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ROBUST ARTIFICIAL INTELLIGENCE MODEL-BASE WITH FUZZY VARIABLE STRUCTURE CONTROLLER WITH APPLICATION TO DYNAMIC UNCERTAINTIES HYPER-REDUNDANT ROBOT

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ABSTRACT

Design a robust artificial intelligent nonlinear controller for second order nonlinear uncertain dynamical systems is one of the most important challenging works.This paperfocuses on the design of a robust chattering free mathematical model-base artificialintelligence (fuzzy inference system) variable structure controller (MFVSC) for highlynonlinear dynamic continuum robot manipulator, in presence of uncertainties. In order toprovide high performance nonlinear methodology, variable structure controller isselected. Pure variable structure controller can be used to control of partly knownnonlinear dynamic parameters of continuum robot manipulator. In order toreduce/eliminate the chattering, this research is used the artificial intelligence (fuzzy logic) theory. The results demonstrate that the model base fuzzy variable structure controller with switching function is a model-based controllers which works well in certain and partly uncertain system. Lyapunov stability is proved in mathematical model based fuzzy variable structure controller with switching (sign) function. This controller has acceptable performance in presence of uncertainty (e.g., overshoot=1%, risetime=0.9 second.

Keywords: **continuum robot manipulator, parallel fuzzy-optimization control, robust control,sliding mode control.**

1. INTRODUCTION

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 classicalcontroller and used in nonlinear, time variant and uncertain plant (*e.g.,* robot manipulator). Fuzzylogic controller (FLC) is one of the most important applications of fuzzy logic theory. Thiscontroller can be used to control nonlinear, uncertain, and noisy systems. This method is free ofsome model techniques as in model-based controllers. As mentioned that fuzzylogic applicationis not only limited to the modelling of nonlinear systems but also this method can helpengineers to design a model-free controller. Control robot arm manipulators using model-basedcontrollers are based on manipulator dynamic model. These controllers often have manyproblems for modelling. Conventional controllers require accurate information of dynamic modelof robot manipulator, but most of time these models are MIMO, nonlinear and partly uncertaintherefore calculate accurate dynamic model is complicated. The main reasons to use

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fuzzylogic methodology are able to give approximate recommended solution for uncertain and alsocertain complicated systems to easy understanding and flexible. Fuzzy logic provides a method todesign a model-free controller for nonlinear plant with a set of IF-THEN rules.

Based on mechanical and control methodologies research in robotic system, mechanicaldesign, type of actuators and type of systems drive play important roles to have the bestperformance controller. This section has focused on the robot manipulator mechanicalclassification. Types of kinematics chain, *i.e.*, serial Vs. parallel manipulators, and types ofconnection between link and join actuators, *i.e.*, highly geared systems Vs. direct-drive systemsare presented in the following sections because these topics played important roles to select anddesign the best acceptable performance controllers . A serial link robot is a sequence ofjoints and links which begins with a base frame and ends with an end-effector. This type of robotmanipulators, comparing with the load capacity is more weightily because each link must besupported the weights of all next links and actuators between the present link and end-effector . Serial robot manipulators have been used in automotive industry, medical application, andalso in research laboratories. In contrast, parallel robot manipulators design according toclose loop which base frame is connected to the end-effector frame with two or more kinematicchains . In the other words, a parallel link robot has two or more branches with some joints andlinks, which support the load in parallel.

Parallel robot have been used in many applications suchas expensive flight simulator, medical robotics (*i.e.*, high accuracy, high repeatability, highprecision robot surgery, and machinery tools. Parallel links robot manipulators have higheraccuracy and faster than serial links robot manipulators but the work space limitation in seriallinks robot manipulator is lower than parallel links robot manipulator. From control point of view,the coupling between different kinematic chains can generate the uncertainty problems whichcause difficult controller design of parallel robot manipulator. anticipated tasks. In other words they must achieve a wide range ofconfigurations with relatively few control inputs. This is partly due to the desire to keep the bodystructures (which, unlike in conventional rigid-link manipulators or fingers, are required todirectly contact the environment) "clean and soft", but also to exploit the extra control authority

2.THEOREM

The Continuum section analytical model developed here consists of three modules stackedtogether in series. In general, the model will be a more precise replication of the behavior of acontinuum arm with a greater of modules included in series. However, we will show that threemodules effectively represent the dynamic behavior of the hardware, so more complex models arenot motivated. Thus, the constant curvature bend exhibited by the section is incorporatedinherently within the model. The model resulting from the application of Lagrange's equations ofmotion obtained for this system can be represented in the form.

$$F_{coeff}\,\underline{\tau} = D\left(\underline{q}\right)\ddot{\underline{q}} + C\left(\underline{q}\right)\dot{\underline{q}} + G\left(\underline{q}\right)$$

where is a vector of input forces and q is a vector of generalized co-ordinates. The forcecoefficient matrixtransforms the input forces to the generalized forces and torques in thesystem. The inertia matrix, is composed of four block matrices. The block

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matrices that correspond to pure linear accelerations and pure angular accelerations in the system (on the topleft and on the bottom right) are symmetric. The matrix contains coefficients of the first order derivatives of the generalized co-ordinates. Since the system is nonlinear, many elements of contain first order derivatives of the generalized co-ordinates. The remaining terms in thedynamic equations resulting from gravitational potential energies and spring energies are collected in the matrix. The coefficient matrices of the dynamic equations are given below, contain first order derivatives of the generalized co-ordinates. The remaining terms in thedynamic equations resulting from gravitational potential energies and spring energies are collected in the matrix. The coefficient matrices of the dynamic equations are given below,

$$Fcoeff = \begin{bmatrix} 1 & 1 & cos(\theta_1) & cos(\theta_1) & cos(\theta_1+\theta_2) & cos(\theta_1+\theta_2) \\ 0 & 0 & 1 & 1 & cos(\theta_2) & cos(\theta_2) \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 1/2 & -1/2 & 1/2 & -1/2 & 1/2+s_2sin(\theta_2) & -1/2+s_2sin(\theta_2) \\ 0 & 0 & 1/2 & -1/2 & 1/2 & -1/2 \\ 0 & 0 & 0 & 0 & 1/2 & -1/2 \end{bmatrix} \quad (2)$$

$$D(\underline{q}) = \begin{bmatrix} m_1+m_2+m_3 & m_2cos(\theta_1)+m_3cos(\theta_1) & m_3cos(\theta_1+\theta_2) & -m_2s_2sin(\theta_1)-m_3s_2sin(\theta_1)-m_3s_3sin(\theta_1+\theta_2) & -m_3s_3sin(\theta_1+\theta_2) & 0 \\ m_2cos(\theta_1)+m_3cos(\theta_1) & m_2+m_3 & m_3cos(\theta_2) & -m_3s_3sin(\theta_2) & -m_3s_3sin(\theta_2) & 0 \\ m_3cos(\theta_1+\theta_2) & m_3cos(\theta_2) & m_3 & m_3s_3sin(\theta_2) & 0 & 0 \\ -m_2s_2sin(\theta_1)-m_3s_2sin(\theta_1)-m_3s_3sin(\theta_1+\theta_2) & -m_3s_3sin(\theta_2) & m_3s_3sin(\theta_2) & m_2s_2^2+I_1+I_2+I_3+m_3s_2^2+m_3s_3^2+2m_3s_3cos(\theta_2)s_2 & I_2+m_3s_3^2+I_3+m_3s_3cos(\theta_2)s_2 & I_3 \\ -m_3s_3sin(\theta_1+\theta_2) & -m_3s_3sin(\theta_2) & 0 & I_2+m_3s_3^2+I_3+m_3s_3cos(\theta_2)s_2I & I_2+m_3s_3^2+I_3 & I_3 \\ 0 & 0 & 0 & I_3 & I_3 & I_3 \end{bmatrix} \quad (3)$$

Loosely speaking, a serial robot is a set of bodies (called links) connected in series through actuated joints, which are typically either revolute (i.e. rotating) or prismatic (i.e. translating). One extremity of this serial chain of links is called the base and the other the end-effector. Serial robots are also called robot arms. Most industrial robots are serial. Although some of them contain parallelogram linkages (e.g. robot palletizers), they are still referred to as serial robots. In a parallel robot, the end-effector is connected to the base through several chains of interconnected links. the variety of parallel robots is larger ad used in movie theaters.

$$G(\underline{q}) = \begin{bmatrix} -m_1g-m_2g+k_{11}(s_1+(1/2)\theta_1-s_{01})+k_{21}(s_1-(1/2)\theta_1-s_{01})-m_3g \\ -m_2gcos(\theta_1)+k_{12}(s_2+(1/2)\theta_2-s_{02})+k_{22}(s_2-(1/2)\theta_2-s_{02})-m_3gcos(\theta_1) \\ -m_3gcos(\theta_1+\theta_2)+k_{13}(s_3+(1/2)\theta_3-s_{03})+k_{23}(s_3-(1/2)\theta_3-s_{03}) \\ m_2s_2gsin(\theta_1)+m_3s_3gsin(\theta_1+\theta_2)+m_3s_2gsin(\theta_1)+k_{11}(s_1+(1/2)\theta_1-s_{01})(1/2)+k_{21}(s_1-(1/2)\theta_1-s_{01})(-1/2) \\ m_3s_3gsin(\theta_1+\theta_2)+k_{12}(s_2+(1/2)\theta_2-s_{02})(1/2)+k_{22}(s_2-(1/2)\theta_2-s_{02})(-1/2) \\ k_{13}(s_3+(1/2)\theta_3-s_{03})(1/2)+k_{23}(s_3-(1/2)\theta_3-s_{03})(-1/2) \end{bmatrix}$$

Sliding mode controller

Consider a nonlinear single input dynamic system is defined by [6]:

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

Where u is the vector of control inputis the derivationisthe state vectoris unknown or uncertainty, and is of known *sign* function. The maingoal to design this controller is train to the desired state, andtrucking error vector is defined by [6]:

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

A time-varying sliding surfacein the state space is given by [6]:

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

Where λ is a positive constant. To further penalize tracking error, integral part can be used insliding surface part as follows [6]:

In other words, a parallel robot has at least two "legs" (or "arms"). Most of its joints are not actuated, and many of these passive joints have several degrees-of-freedom (DOFs)spherical, universal, and planar joints). Two of the most popular parallel robots are the telescoping-leg hexapod used in most motion simulators

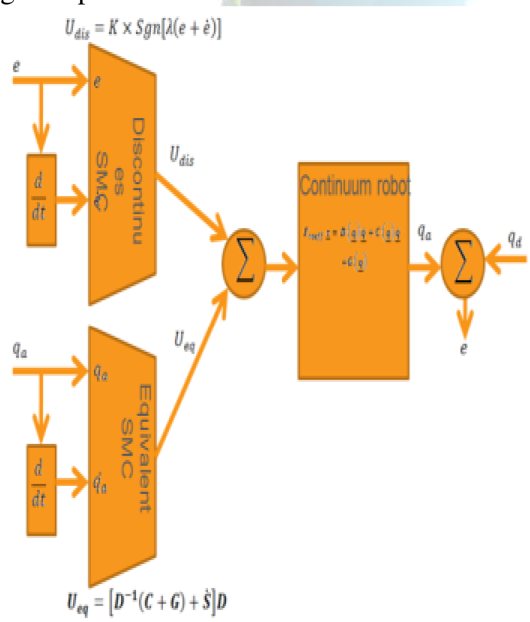

Figure 1. Sliding Mode Controller

Fuzzy Logic Control

Fuzzy-logic aims to provide an approximate but effective means ofdescribing the behavior of systems that are not easy to describe precisely, and which are complexor ill-defined. It is based on the assumption that, in contrast to Boolean logic, a statement can bepartially true (or false). For example, the expression (I live near IAU) where the fuzzy value(near) applied to the fuzzy variable (distance), in addition to being imprecise, is subject tointerpretation. The essence of fuzzy control is to build a model of human expert who is capable ofcontrolling the plant without thinking in terms of its mathematical model. The central idea of *fuzzy sets* is that elements can have partial membership in a contrast to a classical set, a fuzzy set, as the name implies, is a set without a crisp boundary. Inthis respect, fuzzy sets are functions that map a value to a number between zero and one,indicating its actual degree of membership. A degree of zero means that the value is not in the set,and a degree of one means that the value is completely representative of the set.. The fuzziness does notcome from the randomness of the constituent members of the set, but from the uncertainties andimprecise nature of abstract thoughts and concepts. A Fuzzy-Logic System (FLS) is a non-linearmapping from the input to output space, where input is first fuzzified as shown in Figure2.

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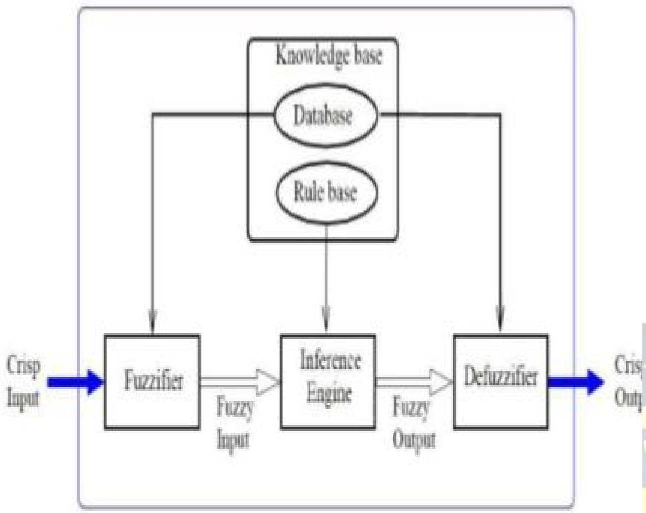

Figure 2. Implementation of Fuzzy-Logic Control System, Adapted From

The fuzzy sets computed by the fuzzy inference as the output of each rule are then composedand defuzzified. Fuzzification helps in evaluating the rules, but the final output of a fuzzy systemhas to always be a crisp number. (i.e. conversion from a fuzzy set to a crisp number). Fuzzymembership functions on the other hand, are defined in terms of numerical values of anunderlying crisp attribute. For example: Short, Medium and Tall in terms of the fuzzy variable:height. In other words, determining how much each discrete input value belongs to each inputfuzzy set using the corresponding membership function.Fuzzification is the process of translating crisp input values into fuzzy linguistic values (fuzzy sets) through the use of membership functions. Generally, fuzzy membership functions are defined in terms of numerical values of anunderlying crisp attribute such as short, medium and tall in terms of the fuzzy variableHeight. They are subsequently processed by the inference engine that retrieves knowledge in the form of fuzzy rules contained in the knowledge-base. Fuzzy knowledge-bases is implemented as a set ofIF-THEN rules as follows:

IF(condition1AND/ORcondition2)THEN (consequence)

In fuzzy logic terminology, the statement following the IF is known as the premise, antecedent,or condition. The corresponding statement following THEN is known as the conclusion orconsequent, and the actual calculation of the consequent using the premises calculated from thefuzzified inputs is reserved for the inference engine. In designing fuzzy systems, one shoulddecide whether the number of rules is sufficient and if there are specific interactions between therules. These problems were discussed in detail in the works. The inference engine is the heart of a FLC and acts as the bridge between the fuzzification and defuzzification stages. It aims attranslating the designers desired control rules from a linguistic representation to a numeric computation, and can be divided into three elements: aggregation, composition, and accumulation. There are several types of FIS, which may be limited to two FIS, the most currently used, those of Takagi-Sugeno or Mamdani type, which is the FIS used in the currentwork. The performance of any fuzzy logic controller (FLC) is greatly dependent on its inferencerules and can be drastically affected by the choice of membership functions. Thus, methods fortuning the fuzzy logic controllers are needed. Some applications considered neural networks andgenetic algorithms to solve the problem of tuning a fuzzy-logic controller. In general, the systemto be controlled using a FLC requires a crisp

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or discrete input, rather than a membership functionthat is produced by the inference engine. Defuzzificationis the process of converting the fuzzyoutput set resulting from the inference process into a discrete number suitable for input to theplant. There are many different methods of defuzzification described in the literature, withvarying levels of complexity.

1. Methodology

Sliding mode controller (SMC) is an important nonlinear controller in a partly uncertaindynamic system's parameters. This controller is used in several applications such as in robotics,process control, aerospace and power electronics. Sliding mode controller is used to control ofnonlinear dynamic systems particularly for robot manipulators, because it has a suitable controlperformance and it is a robust and stable. Conversely pure sliding mode controller is a highquality nonlinear controller; it has two important problems; chattering phenomenon and nonlinearequivalent dynamic formulation in uncertain dynamic parameter. To reduce the chatteringphenomenon and equivalent dynamic problems, this research is focused on applied parallel fuzzylogic theorem in sliding mode controller as a compensator. Fuzzy logic theory is used in parallelwith sliding mode controller to compensate the limited uncertainty in system's dynamic. In thismethod fuzzy logic theorem is applied to sliding mode controller to remove the nonlinearuncertainty part which it is based on nonlinear dynamic formulation. To achieve this goal, thedynamic equivalent part of pure sliding mode controller is modeled by Mamdani's performanceerror-based fuzzy logic methodology. Another researcher's method is based on appliedfuzzylogic theorem in sliding mode controller to design a fuzzy model-based controller. This techniquewas employed to obtain the desired control behavior with a number of information about dynamicmodel of system and a fuzzy switching control was applied to reinforce system performance.

Reduce or eliminate the chattering phenomenon and reduce the error are played important role, therefore switching method is used beside the artificial intelligence part to solve the chattering problem with respect to reduce the error. Equivalent part of sliding mode controller is based onnonlinear dynamic formulations of robot manipulator. Robot manipulator's dynamic formulationsare highly nonlinear and some of parameters are unknown therefore design a controller based ondynamic formulation is complicated. To solve this challenge parallel fuzzy logic methodology is applied to sliding mode controller. In this method fuzzy logic method is used to compensate somedynamic formulation that they are used in equivalent part. To solve the challenge of sliding modecontroller based on nonlinear dynamic formulation this research is focused on compensate thenonlinear equivalent formulation by parallel fuzzy logic controller. In this method; dynamicnonlinear equivalent part is modelled by performance/error-based fuzzy logic controller. In thismethod; error based Mamdani's fuzzy inference system has considered with two inputs, oneoutput and totally 49 rules. Figure 3 shows error-based parallel fuzzy plus sliding modecontroller.

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzylogic. The mapping then provides a basis from which decisions can be made, or patterns discerned

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The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. In Fuzzy Logic Toolbox™ software, the input is always a crisp numerical value limited to the universe of discourse of the input variable case the interval between 0 and 10.

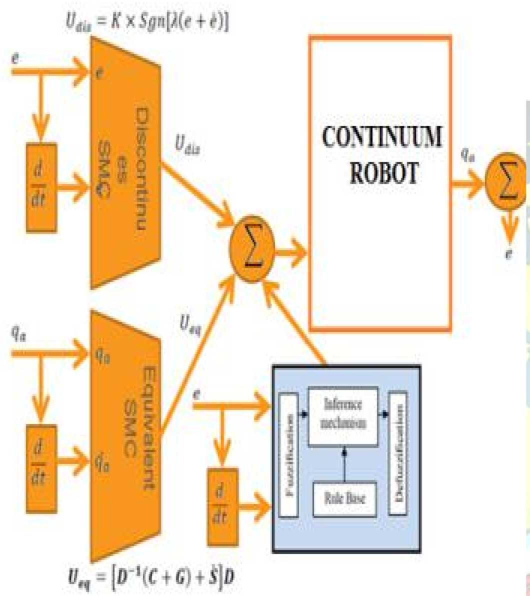

Figure 3. Parallel Optimization of Pure Sliding Mode Controller based on Fuzzy Inference Engine

For both sliding mode controller and parallel fuzzy inference system plus sliding modecontroller applications the system performance is sensitive to the sliding surface slopecoefficient. For instance, if large value of is chosen the response is very fast the system is unstable and conversely, if small value of is considered the response of system is very slow butsystem is stable. Therefore to have a good response, compute the best value sliding surface slopecoefficient is very important.

2. Fuzzification

The first step in fuzzification is determining inputs and outputs which; it has two inputs and one output. The inputs are error (e) which measures the differencebetween desired and actual output position, and the change of error which measures thedifference between desired and actual velocity and output is fuzzy equivalent torque. The secondstep is chosen an appropriate membership function for inputs and output which, to simplicity inimplementation because it is a linear function with regard to acceptable performance triangularmembership function is selected in this research as shown in Figure 3.6. The third step is chosenthe correct labels for each fuzzy set which, in this research namely as linguistic variable. Basedon experience knowledge the linguistic variables for error (e) are; Negative Big (NB), NegativeMedium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM),Positive Big (PB), and based on literature [40] and experience knowledge it is quantized into 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 the linguistic variables for change of error (˙) are; Fast Left (FL), Medium Left (ML), Slow Left(SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized in tothirteen levels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, and the linguistic variablesto find the output are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), SmallRight (SR), Medium Right (MR), Large Right (LR) and it is quantized in to thirteen levelsrepresented by: -85, -70.8, -56.7, -42.5, -28.3, -14.2, 0, 14.2, 28.3, 42.5, 56.7, 70.8, 85.

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Fuzzy rule base and rule evaluation

The first step in rule base and evaluation is to provide atleast structured method to derive the fuzzy rule base which, expert experience and controlengineering knowledge is used because this method is the least structure of the other one and theresearcher 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 todesign the best performance of parallel fuzzy plus 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 control of robot manipulator. The complete rule base for this controller is shown in Table 1. Rule evaluation focuses on operation in the antecedent of fuzzy rules in fuzzy sliding modecontroller. This part is used fuzzy operation in antecedent part which operation isused.

Aggregation of the rule output (Fuzzy inference) Based onfuzzy methodology, Max-Minaggregation is used in this work.

Table 1. Modified Fuzzy Rule Base Table

Decrease the overshoot

$\dot{e}$ \ e	FL	ML	SL	Z	SR	MR	FR
NB	LL	LL	LL	ML	SL	SL	Z
NM	LL	ML	ML	ML	SL	Z	SR
NS	LL	ML	SL	SL	Z	SR	MR
Z	LL	ML	SL	Z	SR	MR	LR
PS	ML	SL	Z	SR	SR	MR	LR
PM	SL	Z	SR	MR	MR	MR	LR
PB	Z	SR	SR	MR	LR	LR	LR

Decrease the rise time

Defuzzification

The last step to design fuzzy inference in our parallel fuzzy compensator plussliding 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. Based on fuzzy methodology Center of gravity method is used in this research. Above table shows the lookup table in parallel fuzzy compensator sliding mode controller which iscomputed by COG defuzzification method. Table 2 has 169 cells to shows the error-based fuzzycompensate of equivalent part behavior.

5. Results and Discussion

In this section, we use a benchmark model, robot manipulator, to evaluate our controlalgorithms. We compare the following managements: pure sliding mode controller and parallelfuzzy inference compensator plus sliding mode controller with application to continuum robotwhich is proposed method in this paper. The simulation was implemented in MATLAB/SIMULINK environment.

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Close loop response of continuum robot manipulator trajectory planning: Figures 4 and 5illustrates the tracking performance in two types of controllers.

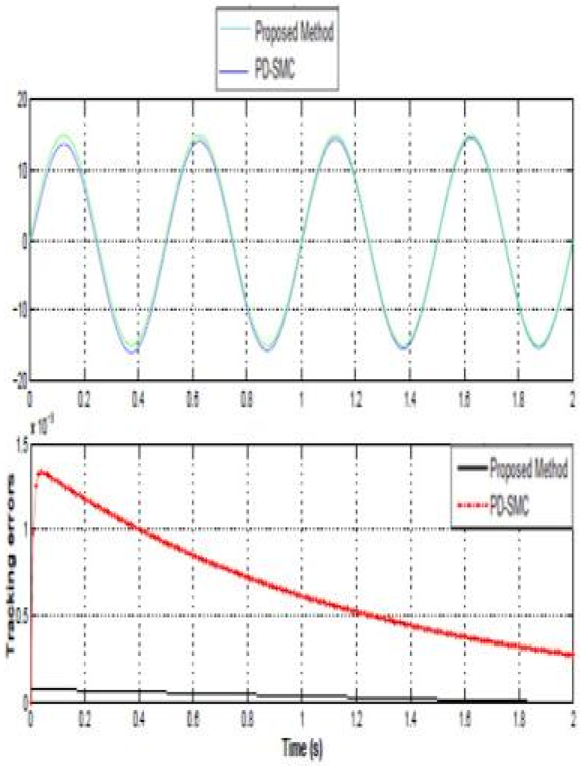

Figure 4. Pure SMC and Proposed Method SIN Trajectory Following and Error without Disturbance

Table 2. Performance: Lookup Table in Parallel Fuzzy Compensate of Sliding Mode Controller by COG.

$\dot{e}$ → / e ↓	Membership Function (τ_{fuzzy})												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-1	-85	-84.8	-84.8	-84	-82.1	-81	-79	-71	-68	-65	-62	-60	-54
-0.83	-84.8	-84	-82	-80	-78	-77	-74	-70	-64	-60	-56	-54	-47
-0.66	-78	-73	-70	-68	-64	-61	-60	-57	-55	-50	-47	-40	-38
-0.5	-70	-60	-58	-51	-42	-38	-34	-33	-31	-29	-28.4	-28.1	-28
-0.33	-50	-48	-45	-40	-38	-34	-32	-30	-28	-26	-25	-21	-20
-0.16	-30	-25	-21	-18	-16	-14	-10	-9	-8	-7	-6.8	-6	-5
0	-10	-8	-6	-1	2	3	6	7	8	10	12	15	17
0.16	15	18	21	22	23	25	27	28	29	30	30.5	30.8	31
0.33	29	29.8	31	33	34	34.6	35	35.2	36	37	38	39	42
0.5	40	41	42	43	45	45	46	46.3	46.8	47	48	51	52
0.66	48	49	50	52	53	55	56	57	58	59	60	61	63
0.83	60	61	62	63	64	66	67	68	68.5	69	70	70.8	71
1	66	68.7	68.9	70	72	74	75	77	78	79	81	83	84

Based on Figure 4 and 5; pure SMC controller has error in all links, because robot is a highlynonlinear system and control of this system by pure nonlinear method is very difficult. Based onabove graph, however SMC controller is a chattering free, but it has a boundary steady stateerrorto control of this plant.

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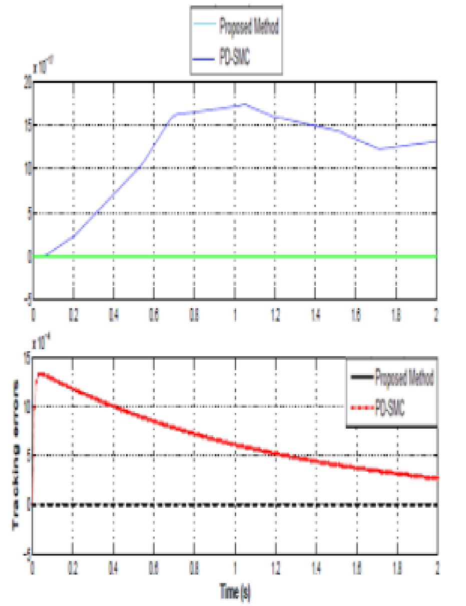

Figure 5. Pure SMC and ProposedMethod ZERO Trajectory Following and Error without Disturbance

6. Conclusion

Based on the dynamic formulation of continuum robot arm it is clear that; this system is highlynonlinear and uncertain dynamic parameters. Control of this system based on classicalmethodology is very complicated. The main contributions of this paper are compensating thenonlinear model base controller by nonlinear artificial intelligence model-free compensator. The structure of sliding mode controller with parallel fuzzy inference compensator is new. Wepropose parallel structure and chattering free compensator: parallel compensation, and chatteringfree method. The key technique is dead-zone. The stability analysis of parallel fuzzy compensator plus sliding mode controller is test via Lyapunov methodology. The benefits of the proposedmethod; the chattering effects of parallel fuzzy inference compensator plus sliding modecontroller, the slow convergence of the fuzzy and the chattering problem of sliding mode methodare avoided effectively.

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