Design and Implementation of Sliding Mode Algorithm: Applied to Robot Manipulator-A Review

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Abstract

Refer to the research, review of sliding mode controller is introduced and application to robot manipulator has proposed in order to design high performance nonlinear controller in the presence of uncertainties. Regarding to the positive points in sliding mode controller, fuzzy logic controller and adaptive method, the output in most of research have improved. Each method by adding to the previous algorithm has covered negative points. Obviously robot manipulator is nonlinear, and a number of parameters are uncertain, this research focuses on comparison between sliding mode algorithm which analyzed by many researcher. Sliding mode controller (SMC) is one of the nonlinear robust controllers which it can be used in uncertainty nonlinear dynamic systems. This nonlinear controller has two challenges namely nonlinear dynamic equivalent part and chattering phenomenon. A review of sliding mode controller for robot manipulator will be investigated in this research.

Keywords: Robotic System, Nonlinear System, Robust Controller, Sliding Mode Controller.

1. INTRODUCTION

There are a lot of control methodologies that can be used for control of robot manipulators. These range of various controllers applied from linear to nonlinear, to lots of non-classical non-linear and adaptive non-classical non-linear. In this paper an attempted has been made to do a review of sliding mode control (SMC) for robotics manipulator.

Non linear control methodologies are more general because they can be used in linear and non linear systems. These controllers can solve different problems such as, invariance to system uncertainties, and resistance to the external disturbance. The most common non linear methodologies that have been proposed to solve the control problem consist of the following methodologies: feedback linearization control methodology, passivity-based control methodology, sliding mode control methodology, robust Lyapunov-based control methodology, adaptive control methodology, and artificial intelligence- based methodology [2].

Sliding mode controller (SMC) is a powerful nonlinear controller which has been analysed by many researchers especially in recent years. This theory was first proposed in the early 1950 by Emelyanov and several co-workers and has been extensively developed since then with the invention of high speed control devices [19, 21]. The main reason to select this controller in wide range area is have acceptable control performance and solve two most important challenging topics in control which names, stability and robustness [2; 17; 62]. However, this controller used in wide range but, pure sliding mode controller has following disadvantages. Firstly, chattering problem; which can caused the high frequency oscillation of the controllers output. Secondly, sensitivity; this controller is very sensitive to the noise when the input signals very close to the zero. Last but not the least, nonlinear equivalent dynamic formulation; which this problem is very important to have a good performance and it is difficult to calculation because it is depending on the nonlinear dynamic equation [63, 25].

Chattering phenomenon can cause some problems such as saturation and heat for mechanical parts of robot manipulators or drivers. To reduce or eliminate the chattering, various papers have been reported by many researchers and classified in two most important methods, namely, boundary layer saturation method and estimated uncertainties method [2, 19, 21-23, 27, 51, 53, 56].

In recent years, artificial intelligence theory has been used in sliding mode control systems. Neural network, fuzzy logic, and neuro-fuzzy are synergically combined with sliding mode controller and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). The strategies for robotics are classified in two main groups: classical and non-classical methods, where the classical methods use the mathematical models to control systems and non-classical methods use the artificial intelligence theory such as fuzzy logic, neural networks and/or neuro-fuzzy.

After the invention of fuzzy logic theory in 1965 by Zadeh, this theory was used in wide range applications. Fuzzy logic controller (FLC) is one of the most important applications in fuzzy logic theory. This controller can be used to control of nonlinear, uncertain systems and transfer expert knowledge to mathematical formulation. However pure FLC works in many areas but, it cannot guarantee the basic requirement of stability and acceptable performance [53]. Some researchers applied fuzzy logic methodology in sliding mode controllers (FSMC) to reduce the chattering and equivalent problems in pure sliding mode controller so called fuzzy sliding mode controller [41, 46, 61] and the other researchers applied sliding mode methodology in fuzzy logic controller (SMFC) to improve the stability of system that is most important challenge in pure FLC [4, 23, 48-50].

Fuzzy sliding mode controller (FSMC) is a sliding mode controller which combined to fuzzy logic system (FLS) to reduce or eliminate the high frequency oscillation (chattering), to compensate the unknown system dynamics, and also to adjustment of the linear sliding surface slope. H.Temeltas [46] has proposed FSMC to achieving robust tracking of nonlinear systems. C. L. Hwang et al. [8] have proposed a fuzzy model based sliding mode control based on N fuzzy based linear state-space. A multi-input multi-output FSMC to reduce the chattering and constructed to approximate the unknown system has been presented for a robot manipulator [42].

Sliding mode fuzzy controller (SMFC) is a fuzzy logic controller based on sliding mode methodology to reduce the fuzzy rules and to refine the stability of close loop system. Research on SMFC is significantly growing as their applications, for instance, in control robot manipulator which, have been reported in [4, 23, 48-50]. H.K.Lee et al. [52] have presented self tuning SMFC to reduce the fuzzy rules, increase the stability and to automatically adjusted control parameters. Palm R [23] has proposed SMFC to increase the robustness and trajectory disturbance.

Another method to intelligent control of robot manipulator is Artificial Neural Networks (ANNS) or Neural networks (NNs). It is a parametric nonlinear function and the parameters are the weights of the NNs. It can be used in two areas in robotics, namely, control robot manipulator and identification. Neural networks control is very effective tool to control robot manipulator when robot manipulators have uncertainty in dynamic part. With this method, researcher can design approximate for an unknown dynamical system only by knowing the input-output data of systems (i.e., training data) [24-25].

Adaptive control used in systems whose dynamic parameters are varying and need to be training on line. In general states adaptive control classified in two main groups: traditional adaptive method and fuzzy adaptive method, that traditional adaptive method need to have some information about dynamic plant and some dynamic parameters must be known but fuzzy adaptive method can training the variation of parameters by expert knowledge. Combined adaptive method to artificial sliding mode controllers can help to controllers to have better performance by online tuning the nonlinear and time variant parameters. F Y Hsu et al. [54] have presented adaptive fuzzy sliding mode control, which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability robot manipulator controller. Y.C. Hsueh et al. [43] have presented self tuning sliding mode controller which can resolve the chattering problem without to use of saturation function.

This paper is organized as follows. In section 2, main subject of sliding mode controller and formulation are presented. This section covered the following details, classical sliding mode control, classical sliding for robotic manipulators, equivalent control and chatter free sliding control. A review of the fuzzy logic system and application to sliding mode controller is presented and introduces the description and analysis of adaptive artificial sliding mode controller is presented in section 3. In section 4, the conclusion is presented.

2 SLIDING MODE CONTROL (VARIABLE STRUCTURE CONTROL) AND THE ROBOT MANIPULATOR APPLICATIONS

Sliding mode controller (SMC) is a powerful nonlinear controller which has been analyzed by many researchers especially in recent years. This theory was first proposed in the early 1950 by Emelyanov and several co-workers and has been extensively developed since then with the invention of high speed control devices [2]. The main reason to opt for this controller is its acceptable control performance in wide range and solves two most important challenging topics in control which names, stability and robustness [7, 17-20]. 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 [19, 3];

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

where S_i is sliding surface (switching surface), $i = 1, 2, \ldots\ldots, n$ 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]. However, this controller used in many applications but, pure sliding mode controller has following challenges: chattering phenomenon, and nonlinear equivalent dynamic formulation [20].

Chattering phenomenon can causes some problems such as saturation and heat the mechanical parts of robot manipulators or drivers that has shown in Figure 2.6. 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]. R. Palm has presented a fuzzy method to nonlinear approximation instead of linear approximation inside the boundary layer to improve the chattering and control the result performance[23]. Moreover, C. C. Weng and W. S. Yu improved the previous method by using a new method in fuzzy nonlinear approximation inside the boundary layer and adaptive method[24]. As mentioned [24]sliding mode fuzzy controller (SMFC) is fuzzy controller based on sliding mode technique to simple implement, most exceptional stability and robustness. Conversely above method has the following advantages; reducing the number of fuzzy rule base and increasing robustness and stability, the main disadvantage of SMFC is need to define the sliding surface slope coefficient very carefully. To eliminate the above problems control researchers have applied artificial intelligence method (e.g., fuzzy logic) in nonlinear robust controller (e.g., sliding mode controller) besides this technique is very useful in order to implement easily.

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]. Wu et al. [30] 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. Elmali et al. [27]and Li and Xu [29]have addressed sliding mode control with perturbation estimation method (SMCPE) to reduce the classical sliding mode chattering. This method was tested for the tracking control of the first two links of a SCARA type HITACHI robot. In this technique, digital controller is used to increase the system's response quality. Conversely this method has the following advantages; increasing the controller's response speed and reducing dependence on dynamic system model by on-line control, the main disadvantage are chattering phenomenon and need to improve the performance.

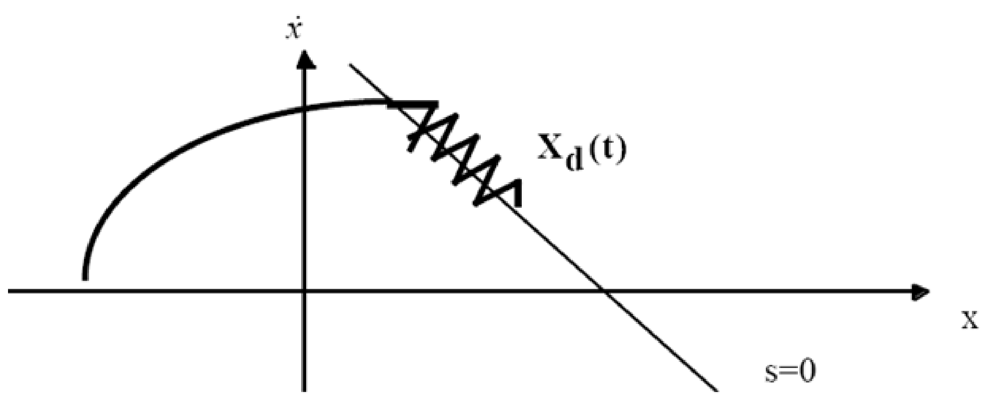

FIGURE 1: Chattering as a result of imperfect control switching [1]

Robot manipulators are one of the highly nonlinear and uncertain systems which caused to needed to robust controller. This section provides introducing the formulation of sliding mode controller to robot manipulator based on [1, 6]Consider a nonlinear single input dynamic system of the form [6]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \quad \textbf{(2)}$$

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:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \quad (3)$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \tilde{x} = 0 \quad (4)$$

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

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \left(\int_0^t \tilde{x} \, dt \right) = 0 \quad (5)$$

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 $s(x,t)$.

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) \le -\zeta |s(x,t)| \quad (6)$$

where ζ is positive constant and in equation (6) forces tracking trajectories is towards sliding condition as shown in Figure 2.

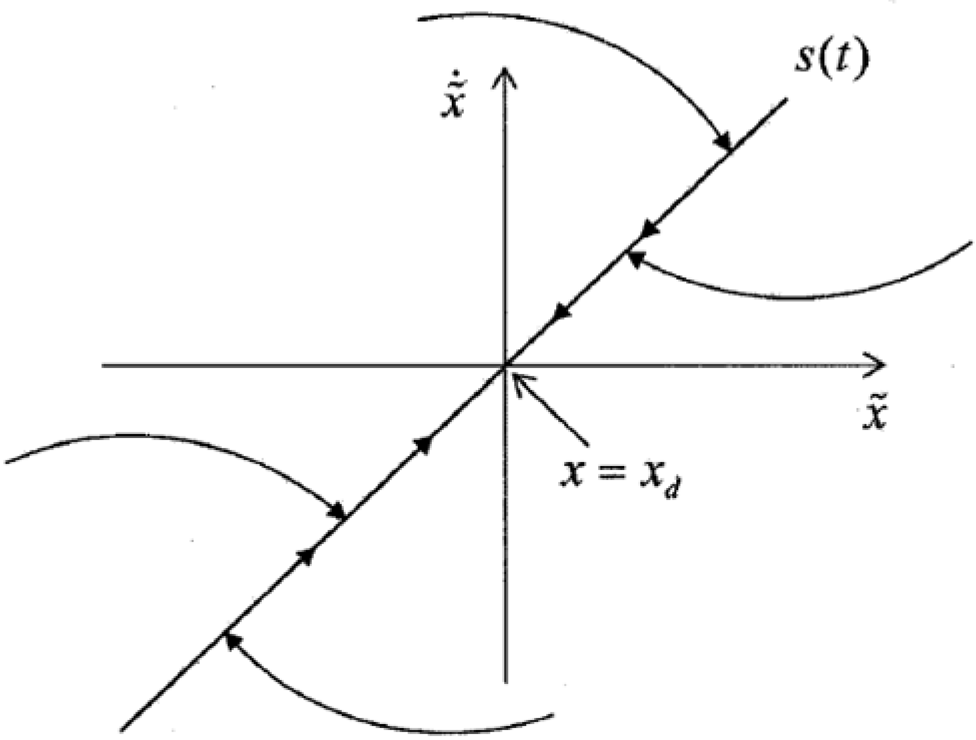

FIGURE 2: Sliding surface [2]

$$\text{If } S(0)>0 \rightarrow \frac{d}{dt} S(t) \le -\zeta \quad (7)$$

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

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \quad (8)$$

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

$$0-S(0)\le -\eta(t_{reach}) \to t_{reach} \le \frac{S(0)}{\zeta} \tag{9}$$

and

$$if\ S(0)<0 \to 0-S(0)\le -\eta(t_{reach}) \to S(0)\le -\zeta(t_{reach}) \to t_{reach} \le \frac{|S(0)|}{\eta} \tag{10}$$

Equation (2.41) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \to error(x-x_d)=0 \tag{11}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt}+\lambda)\quad \tilde{x} = (\dot{x}-\dot{x}_d)+\lambda(x-x_d) \tag{12}$$

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

$$\dot{S} = (\ddot{x}-\ddot{x}_d)+\lambda(\dot{x}-\dot{x}_d) \tag{13}$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \ \to \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x}-\dot{x}_d) \tag{14}$$

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

$$\hat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x}-\dot{x}_d) \tag{15}$$

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

$$U_{dis} = \hat{U} - K(\vec{x},t)\cdot \mathrm{sgn}(s) \tag{16}$$

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

$$sgn(s) = \begin{cases} 1 & s>0 \\ -1 & s<0 \\ 0 & s=0 \end{cases} \tag{17}$$

and the $K(\vec{x},t)$ is the positive constant. Suppose by (16) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt}s^2(x,t) = \dot{S}\cdot S = \left[f-\hat{f}-K\mathrm{sgn}(s)\right]\cdot S = \left(f-\hat{f}\right)\cdot S - K|S| \tag{18}$$

and if the equation (17) instead of (18) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt}+\lambda)^2 \left(\int_0^t \tilde{x}\,dt\right) = (\dot{x}-\dot{x}_d)+2\lambda(\dot{x}-\dot{x}_d)-\lambda^2(x-x_d) \tag{19}$$

in this method the approximation of U is computed as

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x}-\dot{x}_d) + \lambda^2(x-x_d) \tag{20}$$

To reduce or eliminate the chattering it 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. Figure 3 is shown the control law in boundary layer.

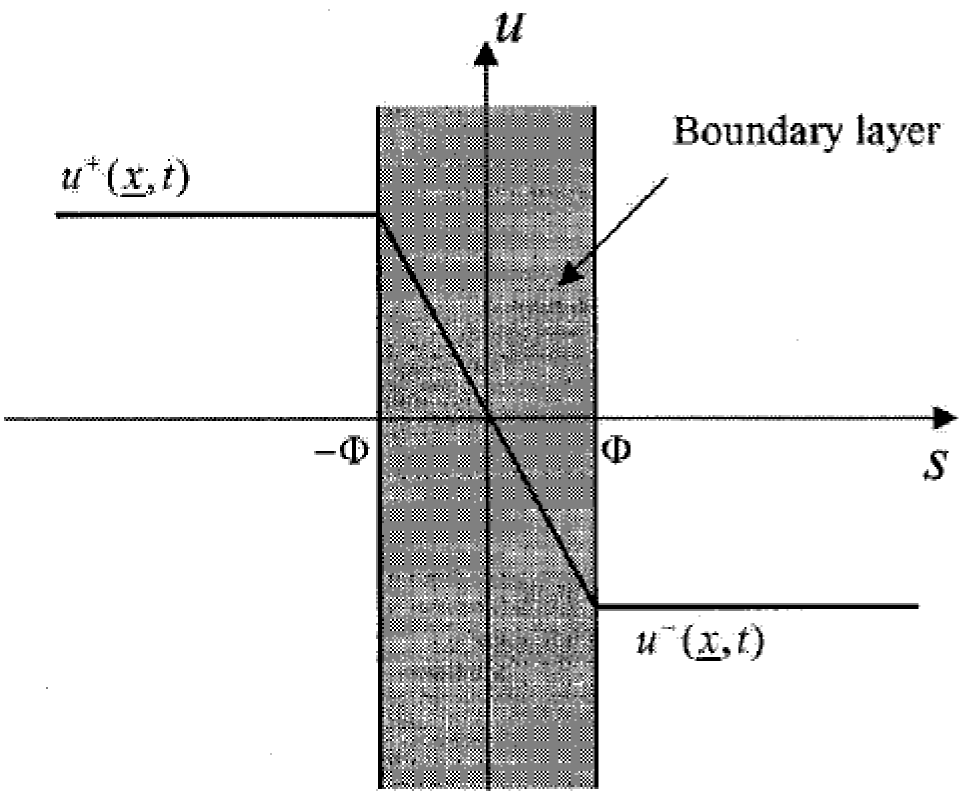

FIGURE 3: Boundary layer applied in discontinuous part [2]

$$B(t) = \{x, |S(t)| \le \emptyset\}; \emptyset > 0 \quad \textbf{(21)}$$

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

$$U = K(\vec{x},t) \cdot \mathrm{Sat}\left(^{S}/_{\emptyset}\right) \quad \textbf{(22)}$$

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

$$\mathrm{sat}\left(^{S}/_{\emptyset}\right) = \begin{cases} 1 & (^{S}/_{\emptyset} > 1) \\ -1 & (^{s}/_{\emptyset} < 1) \\ ^{s}/_{\emptyset} & (-1 < ^{S}/_{\emptyset} < 1) \end{cases} \quad \textbf{(23)}$$

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

$$\tau = \tau_{eq} + \tau_{sat} \quad \textbf{(24)}$$

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

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

Where τ is $n \times 1$ vector of actuation torque, M (q) is $n \times n$ symmetric and positive define inertia matrix, $B(q)$ is matrix of coriolis torques, $C(q)$ is matrix of centrifugal torque, $[\dot{q}\,\dot{q}]$ is vector of joint velocity that it can give by: $[\dot{q}_1.\dot{q}_2,\dot{q}_1.\dot{q}_3,\dots,\dot{q}_1.\dot{q}_n,\dot{q}_2.\dot{q}_3,\dots]^T$ and $[\dot{q}]^2$ is vector, that it can given by: $[\dot{q}_1{}^2,\dot{q}_2{}^2,\dot{q}_3{}^2,\dots]^T$and $G(q)$ is Gravity terms,
As mentioned above the kinetic energy matrix in n DOF is a $n \times n$ matrix that can be calculated by the following matrix [1, 6]

$$M(q) = \begin{bmatrix} M_{11} & M_{12} & \dots & \dots & \dots & M_{1n} \\ M_{21} & \dots & \dots & \dots & \dots & M_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ M_{n.1} & \dots & \dots & \dots & \dots & M_{n.n} \end{bmatrix} \qquad (26)$$

The Coriolis matrix (B) is a $n \times \frac{n(n-1)}{2}$ matrix which calculated as follows;

$$B(q) = \begin{bmatrix} b_{112} & b_{113} & \dots & b_{11n} & b_{123} & \dots & b_{12n} & \dots & \dots & b_{1.n-1.n} \\ b_{212} & \dots & \dots & b_{21n} & b_{223} & \dots & \dots & \dots & \dots & b_{2.n-1.n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ b_{n.1.2} & \dots & \dots & b_{n.1.n} & \dots & \dots & \dots & \dots & \dots & b_{n.n-1.n} \end{bmatrix} \qquad (27)$$

and the Centrifugal matrix (C) is a $n \times n$ matrix;

$$C(q) = \begin{bmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nn} \end{bmatrix} \qquad (28)$$

And last the Gravity vector (G) is a $n \times 1$ vector;

$$G(q) = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_n \end{bmatrix} \qquad (29)$$

and τ_{sat} is computed as;

$$\tau_{sat} = K \cdot \mathrm{sat}\left({}^{S}/_{\emptyset}\right) \qquad (30)$$

the control output can be written as;

$$\tau = \tau_{eq} + K.\mathrm{sat}\left({}^{S}/_{\emptyset}\right) = \begin{cases} \tau_{eq} + K.\mathrm{sgn}(S) & ,|S| \ge \emptyset \\ \tau_{eq} + K.{}^{S}/_{\emptyset} & ,|S| < \emptyset \end{cases} \qquad (31)$$

Figure 4 shows the position classical sliding mode control for robot manipulator. By (30) and (31) the sliding mode control of robot manipulator is calculated as;

$$\tau = \left[M^{-1}(B + C + G) + \dot{S}\right]M + K \cdot \mathrm{sat}\left({}^{S}/_{\emptyset}\right) \qquad (32)$$

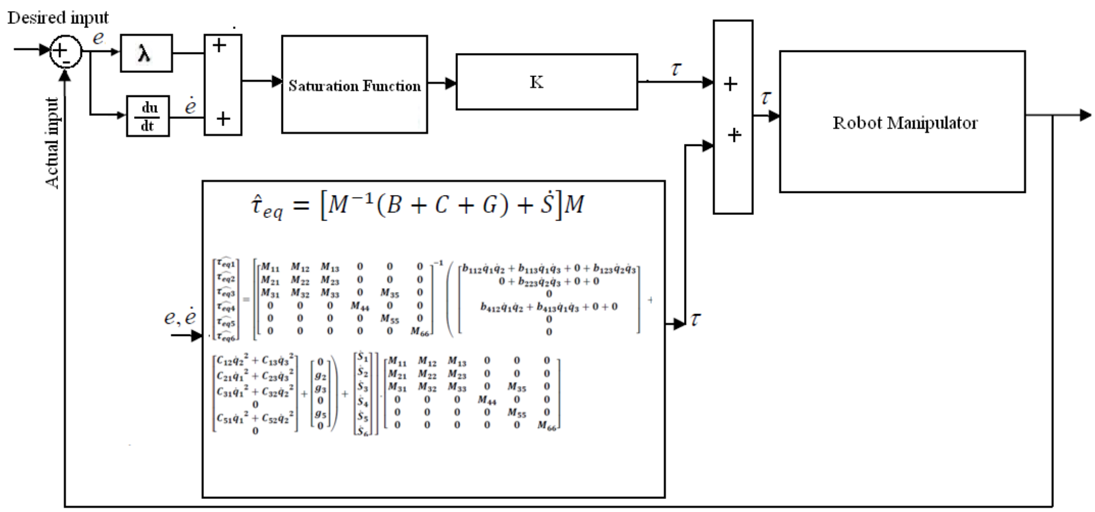

FIGURE 4: diagram of classical sliding mode controller [3, 10-14, 64]

3 INTRODUCTION TO FUZZY CONTROL AND ITS APPLICATION TO SMC

In recent years, artificial intelligence theory has been used in sliding mode control systems. Neural network, fuzzy logic, and neuro-fuzzy are synergically combined with nonlinear classical controller and used in nonlinear, time variant, and uncertainty plant (e.g., robot manipulator). Fuzzy logic controller (FLC) is one of the most important applications of fuzzy logic theory. This controller can be used to control nonlinear, uncertain, and noisy systems. This method is free of some model-based techniques as in classical controllers. As mentioned that fuzzy logic application is not only limited to the modelling of nonlinear systems [31-36]but also this method can help engineers to design easier controller. The complete fuzzy rule base for conventional fuzzy controller is shown in Table 1.

Control robot arm manipulators using classical controllers are based on manipulator dynamic model. These controllers often have many problems for modelling. Conventional controllers require accurate information of dynamic model of robot manipulator, but these models are multi-input, multi-output and non-linear and calculate accurate model can be very difficult. When the system model is unknown or when it is known but complicated, it is difficult or impossible to use classical mathematics to process this model[32].

TABLE 1: Rule table for 2 DOF robot manipulator [40]

$\dot{e}/e$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

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. It should be mentioned that application of fuzzy logic is not limited to a system that's difficult for modeling, but it can be used in clear systems that have complicated mathematics models because most of the time it can be shortened in design but there is no high quality design just sometimes we can find design with high quality. Besides using 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 [32].

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) [5, 15-18].

The basic structure of a fuzzy controller is shown in Figure 5.

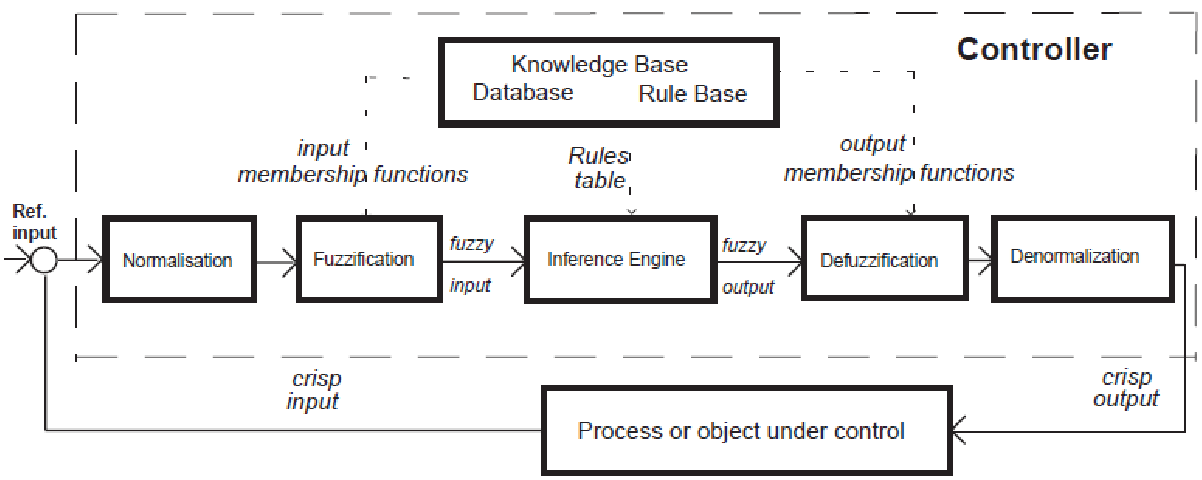

FIGURE 5: Block diagram of a fuzzy controller with details.

The applications of artificial intelligence such as neural networks and fuzzy logic in modelling and control are significantly growing especially in recent years. For instance, the applications of artificial intelligence, neural networks and fuzzy logic, on robot arm control have reported in [37-39]. Wai et al. [37-38]have proposed a fuzzy neural network (FNN) optimal control system to learn a nonlinear function in the optimal control law. This controller is divided into three main groups: arterial intelligence controller (fuzzy neural network) which it is used to compensate the system's nonlinearity and improves by adaptive method, robust controller to reduce the error and optimal controller which is the main part of this controller. Mohan and Bhanot [40] have addressed comparative study between some adaptive fuzzy, and a new hybrid fuzzy control algorithm for manipulator control. They found that self-organizing fuzzy logic controller and proposed hybrid integrator fuzzy give the best performance as well as simple structure. Research on combinations of fuzzy logic systems with sliding mode method is significantly growing as nonlinear control applications. For instance, the applications of fuzzy logic on sliding mode controller have reported in [24, 41-45].

Research on applied fuzzy logic methodology in sliding mode controller (FSMC) to reduce or eliminate the high frequency oscillation (chattering), to compensate the unknown system dynamics and also to adjust the linear sliding surface slope in pure sliding mode controller considerably improves the robot manipulator control process [42-43]. H.Temeltas [46] has proposed fuzzy adaption techniques for SMC to achieve robust tracking of nonlinear systems and solves the chattering problem. Conversely system's performance is better than sliding mode controller; it is depended on nonlinear dynamic equqation. C. L. Hwang *et al.* [47]have proposed a Tagaki-Sugeno (TS) fuzzy model based sliding mode control based on *N* fuzzy based linear state-space to estimate the uncertainties (Figure 6). A multi-input multi-output FSMC reduces the chattering phenomenon and reconstructs the approximate the unknown system has been presented for a robot manipulator [42].

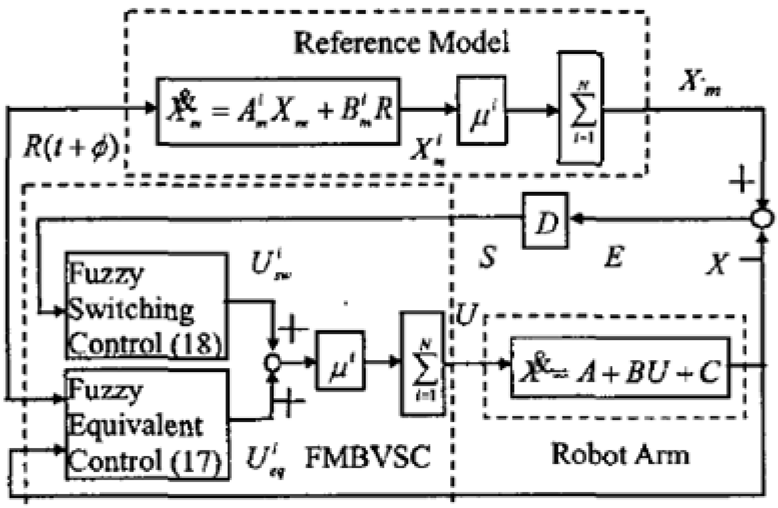

FIGURE 6: Fuzzy model base sliding mode controller [47]

Investigation on applied sliding mode methodology in fuzzy logic controller (SMFC) to reduce the fuzzy rules and refine the stability of close loop system in fuzzy logic controller has grown specially in recent years as the robot manipulator control [23]; [48-50]. Lhee et al. [48]have presented a fuzzy logic controller based on sliding mode controller to more formalize and boundary layer thickness. Emami *et al.* [51]have proposed a fuzzy logic approximate inside the boundary layer. H.K.Lee *et al.* [52] have presented self tuning SMFC to reduce the fuzzy rules, increase the stability and to adjust control parameters control automatically. Figure 7 is shown the sliding mode fuzzy rule table and the block diagram of SMFC.

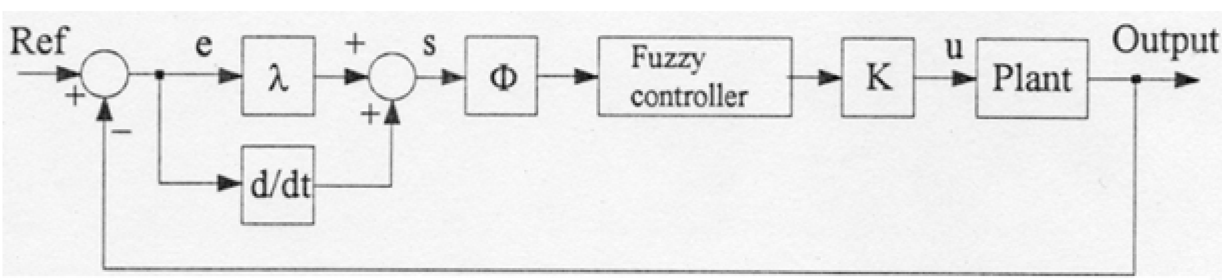

FIGURE 7: The structure of sliding mode fuzzy controller [52]

However the application of FSMC and SMFC are growing but the main SMFC drawback compared to FSMC is calculation the value of sliding surface λ pri-defined very carefully. Moreover, the advantages of SMFC compared to FLC reduce the number of fuzzy rule base and increase the robustness and stability. At last FSMC compare to the SMFC is more suitable for implementation action.

In various dynamic parameters systems that need to be training on-line adaptive control methodology is used. Adaptive control methodology can be classified into two main groups, namely, traditional adaptive method and fuzzy adaptive method. Fuzzy adaptive method is used in systems which want to training parameters by expert knowledge. Traditional adaptive method is used in systems which some dynamic parameters are known. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, adaptive method is applied to artificial sliding mode controller. F Y Hsu et al. [54]have presented adaptive fuzzy sliding mode control which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability robot manipulator controller. Y.C. Hsueh et al. [43] have presented self tuning sliding mode controller which can resolve the chattering problem without to using saturation function.

For nonlinear dynamic systems (e.g., robot manipulators) with various parameters, adaptive control technique can train the dynamic parameter to have an acceptable controller performance. Calculate several scale factors are common challenge in classical sliding mode controller and fuzzy logic controller, as a result it is used to adjust and tune coefficient. Research on adaptive fuzzy control is significantly growing, for instance, different adaptive fuzzy controllers have been reported in [40, 55-57].

Research on adaptive fuzzy sliding mode controller is significantly growing as many applications and it can caused to improve the tracking performance by online tuning the parameters. The adaptive sliding mode controller is used to estimate the unknown dynamic parameters and external disturbances. For instance, the applications of adaptive fuzzy sliding mode controller to control the robot manipulators have been reported in [24, 29, 45]. Generally, adaptive fuzzy sliding mode control of robot manipulator is classified into two main groups' i.e. multi-input multi-output (MIMO) and single-input single-output (SISO) fuzzy systems.

Yoo and Ham [58]have proposed a MIMO fuzzy system to help the compensation and estimation the torque coupling. In $n-DOF$ robot manipulator with k membership function for each input variable, the number of fuzzy rules for each joint is equal to $3k^{2n}$ that causes to high computation load and also this controller has chattering. This method can only tune the consequence part of the fuzzy rules (Figure 8).

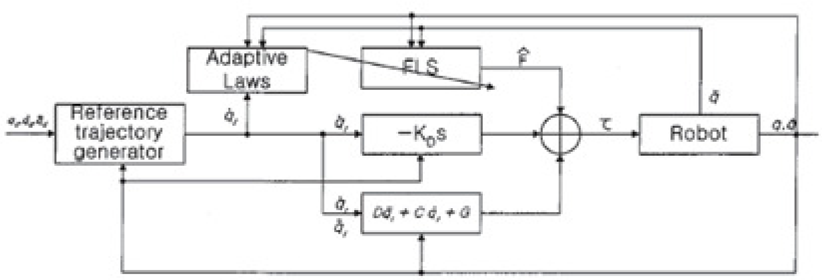

FIGURE 8: The structure of adaptive fuzzy compensate control of robot [58]

Medhafer et al. [59] have proposed an indirect adaptive fuzzy sliding mode controller to control robot manipulator. This MIMO algorithm, applies to estimate the nonlinear dynamic parameters. If each input variable have K_2 membership functions, the number of fuzzy rules for each joint is $(m+1)K_2^m + K_2$. Compared with the previous algorithm the number of fuzzy rules have reduced by introducing the sliding surface as inputs of fuzzy systems.

Y. Guo and P. Y. Woo [60]have proposed a SISO fuzzy system compensate and reduce the chattering. First suppose each input variable with K_2 membership function the number of fuzzy rules for each joint is K_2 which decreases the fuzzy rules and the chattering is also removed. C. M. Lin and C. F. Hsu [61] can tune both systems by fuzzy rules. In this method the number of fuzzy rules equal to K_2 with low computational load but it has chattering (Figure 9). Shahnazi et al., have proposed a SISO PI direct adaptive fuzzy sliding mode controller based on Lin and Hsu algorithm to reduce or eliminate chattering with K_2 fuzzy rules numbers. The bounds of PI controller and the parameters are online adjusted by low adaption computation [44]. Table 2 is illustrated a comparison between computed torque controller[9, 15-16], sliding mode controller[1, 3, 6, 10-14, 17-23, 26], fuzzy logic controller (FLC)[31-40], applied sliding mode in fuzzy logic controller (SMFC)[23, 14, 48-50], applied fuzzy logic method in sliding mode controller (FSMC)[10-14, 54-55, 60-61, 64] and adaptive fuzzy sliding mode controller [3, 10-14, 64].

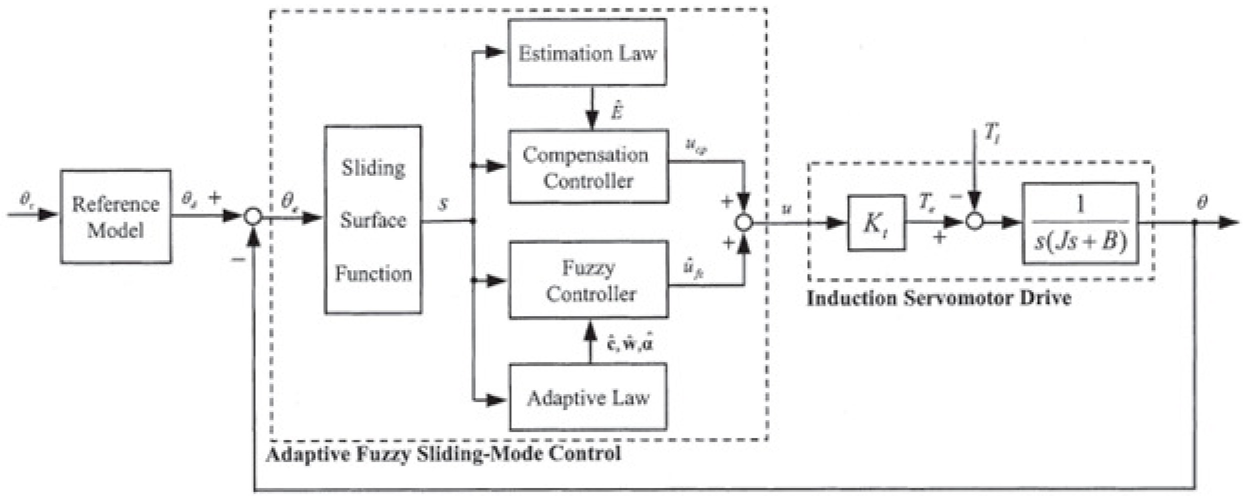

FIGURE 9: The structure of adaptive fuzzy sliding mode controller [61]

4 CONCLUSIONS

Refer to the research, review of sliding mode control and application to robot manipulator has explained in order to design high performance nonlinear controller in the presence of uncertainties. Sliding mode controller (SMC) is a significant nonlinear controller in certain and uncertain dynamic parameters systems. This controller is used to present a systematic solution for stability and robustness which they can play important role to select the best controller. 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. One of the most important techniques to reduce or remove above two challenges is applying non-classical (artificial intelligence) method in robust classical such as sliding mode controller method. In order to solve the uncertain dynamic parameters and complex parameters systems with an artificial intelligence theory, fuzzy logic is one of the best choice which it is used in this research. However fuzzy logic method is useful to control complicated nonlinear dynamic mathematical models but the response quality may not always be so high. This controller can be used in main part of controller (e.g., pure fuzzy logic controller), it can be used to design adaptive controller (e.g., adaptive fuzzy controller), tuning parameters and finally applied to the classical controllers. As mentioned above to improve stability and reduce the fuzzy rule base in fuzzy logic controller one of the major methods is applied sliding mode controller in fuzzy logic methodology. Sliding mode fuzzy controller (SMFC) is fuzzy controller based on sliding mode technique to simple implement, most excellent stability and robustness. Conversely SMFC has the following advantages; reducing the number of fuzzy rule base and increasing robustness and stability, the main disadvantage of SMFC is need to define the sliding surface slope coefficient very carefully. As mentioned above sliding mode controller has some limitations which applied fuzzy logic in sliding mode controller can causes to reduce the limitations. To compensate the nonlinearity of dynamic equivalent control, several researchers are used model base fuzzy controller instead classical equivalent controller. However FSMC has an acceptable performance but calculate the sliding surface slope by experience knowledge is difficult, particularly when system has structure or unstructured uncertainties, self tuning sliding surface slope fuzzy sliding mode controller is recommended.

TABLE 2: Comparison of six important algorithms [3, 10-14, 64]

Type of method	Advantages	Disadvantages	What to do?
1. CTC	• Higher tracking accuracy • Lower energy • Easy to implement	• That is required accurate dynamic formulation • It has problem under condition of : uncertain system and external disturbance	Design computed torque like controller or the other robust controller such as SMC
2. SMC	• Good control performance for nonlinear systems • In MIMO systems • In discrete time circuit	• Equivalent dynamic formulation • Chattering • It has limitation under condition of : uncertain system and external disturbance	Applied artificial intelligent method in SMC (e.g., FSMC or SMFC)
3. FLC	• Used in unclear and uncertain systems • Flexible • Easy to understand • Shortened in design	• Quality of design • Should be to defined fuzzy coefficient very carefully • Cannot guarantee the stability • reliability	Applied adaptive method in FLC, tuning parameters and applied to classical linear or nonlinear controller
4. SMFC	• Reduce the rule base • Reduce the chattering • Increase the stability and robustness	• Equivalent part • Defined sliding surface slope coefficient very carefully • Difficult to implement • Limitation in noisy and uncertain system	Applied adaptive method, self learning and self organizing method in SMFC
5. FSMC	• More robust • Reduce the chattering • Estimate the equivalent • Easy to implement	• Model base estimate the equivalent part • Limitation in noisy and uncertain system	Design fuzzy error base like equivalent controller and applied adaptive method
6. Adaptive FSMC	• More robust • eliminate the chattering • Estimate the equivalent	• Model base estimate the equivalent part	

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