(M\dot{S} + VS + G - \tau) = S^T(M\dot{S} + VS + G - \tau) \tag{32}$$

suppose the control input is written as follows

$$\hat{\tau} = \widehat{\tau_{eq}} + \widehat{\tau_{dis}} = [\hat{M}^{-1}(\hat{V} + \hat{G}) + \dot{S}]\hat{M} + K.sgn(S) + K_vS \tag{33}$$

by replacing the equation (33) in (32)

$$\dot{V} = S^T(M\dot{S} + VS + G - \hat{M}\dot{S} - \hat{V}S - \hat{G} - K_vS - Ksgn(S) = S^T\left(\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K\right. \tag{34}$$

it is obvious that

$$\left|\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K_vS\right| \le \left|\tilde{M}\dot{S}\right| + \left|\tilde{V}S\right| + \left|\tilde{G}\right| + |K_vS| \tag{35}$$

the Lemma equation in robot manipulator system can be written as follows

$$K_u = \left[\left|\tilde{M}\dot{S}\right| + |VS| + |G| + |K_vS| + \eta\right]_i, i = 1,2,3,4,\dots \tag{36}$$

the equation (31) can be written as

$$K_u \ge \left|\left[\tilde{M}\dot{S} + VS + G - K_vS\right]_i\right| + \eta_i \tag{37}$$

therefore, it can be shown that

$$\dot{V} \le -\sum_{i=1}^{n}\eta_i|S_i| \tag{38}$$

Consequently the equation (38) guaranties the stability of the Lyapunov equation.

3. METHODOLOGY: DESIGN AUTO ADJUST SLIDING SURFACE SLOPE SLIDING MODE FUZZY CONTROLLER

First Step: Improve Chattering Free Sliding Mode Controller: To reduce or eliminate the chattering in this research is used the boundary layer method; in boundary layer method the basic idea is replace the discontinuous method by saturation (linear) method with small neighborhood of the switching surface.

$$B(t) = \{x, |S(t)| \le \varnothing\}; \varnothing > 0 \tag{39}$$

Where $\varnothing$ is the boundary layer thickness. Therefore the saturation function $\mathbf{Sat}(S/_{\varnothing})$ is added to the control law as

$$U = K(\vec{x},t) \cdot \mathrm{Sat}\left(S/_{\varnothing}\right) \tag{40}$$

Where $\mathbf{Sat}\left(S/_{\varnothing}\right)$ can be defined as

$$\mathrm{sat}\left(S/_{\varnothing}\right) = \begin{cases} 1 & (S/_{\varnothing} > 1) \\ -1 & (s/_{\varnothing} < 1) \\ s/_{\varnothing} & (-1 < s/_{\varnothing} < 1) \end{cases} \tag{41}$$

Based on above discussion, the control law for a multi degrees of freedom robot manipulator is written as:

$$\tau = \tau_{eq} + \tau_{sat} \tag{42}$$

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

$$\tau_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{43}$$

Where

$$\tau_{eq} = \begin{bmatrix} \tau_{eq1} \\ \tau_{eq2} \\ \tau_{eq3} \\ \tau_{eq4} \\ \tau_{eq5} \\ \tau_{eq6} \end{bmatrix}, M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

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

$$\dot{S} = \begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \\ \dot{S}_3 \\ \dot{S}_4 \\ \dot{S}_5 \\ \dot{S}_6 \end{bmatrix} \text{ and } M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}$$

and τ_{sat} is computed as;

$$\tau_{sat} = K \cdot \mathrm{sat}\left(S/_{\varnothing}\right) \tag{44}$$

where

$$\tau_{sat} = \begin{bmatrix} \tau_{dis1} \\ \tau_{dis2} \\ \tau_{dis3} \\ \tau_{dis4} \\ \tau_{dis5} \\ \tau_{dis6} \end{bmatrix}, K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \end{bmatrix}, \left(S/_{\emptyset}\right) = \begin{bmatrix} \frac{S_1}{\emptyset_1} \\ \frac{S_2}{\emptyset_2} \\ \frac{S_3}{\emptyset_3} \\ \frac{S_4}{\emptyset_4} \\ \frac{S_5}{\emptyset_5} \\ \frac{S_6}{\emptyset_6} \end{bmatrix} \quad and \quad S = \lambda e + \dot{e}$$

by replace the formulation (44) in (42) the control output can be written as;

$$\tau = \tau_{eq} + K.\text{sat}\left(S/_{\emptyset}\right) = \begin{cases} \tau_{eq} + K.\text{sgn}(S) & ,|S| \geq \emptyset \\ \tau_{eq} + K.S/_{\emptyset} & ,|S| < \emptyset \end{cases} \tag{45}$$

Figure 2 shows the chattering free sliding mode control for robot manipulator. By (45) and (43) the sliding mode control of PUMA 560 robot manipulator is calculated as;

$$\tau = \left[M^{-1}(B + C + G) + \dot{S}\right]M + K \cdot \text{sat}\left(S/_{\emptyset}\right) \tag{46}$$

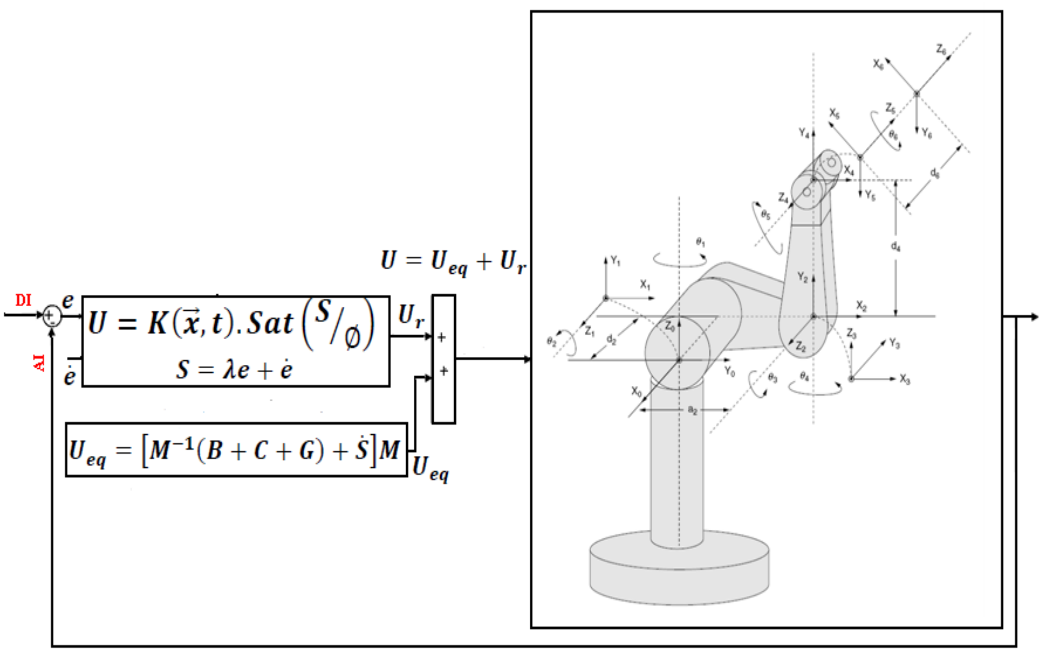

FIGURE 2: Block diagram of chattering free Sliding Mode Controller (SMC)

Second Step, Design Sliding Mode Fuzzy Controller: As shown in Figure 1, sliding mode controller divided into two main parts: equivalent controller, based on dynamics formulation of robot manipulators and sliding surface saturation part based on saturation continuous function to reduce the chattering. Boundary layer method (saturation function) is used to reduce the chattering. Reduce or eliminate the chattering regarding to reduce the error is play important role in this research therefore boundary layer method is used beside the equivalent part to solve the chattering problem besides reduce the error.

Combinations of fuzzy logic systems with sliding mode method have been proposed by several researchers. SMFC is fuzzy controller based on sliding mode method for easy implementation, stability, and robustness. Control rules for SMFC can be described as:

IF S is<ling.var> THEN U is<ling.var> **(47)**

Table 1 is shown the fuzzy rule table for SMFC, respectively:

S	NB	NM	NS	Z	PS	PM	PB
T	NB	NM	NS	Z	PS	PM	PB

Table 1. Rule table (SMFC)

A block diagram for sliding mode fuzzy controller is shown in Figure 3.

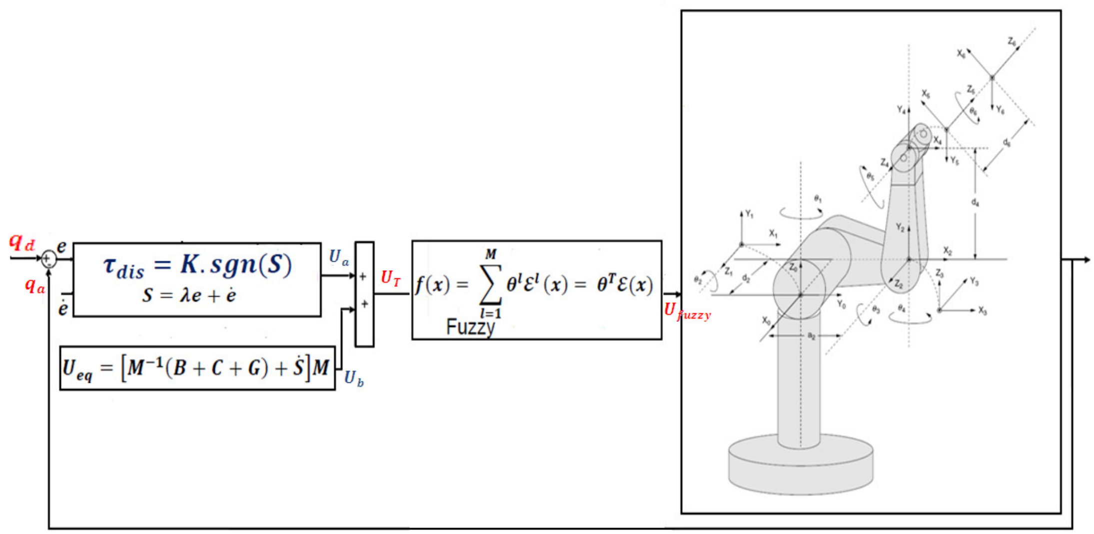

FIGURE3: Block Diagram of sliding mode Fuzzy Controller with Minimum Rule Base

It is basic that the system performance is sensitive to the sliding surface slope λ for sliding mode fuzzy controller. For instance, if large value of λ are chosen the response is very fast but the system is very unstable and conversely, if small value of λ considered the response of system is very slow but the system is very stable. Therefore, calculate the optimum value of λ for a system is one of the most important challenging works. SMFC has two most important advantages i.e. the number of rule base is smaller and Increase the robustness and stability.
In this method the control output can be calculated by

$$U_T = U_{dis} + U_{eq} \tag{48}$$

Where U_{eq} the nominal compensation is term and U_{dis} is the output of sliding function [9].

Third Step; Auto Tuning Sliding Surface Slope: All conventional controller have common difficulty, they need to find and estimate several nonlinear parameters. Tuning sliding surface slope can tune by mathematical automatically the scale parameters using mathematical model free method. To keep the structure of the controller as simple as possible and to avoid heavy computation, in this design model free mathematical supervisor tuner is selected. For nonlinear, uncertain, and time-variant plants (e.g., robot manipulators) adaptive method can be used to self adjusting the surface slope and gain updating factors. Research on adaptive sliding mode fuzzy controller is significantly growing, for instance, the different ASMFC have been reported in [5]; [10-12]. It is a basic fact that the system performance in SMFC is sensitive to sliding surface slope, λ. Thus, determination of an optimum λ value for a system is an important problem. If the system parameters are unknown or uncertain, the problem becomes more highlighted. This problem may be solved by adjusting the surface slope and boundary layer thickness of the sliding mode controller continuously in real-time. To keep the structure of the controller as simple as possible and to avoid heavy computation, a new supervisor tuner based on updated by a new coefficient factor kn is presented. In this method the supervisor part tunes the output scaling factors using gain online updating factors. The inputs of the supervisor term are error and change of error $(e,\dot{e})$ and the output of this controller is U, which it can be used to tune sliding surface slope, λ.

$$k_n = e^2 - \frac{(r_v - r_{vmin})^5}{1+|e|} + r_{vmin} \tag{49}$$

$$r_v = \frac{\left(de(k) - de(k-1)\right)}{de(.)} = \frac{\ddot{e}(t)}{\dot{e}(.)} \tag{50}$$

$$de(.) = \begin{Bmatrix} de(k); & if\ de(k) \geq de(k-1) \\ de(k-1) & if\ de(k) < de(k-1) \end{Bmatrix}$$

$$S_{new} = \lambda_{new} \times e_{new} + \dot{e}_{new}$$

$$e_{new} = e \times \lambda_{new}$$

$$\lambda_{new} = \lambda \times K_n$$

In this way, the performance of the system is improved with respect to the SMFC controller.

In this method the tunable part tunes the sliding surface slope. However pure sliding mode controller has satisfactory performance in a limit uncertainty but tune the performance of this controller in highly nonlinear and uncertain parameters (e.g., robot manipulator) is a difficult work which proposed methodology can solve above challenge by applied adaptive. The lyapunov candidate formulation for our design is defined by:

$$V = \frac{1}{2}S^T M S + \frac{1}{2}\sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{51}$$

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

$$S^T M\dot{S} + \frac{1}{2}S^T \dot{M} S = S^T(M\dot{S} + VS) \tag{52}$$

From following two functions:

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \tag{53}$$

And

$$\tau = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \tag{54}$$

We can get:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) = \hat{M}\ddot{q}_r + \hat{V}\dot{q}_r + \hat{G} - AS - K \tag{55}$$

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

$$M\dot{S} + (V + A)S = \Delta f - K \tag{56}$$

$$M\dot{S} = \Delta f - K - VS - AS$$

The derivative of V defined by;

$$\dot{V} = S^T M\dot{S} + \frac{1}{2}S^T\dot{M}S + \sum_{j=1}^{M}\frac{1}{\gamma_{sj}}\phi^T.\phi_j \tag{57}$$

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

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

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

suppose K_n is defined as follows

$$k_n = e^2 - \frac{(r_v - r_{vmin})^5}{1+|e|} + r_{vmin} \quad \textbf{(58)}$$

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

$$\dot{V} = \sum_{j=1}^{M} [S_j(\Delta f_j - (\theta^*)^T \zeta(S_j) k_n] - S^T AS + \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi_j^T [\gamma_{sj}.S_j.\zeta_j(S_j) + \dot{\phi}_j]) \quad \textbf{(59)}$$

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

$$\dot{V} = \sum_{j=1}^{m} [S_j \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j) k_n)] - S^T AS \quad \textbf{(60)}$$

If the minimum error can be defined by

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

□**(61)**□□$\dot{V}$ is intended as follows

(61)□□$\dot{V}$ is intended as follows

$\dot{V}$ is intended as follows

$$\dot{V} = \sum_{j=1}^{m} [S_j e_{mj}] - S^T AS \quad \textbf{(62)}$$

$$\leq \sum_{j=1}^{m} |S_j||e_{mj}| - S^T AS$$

$$= \sum_{j=1}^{m} |S_j||e_{mj}| - k_n S_j^2$$

$$= \sum_{j=1}^{m} |S_j|(|e_{mj}| - a_j S_j)$$

For continuous function $g(x)$, and suppose $\varepsilon > 0$ it is defined mathematical model free in form of $k_n|f(x) - g(x)| < \epsilon$

the minimum approximation error (e_{mj}) is very small.

$$that \quad k_n|S_j| > e_{mj} \ (S_j \neq 0) \qquad then \quad \dot{V} < 0 \ for \ (S_j \neq 0)$$

4 SIMULATION RESULTS

Classical sliding mode control (SMC) and adaptive sliding mode fuzzy control (ASMFC) are implemented in Matlab/Simulink environment. In theses controllers changing updating factor performance, tracking performance, error, and robustness are compared.

Changing Sliding Surface Slope Performance: For various value of sliding surface slope (λ) in SMC and ASMFC the trajectory performances have shown in Figures 4 and 5.

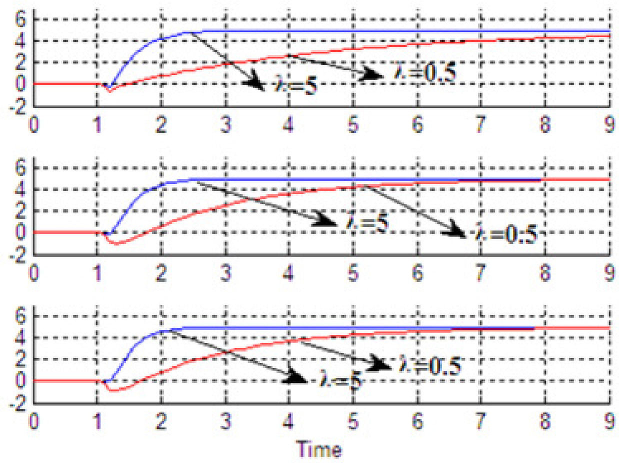

FIGURE 4 : Sliding surface slope in SMC: applied to 3DOF's robot manipulator

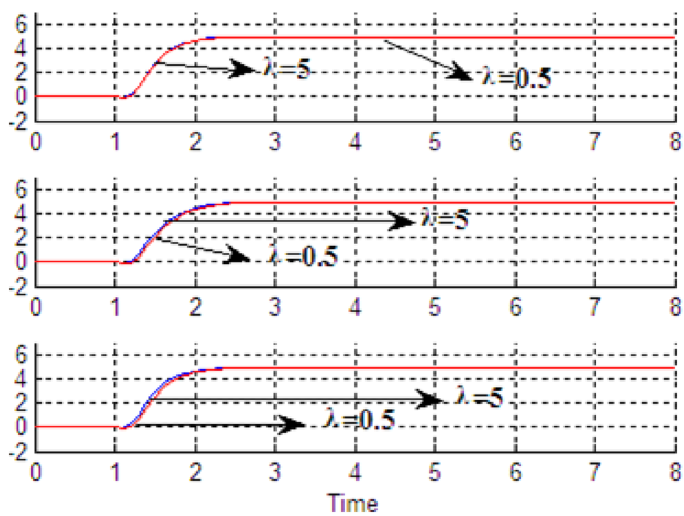

FIGURE 5: Sliding surface slope in ASMFC: applied to 3DOF's robot manipulator

Figures 4 and 5 are shown trajectory performance with different sliding surface slope; it is seen that AFSMC has the better performance in comparison with classical SMC.

Tracking Performances

From the simulation for first, second and third trajectory without any disturbance, it was seen that SMC and ASMFC have the about the same performance because this system is worked on certain environment and in sliding mode controller also is a robust nonlinear controller with acceptable performance. Figure 6 shows tracking performance without any disturbance for SMC and ASMFC.

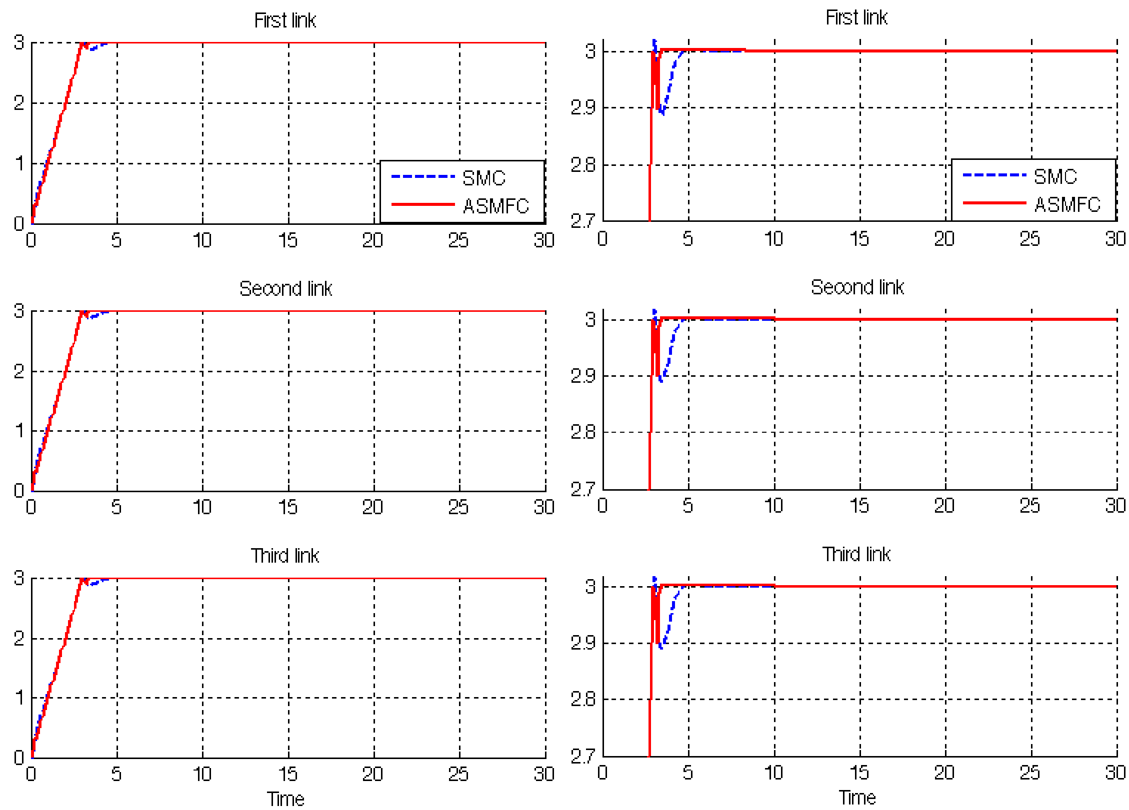

FIGURE 6 : SMC Vs. ASMFC: applied to 3DOF's robot manipulator

By comparing trajectory response trajectory without disturbance in SMC and ASMFC, it is found that the SMFC's overshoot **(0%)** is lower than IDC's **(3.33%)** and the rise time in both of controllers are the same.

Disturbance Rejection

Figure 7 has shown the power disturbance elimination in SMC and ASMFC. The main targets in these controllers are disturbance rejection as well as the remove the chattering phenomenon. A band limited white noise with predefined of 40% the power of input signal is applied to the SMC and SMFC. It found fairly fluctuations in SMC trajectory responses.

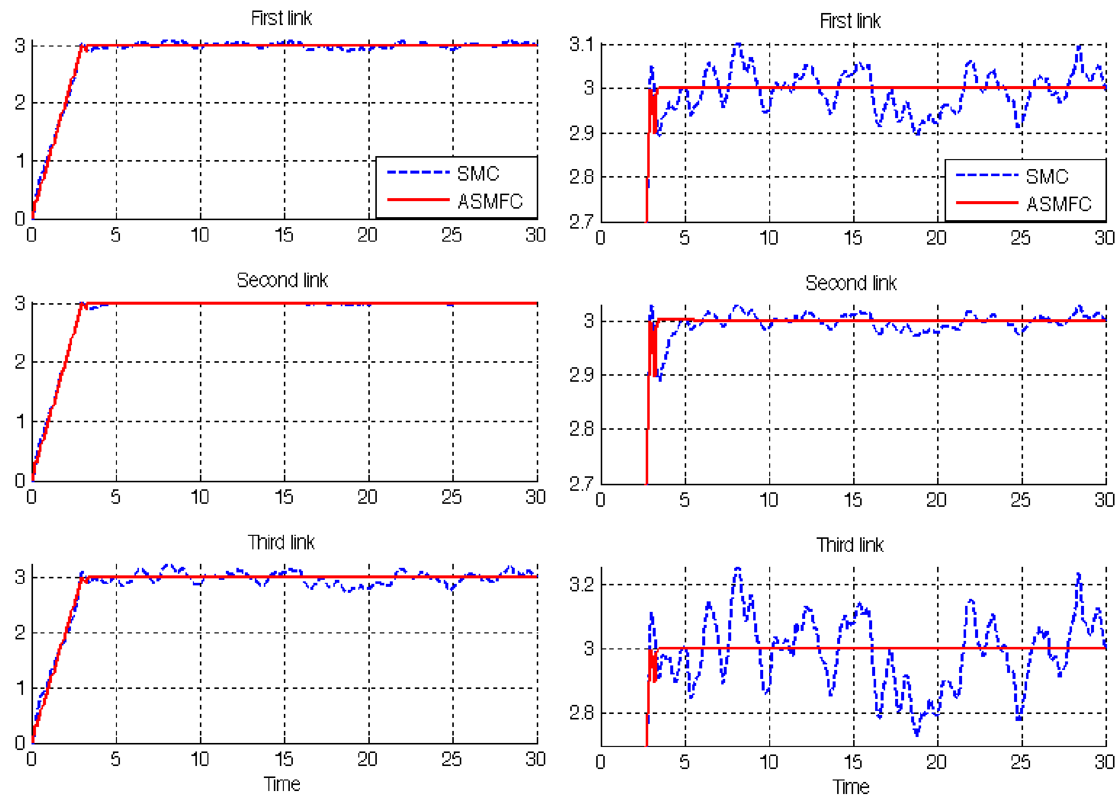

FIGURE 7: SMC Vs. ASMFC in presence of uncertainty: applied to robot manipulator.

Among above graph relating to trajectory following with external disturbance, SMC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the ASMFC's overshoot **(0%)** is lower than SMC's **(12.4%)**, although both of them have about the same rise time**.**

5 CONCLUSIONS

This research presents a design auto adjust sliding surface slope in sliding mode fuzzy controller (ASMFC) with improved in sliding mode controller which offers a model-free sliding mode controller. The sliding mode fuzzy controller is designed as 7 rules Mamdani's error-based to estimate the uncertainties in nonlinear equivalent part. To eliminate the chattering with regard to the uncertainty and external disturbance applied mathematical self tuning method to sliding mode fuzzy controller for adjusting the sliding surface slope coefficient (λ). In this research new λ is obtained by the previous λ multiple gains updating factor (K_n) which it also is based on error and change of error and also the second derivation of error. The proof of stability in this method is discussed. As a result auto adjust sliding surface slope in sliding mode fuzzy controller has superior performance in presence of structure and unstructured uncertainty (e.g., overshoot=0%, rise time=0.9 s, steady state error = 1e-7 and RMS error=0.00016) and eliminate the chattering.

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A New Estimate Sliding Mode Fuzzy Controller for Robotic Manipulator

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Abstract

One of the most active research areas in field of robotics is control of robot manipulator because this system has highly nonlinear dynamic parameters and most of dynamic parameters are unknown so design an acceptable controller is the main goal in this work. To solve this challenge position new estimation sliding mode fuzzy controller is introduced and applied to robot manipulator. This controller can solve to most important challenge in classical sliding mode controller in presence of highly uncertainty, namely; chattering phenomenon based on fuzzy estimator and online tuning and equivalent nonlinear dynamic based on estimation. Proposed method has acceptable performance in presence of uncertainty (e.g., overshoot=0%, rise time=0.8 s, steady state error = 1e-9 and RMS error=0.0001632).

Keywords: Sliding Mode Controller, Fuzzy Logic Methodology, Estimation, Sliding Mode Fuzzy Methodology, Robotic Manipulator.

1. INTRODUCTION, BACKGROUND and MOTIVATION

A robot is a machine that can be programmed to perform a variety of tasks it is divided into three main groups: Robot manipulator, Mobile robot and Hybrid robot, which Robot Manipulator is a set of rigid links interconnected by joints; it is divided into two main groups: open-chain manipulators and closed-chain robot manipulators. 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. PUMA 560 robot manipulator is a 6 DOF serial robot manipulator. It has many applications in industrial and academic. From the control point of view, robot manipulator is divided into two main subparts: Kinematics and Dynamics. Robot manipulator kinematics is essential part to calculate the relationship between rigid bodies and end-effector without any forces. Study of this part is fundamental to design a controller with acceptable performance, in real situations and practical applications. Dynamic is the study of motion with regard to forces. Dynamic modeling is important for control, mechanical design, and simulation. Dynamic parameters are used to describe the behavior of systems, the relationship between displacement, velocity and acceleration to forces acting on robot manipulator [1-2].

Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but while system works with various parameters and hard nonlinearities this technique is very tricky and it has some limitations such as working near the system operating point. Nonlinear control methodology can deal with nonlinear equations in the dynamics of robotic manipulators. Conventional nonlinear control methodology cannot provide good robustness for controlling robot manipulators. The control system designer is often unsure of the exact value of the robot manipulator dynamic parameters which describe the behavior of robot manipulator. Sliding mode controller is an influential nonlinear controller to certain and uncertain systems which it is based on nonlinear Lyapunov formulation and computes the required arm torques using the nonlinear feedback control law. Sliding mode control theory for control of robot manipulator was first proposed in 1978 by Young to solve the set point problem ($\dot{q}_d = 0$) by discontinuous method in the following form;

$$\tau_{(q,t)} = \begin{cases} \tau_i^+(q,t) & if\ S_i > 0 \\ \tau_i^-(q,t) & if\ S_i < 0 \end{cases} \tag{1}$$

where S_i is sliding surface (switching surface), $i = 1, 2, \dots\dots, n$ for *n*-DOF robot manipulator, $\tau_i(q,t)$ is the i^{th} torque of joint. 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[1, 6]. When all dynamic and physical parameters are known or limitation unknown the controller works superbly and output responses are good quality ; practically a large amount of systems have unlimited or highly uncertainties and sliding mode controller with estimator methodology reduce this kind of limitation. Conversely, pure sliding mode controller is used in many applications; it has two important drawbacks namely; chattering phenomenon, and nonlinear equivalent dynamic formulation in uncertain dynamic parameter. Chattering phenomenon can causes some problems such as saturation and heat the mechanical parts of robot manipulators or drivers. 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 [1]. 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. Slotine and Sastry have introduced boundary layer method instead of discontinuous method to reduce the chattering[21]. Slotine has presented sliding mode with boundary layer to improve the industry application [22]. Estimated uncertainty method used in term of uncertainty estimator to compensation of the system uncertainties. It has been used to solve the chattering phenomenon and also nonlinear equivalent dynamic. If estimator has an acceptable performance to compensate the uncertainties, the chattering is reduced. Research on estimated uncertainty to reduce the chattering is significantly growing as their applications such as industrial automation and robot manipulator. For instance, the applications of artificial intelligence, neural networks and fuzzy logic on estimated uncertainty method have been reported in [25-28]. Wang et al. [5] have proposed a simple fuzzy estimator controller beside the discontinuous and equivalent control terms to reduce the chattering. Their design had three main parts i.e. equivalent, discontinuous and fuzzy estimator tuning part which has reduced the chattering very well.

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].

However sliding mode controller has an acceptable performance but when system has unlimited uncertainty it cannot guarantee the best output performance so fuzzy logic method with applied system estimation improve the output response. 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 control estimation 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 a new SISO estimate sliding mode fuzzy algorithm 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, robot manipulator dynamics and introduction to the classical sliding mode controller with proof of stability and its application to robot manipulator. Part 3, introduces and describes the methodology algorithms 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, PROBLEM STATEMENTS and SLIDING MODE CONTROLLER FORMULATION

Robot Manipulator Dynamic Formulation: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 3, 16-28, 30, 38-40]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \tag{2}$$

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:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \tag{3}$$

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 (3) 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]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \tag{4}$$

Sliding Mode Control: This technique is very attractive from a control point of view. The central idea of sliding mode control (SMC) is based on nonlinear dynamic equivalent. 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, 31-44]:

$$e(t) = q_d(t) - q_a(t) \tag{5}$$

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. Consider a nonlinear single input dynamic system of the form [6]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{6}$$

Where u is the vector of control input, $x^{(n)}$ is the n^{th} derivation of$x$, $x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T$ is the state vector, $f(x)$ is unknown or uncertainty, and $b(x)$ is of known *sign* function. The control problem is truck to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and have an acceptable error which is given by:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \tag{7}$$

A time-varying sliding surface $s(x,t)$ is given by the following equation:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\tilde{x} = 0 \tag{8}$$

where λ is the positive constant. To further penalize tracking error integral part can be used in sliding surface part as follows:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\left(\int_0^t \tilde{x}\,dt\right) = 0 \tag{9}$$

The main target in this methodology is kept the sliding surface slope $s(x,t)$ near to the zero. Therefore, one of the common strategies is to find input U outside of $s(x,t)$.

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) \le -\zeta|s(x,t)| \tag{10}$$

where ζ is positive constant.

$$\textbf{If } S(0)>0 \rightarrow \frac{d}{dt}S(t) \le -\zeta \tag{11}$$

To eliminate the derivative term, it is used an integral term from t=0 to t=t_{reach}

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt}S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \tag{12}$$

Where t_{reach} is the time that trajectories reach to the sliding surface so, suppose S($t_{reach} = 0$) defined as

$$0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta} \tag{13}$$

and

$$if\ S(0) < 0 \rightarrow 0 - S(0) \le -\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta} \tag{14}$$

Equation (14) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \tag{15}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda) \quad \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{16}$$

The derivation of S, namely, $\dot{S}$ can be calculated as the following;

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{17}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \rightarrow \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \tag{18}$$

Where f is the dynamic uncertain, and also since $S = 0$ and $\dot{S} = 0$, to have the best approximation ,$\widehat{U}$ is defined as

$$\widehat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \tag{19}$$

A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = \widehat{U} - K(\vec{x}, t) \cdot \mathrm{sgn}(s) \tag{20}$$

where the switching function $\mathrm{sgn}(S)$ is defined as

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{21}$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (10) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) = \dot{S} \cdot S = \left[f - \hat{f} - K\mathrm{sgn}(s)\right] \cdot S = \left(f - \hat{f}\right) \cdot S - K|S| \tag{22}$$

and if the equation (14) instead of (13) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{23}$$

in this method the approximation of U is computed as

$$\widehat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{24}$$

Based on above discussion, the control law for a multi degrees of freedom robot manipulator is written as:

$$\tau = \tau_{eq} + \tau_{dis} \tag{25}$$

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

$$\tau_{eq} = \left[M^{-1}(B + C + G) + \dot{S}\right]M \tag{26}$$

Where [15-44]

$$\tau_{eq} = \begin{bmatrix} \tau_{eq1} \\ \tau_{eq2} \\ \tau_{eq3} \\ \tau_{eq4} \\ \tau_{eq5} \\ \tau_{eq6} \end{bmatrix}, M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

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

$$\dot{S} = \begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \\ \dot{S}_3 \\ \dot{S}_4 \\ \dot{S}_5 \\ \dot{S}_6 \end{bmatrix} \text{ and } M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}$$

and τ_{dis} is computed as;

$$\tau_{dis} = K \cdot \mathrm{sgn}(S) \tag{27}$$

where

$$\tau_{dis} = \begin{bmatrix} \tau_{dis1} \\ \tau_{dis2} \\ \tau_{dis3} \\ \tau_{dis4} \\ \tau_{dis5} \\ \tau_{dis6} \end{bmatrix}, K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \end{bmatrix}, (S) = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} \text{ and } S = \lambda e + \dot{e}$$

The result scheme is shown in Figure 1.

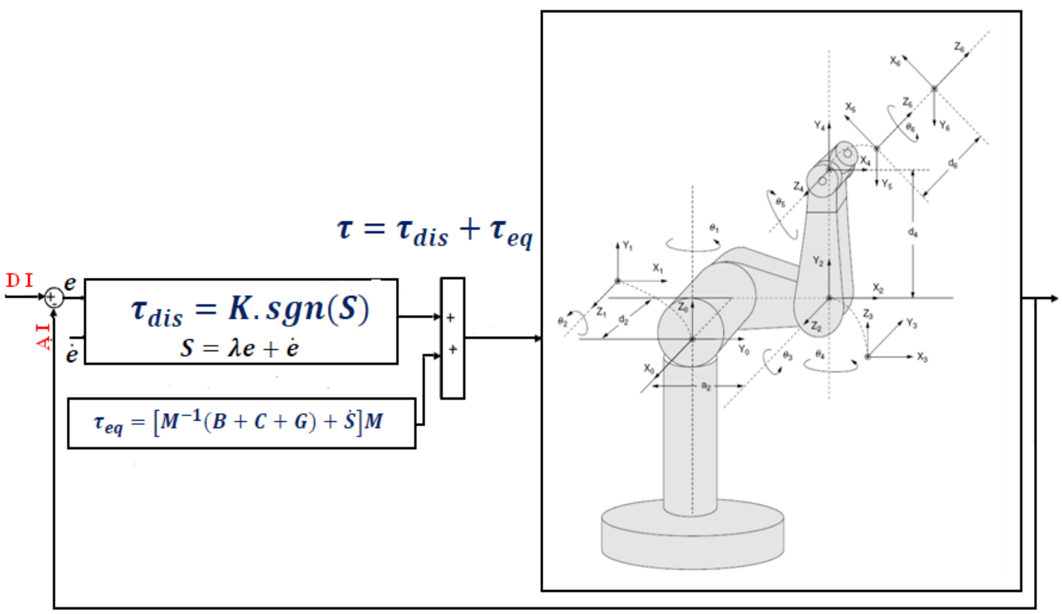

FIGURE 1: Block diagram of Sliding Mode Controller (SMC)

Problem Statement: Even though, SMC is used in wide range areas but, pure SMC has the following disadvantages; namely; chattering phenomenon and nonlinear equivalent dynamic formulation in presence of structure and unstructured uncertain system. Proposed method focuses on substitution fuzzy logic system applied to main controller (SMC) to compensate the uncertainty in nonlinear dynamic equation to implement easily.

Proof of Stability: The proof of Lyapunov function can be determined by the following equations. The dynamic formulation of robot manipulate can be written by the following equation

$$\tau = M(q)\ddot{q} + V(q, \dot{q})\dot{q} + G(q) \tag{28}$$

the lyapunov formulation can be written as follows,

$$V = \frac{1}{2} S^T . M . S \tag{29}$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S^T . \dot{M} . S + S^T \, M \dot{S} \tag{30}$$

the dynamic equation of robot manipulator can be written based on the sliding surface as

$$M\dot{S} = -VS + M\dot{S} + VS + G - \tau \tag{31}$$

it is assumed that

$$S^T \left(\dot{M} - 2V \right) S = 0 \tag{32}$$

by substituting (31) in (30)

$$\dot{V} = \frac{1}{2} S^T \dot{M} S - S^T VS + S^T \left(M\dot{S} + VS + G - \tau \right) = S^T \left(M\dot{S} + VS + G - \tau \right) \tag{33}$$

suppose the control input is written as follows

$$\hat{\tau} = \widehat{\tau_{eq}} + \widehat{\tau_{dis}} = \left[\hat{M}^{-1} \left(\hat{V} + \hat{G} \right) + \dot{S} \right] \hat{M} + K . sgn(S) + K_v S \tag{34}$$

by replacing the equation (34) in (33)

$$\dot{V} = S^T (M\dot{S} + VS + G - \hat{M}\dot{S} - \hat{V}S - \hat{G} - K_v S - K sgn(S) = S^T \left(\tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K \right. \tag{35}$$

it is obvious that

$$\left| \tilde{M}\dot{S} + \tilde{V}S + \tilde{G} - K_v S \right| \le \left| \tilde{M}\dot{S} \right| + \left| \tilde{V}S \right| + \left| \tilde{G} \right| + \left| K_v S \right| \tag{36}$$

the Lemma equation in robot manipulator system can be written as follows

$$K_u = \left[\left| \tilde{M}\dot{S} \right| + |VS| + |G| + |K_v S| + \eta \right]_i , i = 1, 2, 3, 4, \ldots \tag{37}$$

the equation (32) can be written as

$$K_u \ge \left| \left[\tilde{M}\dot{S} + VS + G - K_v S \right]_i \right| + \eta_i \tag{38}$$

therefore, it can be shown that

$$\dot{V} \le - \sum_{i=1}^{n} \eta_i \left| S_i \right| \tag{39}$$

Consequently the equation (39) guaranties the stability of the Lyapunov equation.

3. METHODOLOGY: DESIGN A NEW STIMATE SLIDING MODE FUZZY CONTROLLER

First Step, Design Sliding Mode 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 soft computing control method. The fuzzy inference mechanism provides a mechanism for referring the rule base in fuzzy set. There are two most commonly method that can be used in fuzzy logic controllers, namely, Mamdani method and Sugeno method, which Mamdani built one of the first fuzzy controller to control of system engine and Michio Sugeno suggested to use a singleton as a membership function of the rule consequent. The Mamdani fuzzy inference method has four steps, namely, fuzzification, rule evaluation, aggregation of the rule outputs and defuzzification. Sugeno method is very similar to Mamdani method but Sugeno changed the consequent rule base that he used the mathematical function of the input rule base instead of fuzzy set [15-44].

Fuzzification: Fuzzification is used to determine the membership degrees for antecedent part when x and y have crisp values. The first step in fuzzification is determine inputs and outputs which, it has one input (U_T) and one output (U_{fuzzy}). The input is S which measures the summation of discontinuous and equivalent part 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_T) 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];

$$\textbf{F.R}^1\textbf{:}\ \textit{IF}\ U_T\ \textit{is NB, THEN}\ U_{fuzzy}\ \textit{is LL.} \tag{40}$$

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): There are several methodologies in aggregation of the rule outputs that can be used in fuzzy logic controllers, 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 is used to this work which the calculation is defined as follows;

$$\mu_U(x_k,y_k,U) = \mu_{\cup_{i=1}^r FR^i}(x_k,y_k,U) = max\left\{min_{i=1}^r\left[\mu_{R_{pq}}(x_k,y_k),\mu_{p_m}(U)\right]\right\} \tag{41}$$

Deffuzzification: The last step to design fuzzy inference in our sliding mode fuzzy 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. There are several methodologies in defuzzification of the rule outputs that can be used in fuzzy logic controllers but two most common defuzzification methods are: Center of gravity method (COG) and Center of area (COA) method. In this design the Center of gravity method (COG) is used and calculated by the following equation [36];

$$COG(x_k,y_k) = \frac{\sum_i U_i \sum_{j=1}^r \mu_u(x_k,y_k,U_i)}{\sum_i \sum_{j=1}^r \mu_u(x_k,y_k,U_i)} \tag{42}$$

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

U_T	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 sliding mode fuzzy estimator controller based on fuzzy logic controller and minimum rule base.

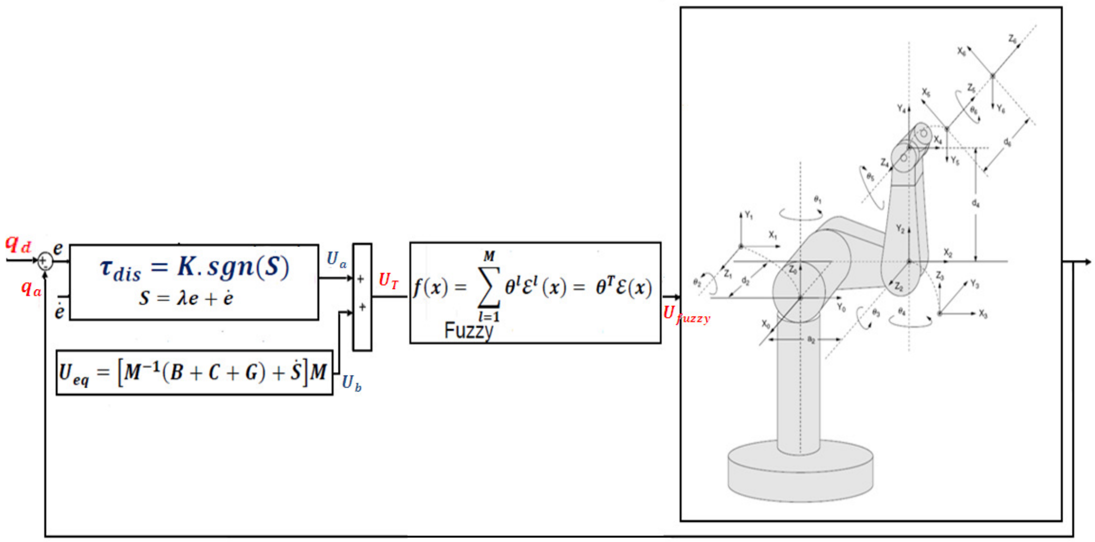

FIGURE2: Block Diagram of sliding mode Fuzzy estimator Controller with Minimum Rule Base

Second step; design sliding mode fuzzy estimator and applied an input fuzzy logic methodology to online tuning: All conventional controller have common difficulty, they need to find and estimate several nonlinear parameters. Tuning sliding mode fuzzy method can tune duration nonlinear parameters automatically the scale parameters using artificial intelligence method. To keep the structure of the controller as simple as possible and to avoid heavy computation, in this design one input Mamdani fuzzy supervisor tuner is selected. In this method the tuneable controller tunes the nonlinear uncertainty and removes the chattering in opt to applied fuzzy logic method to previous fuzzy logic estimator. However pure inverse sliding mode controller has satisfactory performance in a limit uncertainty but tune the performance of this controller in highly nonlinear and uncertain parameters (e.g., robot manipulator) is a difficult work which proposed methodology can solve above challenge by applied two fuzzy methodology; the first one for estimation and the second one for online tuning. The lyapunov candidate formulation for our design is defined by:

$$V = \frac{1}{2} S^T M S + \frac{1}{2} \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi^T . \phi_j \tag{43}$$

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

$$S^T M \dot{S} + \frac{1}{2} S^T \dot{M} S = S^T (M\dot{S} + VS) \tag{44}$$

From following two functions:

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) \tag{45}$$

And

$$\tau = \widehat{M}\ddot{q}_r + \widehat{V}\dot{q}_r + \widehat{G} - AS - K \tag{46}$$

We can get:

$$M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) = \widehat{M}\ddot{q}_r + \widehat{V}\dot{q}_r + \widehat{G} - AS - K \tag{47}$$

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

$$M\dot{S} + (V + A)S = \Delta f - K \tag{48}$$

$$M\dot{S} = \Delta f - K - VS - AS$$

The derivative of V defined by;

$$\dot{V} = S^T M\dot{S} + \frac{1}{2}S^T \dot{M} S + \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi^T . \dot{\phi}_j \tag{49}$$

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

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

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

suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l [\mu_A(S_j)]}{\sum_{l=1}^{M} [\mu_A(S_j)]} = \theta_j^T \zeta_j(S_j) \tag{50}$$

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 $\zeta_j^1(S_j) = \frac{\mu_{(A)}{}_j^l(S_j)}{\sum_i \mu_{(A)}{}_j^l(S_j)}$

$$\dot{V} = \sum_{j=1}^{M} [S_j(\Delta f_j - \theta^T \zeta(S_j)] - S^T AS + \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi^T . \dot{\phi}_j \tag{51}$$

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

$$\dot{V} = \sum_{j=1}^{M} [S_j(\Delta f_j - \theta^{*T} \zeta(S_j) + \phi^T \zeta(S_j)] - S^T AS + \sum_{j=1}^{M} \frac{1}{\gamma_{sj}} \phi^T . \dot{\phi}_j \tag{52}$$

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

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

$$\dot{V} = \sum_{j=1}^{m} [S_j \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j))] - S^T AS \quad \textbf{(53)}$$

If the minimum error can be defined by

$$e_{mj} = \Delta f_j - ((\theta_j^*)^T \zeta_j(S_j)) \quad \textbf{(54)}$$

$\dot{V}$ is intended as follows

$$\begin{aligned} \dot{V} &= \sum_{j=1}^{m} [S_j e_{mj}] - S^T AS \\ &\le \textstyle\sum_{j=1}^{m} |S_j||e_{mj}| - S^T AS \\ &= \sum_{j=1}^{m} |S_j||e_{mj}| - a_j S_j^{\,2} \\ &= \sum_{j=1}^{m} |S_j|(|e_{mj}| - a_j S_j) \end{aligned} \quad \textbf{(55)}$$

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.

$if \quad a_j = \alpha \quad that \quad \alpha|S_j| > e_{mj} \ (S_j \neq 0) \qquad then \quad \dot{V} < 0 \ for \ (S_j \neq 0)$

Figure 3 is shown the block diagram of proposed fuzzy online applied to sliding mode fuzzy estimator controller.

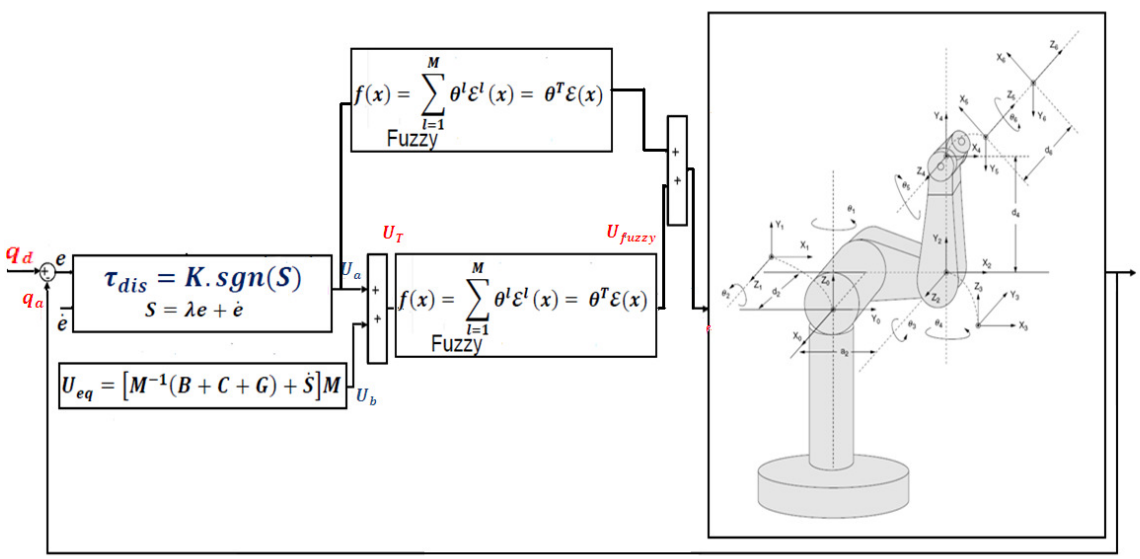

FIGURE 3: Design fuzzy online sliding mode fuzzy estimator controller

4 SIMULATION RESULTS

Pure sliding mode controller (SMC) and fuzzy online sliding mode fuzzy estimator controller (ASMFC) 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 SMC and ASMFC have the about the same performance because this system is worked on certain environment and in sliding mode controller also is a robust nonlinear controller with acceptable performance. Figure 4 shows tracking performance without any disturbance for SMC and ASMFC.

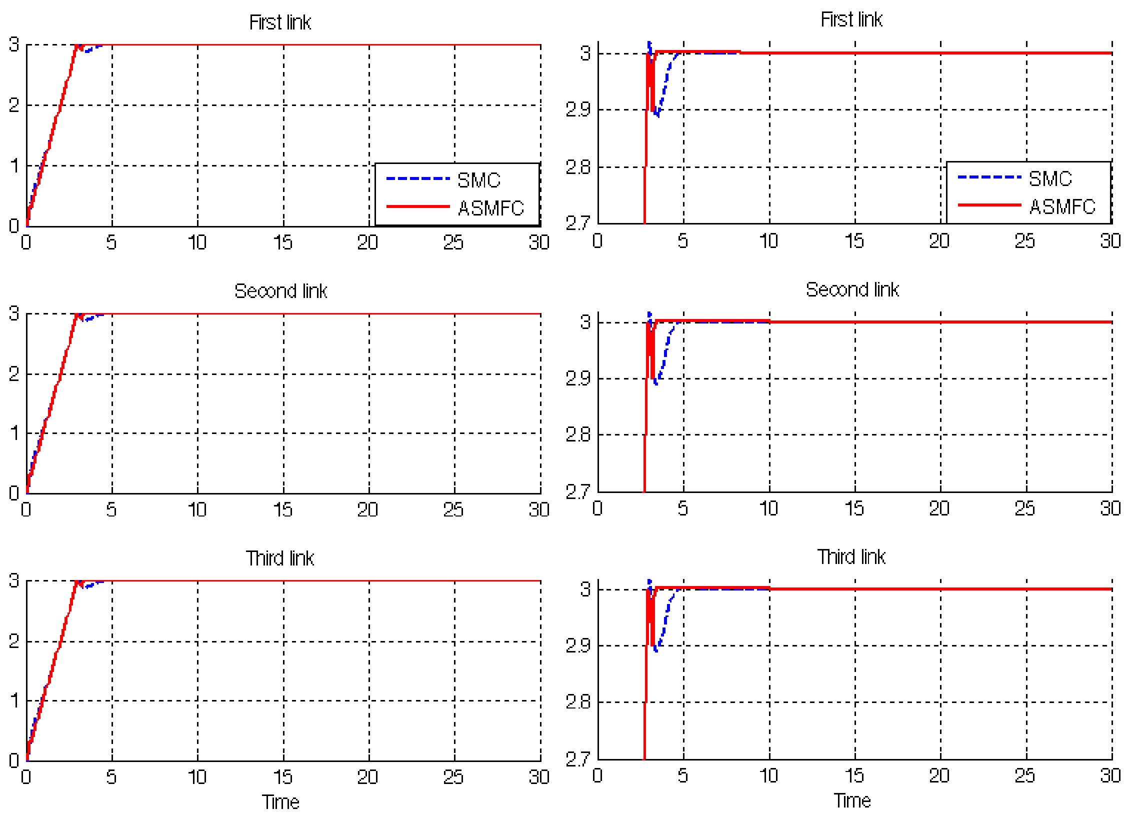

FIGURE 4: SMC Vs. ASMFC: applied to 3DOF's robot manipulator

By comparing trajectory response trajectory without disturbance in SMC and ASMFC, it is found that the SMFC's overshoot **(0%)** is lower than IDC's **(3.3%)** and the rise time in both of controllers are the same.

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

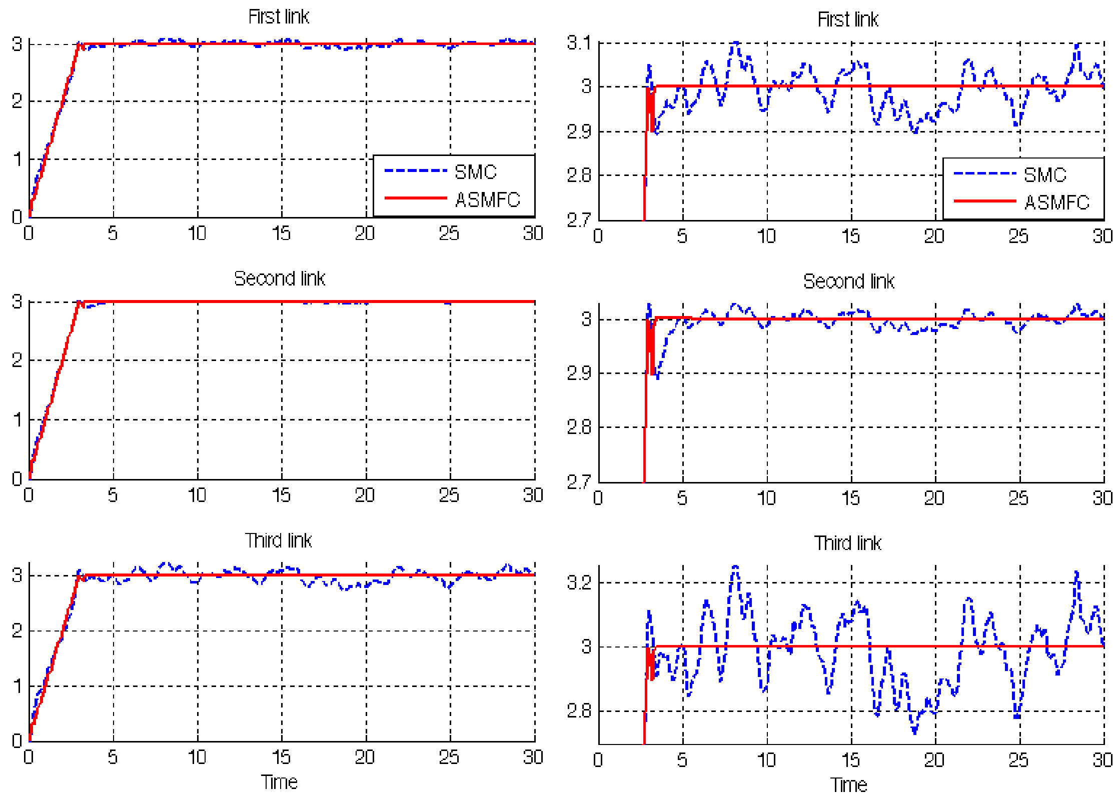

FIGURE 5: SMC Vs. ASMFC in presence of uncertainty: applied to robot manipulator.

Among above graph relating to trajectory following with external disturbance, SMC has fairly fluctuations. By comparing some control parameters such as overshoot and rise time it found that the ASMFC's overshoot **(0%)** is lower than SMC's **(12%)**, although both of them have about the same rise time**.**

5 CONCLUSIONS

Refer to the research, a position online tuning sliding mode fuzzy estimator controller (ASMFC) design and application to robot manipulator has proposed. This research is based on sliding mode controller which eliminate the chattering phenomenon based on nonlinear fuzzy logic method and estimator block, eliminate the uncertainty unknown nonlinearity part based on applied online tuning fuzzy logic methodology in SMFC and reduce the uncertainty challenge based on fuzzy logic methodology and estimate via fuzzy estimator method. As a result proposed method has superior performance in presence of structure and unstructured uncertainty (e.g., overshoot=0%, rise time=0.8 s, steady state error = 1e-9 and RMS error=0.0001632) and eliminate the chattering.

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INSTRUCTIONS TO CONTRIBUTORS

Robots are becoming part of people's everyday social lives - and will increasingly become so. In future years, robots may become caretaking assistants for the elderly or academic tutors for our children, or medical assistants, day care assistants, or psychological counselors. Robots may become our co-workers in factories and offices, or maids in our homes.

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Volume: 3 - **Issue: 2**

i. Paper Submission: February 28, 2012 **ii. Author Notification:** March 31, 2012

iii. Issue Publication: April 2012

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