Robust Dynamic Surface Control of da Vinci Robot Manipulator Considering Uncertainties: A Fuzzy Based Approach

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Abstract— **da Vinci is a robotic platform used to perform surgical tasks. The use of this robotic platform can have a significant effect on the reduction of operation time and improvement of the surgical task outcomes. However, the dynamic model of the da Vinci robot especially the friction model of the prismatic joint is unknown. Therefore, the design of an adaptive torque controller for da Vinci system can be the optimal solution for autonomous control strategies. In this work, we propose a fuzzy dynamic surface controller as a suitable application of the fuzzy method to tune the gain of the dynamic surface as an adaptive and robust controller for the da Vinci robot. The proposed controller is able to observe and eliminate the uncertainties. Lyaponuv method is used to guarantee the stability of the closed loop system. Finally, experiments are conducted to verify the proper performance of the proposed approach. It is worth noting that the experimental results indicate the robustness of the controller against uncertainties of the system.**

Keywords— dynamic surface, fuzzy inference, robust controller, da Vinci

I. INTRODUCTION

External disturbances and uncertainties, among the known challenges in control engineering, are ubiquitous in robotic systems and can lead to stability and performance degradation. Da Vinci is a master-slave robot used to enhance precision of the surgeon that remotely control the system. The master section of the robot includes two Master Tool Manipulators (MTMs). Each MTM is an 8-DOF manipulator. Using MTMs, the surgeon is able to control the slave arms of the da Vinci consisting of two Patient Side Manipulators (PSMs) and an Endoscope Camera Manipulator (ECM). The PSM is 7-DOF manipulator. the joint structure of PSM is RRPRRRR [1-3]. In fact, the third joint of the PSM is a prismatic joint with an unknown friction model. Additionally, Da Vinci research kit (DVRK) is a platform which provides a full ROS-based open controller of all the robotic arms [3]. Todays, The DVRK is used by many research groups as a suitable platform to improve research in haptic teleportation [4] and in semi-autonomous control [5]. The aim of this work is to design a robust torque control using DVRK for da Vinci robots such that the PSM is able to track the desired position autonomously.

Several researchers have focused on the robust controller for robotic manipulators [6-8]. When the robotic system has severe nonlinear dynamics, the control designer resort to the use of nonlinear methods such as sliding mode control [5, 9, 10] or feedback linearization approach [11-13]. Among known nonlinear methods, feedback linearization or model based method are known as a control approach. However, feedback linearization cannot be considered as a robust approach, because the signal control is obtained using the model of the system. Additionally, an uncertainty of a nonlinear system can be classified as either a matched and mismatched uncertainty. A mismatched uncertainty appears in the state equation before the control input while the matched uncertainty appears in the state equation at the same point as the control input. A robotic manipulator with flexible joints is an example of mismatched uncertainty in the robotic systems. The known nonlinear approach such as sliding mode control is not able to stabilize a system with mismatched uncertainties [14]. However, two known methods such as backstepping and dynamic surface control can be used to stabilize the system with mismatched uncertainties. The backstepping control [15-16] is a nonlinear approach to control robot manipulator systems. In [17], a support vector regression-based command filtered adaptive backstepping method is used as a robust adaptive approach to control a robot system by considering disturbances and model uncertainties. However, a so-called Command Filtered Backstepping (CFB) is modified and defines the auxiliary states to extend CFB to the case of the robot manipulator. Using NNs, Kwan and Lewis [18] presented a robust backstepping control method for nonlinear systems to solve two drawbacks of backstepping approach: one is that system dynamics should be linear in unknown parameters, and the other one is that analysis of the systems is required to determine regression matrices. Additionally, backstepping approach suffers from a drawback called the "explosion of complexity" [19, 20] because of repeated differentiation of virtual controllers. Swaroop et al. [19] proposed a Dynamic Surface Control (DSC) technique using a low pass filter of the synthetic virtual control law at each step of the backstepping procedure to solve "explosion of complexity" problem. Several works have been addressed the use of the DSC in the robotic systems [21-22] .

In our work, we used a fuzzy mechanism to tune the gain of DSC to remove the disturbance effect and dynamical model uncertainties of da Vinci system. In fact, the proposed torque control method is able to observe the model uncertainties of the robotic system and external disturbances in order to improve the robustness of the system. Lyapunov is used to guarantee the uniformly ultimately bounded signals in the closed-loop systems. Finally, the performance of the proposed system is verified using experimental results by da Vinci robot.

The rest of the paper is organized as follows: In Section 2, the dynamics of the manipulator is presented. In Section 3, the fuzzy gain dynamic surface and stability conditions are introduced. Section 4 shows the performance of the proposed approach using dVRK, and the last section concludes with a short summary of the paper.

II. PRELIMINARIES AND PROBLEM FORMULATION

Dynamical model of a robot manipulator is described in the following section.

A. *Rigid Body Dynamics*

Assuming that the rigid-body form describes the nominal dynamic equations of the n-link robot manipulator accurately as follows:

$$\mathrm{H}(\mathrm{q})\ddot{\mathrm{q}} + \mathrm{V}(\mathrm{q},\dot{\mathrm{q}})\dot{\mathrm{q}} + \mathrm{G}(\mathrm{q}) + \mathrm{J}^{\mathrm{T}}(\mathrm{q})\mathrm{F}_{\mathrm{e}} + \tilde{F}(t) = \tau \qquad (1)$$

where $q \in \mathbb{R}^{n\times 1}$ is joint displacement vector, $\tau \in \mathbb{R}^{n\times 1}$ isthe applied joint torque or force signal control, $H(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $V(q,\dot{q}) \in \mathbb{R}^{n\times 1}$ consists of the Coriolis and centrifugal terms, $G(q) \in \mathbb{R}^{n\times 1}$ is the gravitational vector and $J(q)$ is the Jacobin matrix. f_e is the interaction forces vector and $\tilde{F}(t)$ is the external disturbances that introduces uncertainty in the interaction forces. We assume that the system states q, $\dot{q}$ and interaction force F_e are available for feedback.

Because of model uncertainty and external disturbance, the nominal values of $H(q)$, $V(q,\dot{q})$ and $G(q)$ are different from the actual values $\hat{H}(q)$, $\hat{V}(q,\dot{q})$ and $\hat{G}(q)$, respectively. Consequently, the nominal values are known and the actual values and $\tilde{F}(t)$, as the external disturbances, are unknown.

Assumption 1. Modeling errors values are bounded although they are not available.

The actual dynamics of the n-link robot system (1) is expressed as,

$$\hat{\mathrm{H}}(\mathrm{q})\ddot{\mathrm{q}} + \hat{\mathrm{V}}(\mathrm{q},\dot{\mathrm{q}})\dot{\mathrm{q}} + \hat{\mathrm{G}}(\mathrm{q}) + \mathrm{J}^{\mathrm{T}}(\mathrm{q})\mathrm{F}_{\mathrm{e}} + \tilde{\mathrm{F}}(\mathrm{t}) = \mathrm{T}. \quad (2)$$

Using the nominal model (1) and the actual robot dynamic(2), we have

$$\mathrm{H}(\mathrm{q})\ddot{\mathrm{q}} + \mathrm{V}(\mathrm{q},\dot{\mathrm{q}}) + \mathrm{G}(\mathrm{q}) + \mathrm{J}^{\mathrm{T}}(\mathrm{q})\mathrm{F}_{\mathrm{e}} + \Pi = \mathrm{T} \qquad (3)$$

where Π denotes the uncertainty of robot dynamics and is defined as follows:

$$\Pi = -\mathrm{H}(\mathrm{q})\hat{\mathrm{H}}(\mathrm{q})^{-1}\{-\tilde{\mathrm{F}}(\mathrm{t}) - \hat{\mathrm{V}}(\mathrm{q},\dot{\mathrm{q}}) - \hat{\mathrm{G}}(\mathrm{q}) - \mathrm{J}^{\mathrm{T}}(\mathrm{q})\mathrm{F}_{\mathrm{e}} + \mathrm{T}\} + \{-\mathrm{V}(\mathrm{q},\dot{\mathrm{q}}) - \mathrm{G}(\mathrm{q}) - \mathrm{J}^{\mathrm{T}}(\mathrm{q})\mathrm{F}_{\mathrm{e}} + \mathrm{T}\} \qquad (4)$$

$\mathrm{x}_1 = \mathrm{q}$, $\mathrm{x}_2 = \dot{\mathrm{q}}$ are defined as the state space variables and the robot dynamic system with uncertainty terms (4) can be described as follows:

$$\dot{\mathrm{x}}_1 = \mathrm{x}_2 \qquad (5)$$

$$\dot{\mathrm{x}}_2 = \mathrm{H}^{-1}(\mathrm{x}_1)[-\mathrm{V}(\mathrm{x}_1,\mathrm{x}_2) - \mathrm{G}(\mathrm{x}_1) + \mathrm{T} - \mathrm{J}^{\mathrm{T}}(\mathrm{q})\mathrm{F}_{\mathrm{e}}] + \mathrm{U} \qquad (6)$$

Where

$$\mathrm{U} = -\mathrm{H}^{-1}(\mathrm{x}_1)\,\Pi \qquad (7)$$

U presents unknown dynamic uncertainty and disturbance effects and according to assumption 1, and U is boundeded such that $|U| < \delta$.

III. PROPOSED CONTROLLER

To present a robust torque controller, we introduce Fuzzy Gain Dynamic Surface (FGDS) as a suitable application of the fuzzy rules in dynamic surface nonlinear control. Using FGDS, the uncertainties and external disturbances in (6) are observed and removed. The stability of the proposed controller is proved using Lyapunov method.

A. *Dynamic Surface Controller*

In the first step, the virtual control law is designed for $x_{\mathrm{R}2}$. We denote x_{d1} and x_{d2} as the state variable for the commanded trajectory x_d and $\dot{x}_d$, respectively. The first error surface is defined as:

$$S_1 = x_1 - x_{d1} \qquad (8)$$

and its derivative is

$$\dot{\mathrm{S}}_1 = \mathrm{x}_2 - \mathrm{x}_{\mathrm{d}2} \qquad (9)$$

A virtual control $\bar{\mathrm{x}}_2$ is designed to drive $\mathrm{S}_1 \to 0$ as follows,

$$\bar{\mathrm{x}}_2 = -\mathrm{K}_1\mathrm{S}_1 + \mathrm{x}_{\mathrm{d}2} \qquad \mathrm{K}_1 > 0 \qquad (10)$$

Because of multiple surface sliding control drawbacks [19], $\bar{\mathrm{x}}_2$ is passed through a first order filter with time constant $\tau_2 > 0$ as,

$$\tau_2\dot{\mathrm{x}}_{2\mathrm{f}} + \mathrm{x}_{2\mathrm{f}} = \bar{\mathrm{x}}_2 \qquad \mathrm{x}_{2\mathrm{f}}(0) = \bar{\mathrm{x}}_2(0) \qquad (11)$$

In the second step, the actual control law for T is designed. Therefore, second error surface S_2, with filtering virtual control vector x_{2f} is defined as follows:

$$S_2 = x_2 - x_{2f} \tag{12}$$

and its derivative is

$$\dot{S}_2 = \dot{x}_2 - \dot{x}_{2f} \tag{13}$$

By substituting (6) and (11) in (13), it yields:

$$\dot{S}_2 = H^{-1}(x_1)[-V(x_1, x_2) - G(x_1) + T - J^T(q)F_e] + U - \frac{\bar{x}_2 - x_{2f}}{\tau_2} \tag{14}$$

A signal control T is proposed such that $S_2 \to 0$. As mentioned, the control objective is to design a fuzzy gain dynamic surface control as an uncertainty observer for the state vector x_{R1}, x_{R2} in order to track the desired state represented by x_{d1}, x_{d2}. The control structure is presented in Fig.1. The proposed control command is given as follows,

$$T = [J^T(q)F_e + G(q) + V(q, \dot{q}) + H(q)\left(-K_2S_2 + \frac{\bar{x}_2 - x_{2f}}{\tau_2}\right) \tag{15}$$

where K_2 is time varying gain which is further designed by fuzzy algorithm. Substituting (15) in (14) yields

$$\dot{S}_2 = -K_2S_2 + U(x_R) \tag{16}$$

Analytic expression of the closed-loop system is derived via surface errors (S_1 and S_2) and boundary layer error. Substituting (12) in (9) yields

$$\dot{S}_1 = S_2 + x_{2f} - x_{d2} \tag{17}$$

The boundary layer error is defined as follows

$$y_2 = x_{2f} - \bar{x}_2 = x_{2f} + K_1S_1 - x_{d2} \tag{18}$$

with time varying gain K_1. Its derivative is

$$\dot{y}_2 = \dot{x}_{2f} + K_1\dot{S}_1 - \dot{x}_{d2} = \frac{\bar{x}_2 - x_{2f}}{\tau_2} + K_1\dot{S}_1 - \dot{x}_{d2} \tag{19}$$

Substituting (17) and (18) in (19) yields

$$\dot{y}_2 = \frac{\bar{x}_2 - x_{2f}}{\tau_2} + K_1S_2 + K_1x_{2f} - \dot{x}_{I2} = -\frac{y_2}{\tau_2} + R_2 \tag{20}$$

where $R_2(S_2, x_{2f}, X_d) = K_1S_2 + K_1x_{2f} - \dot{x}_{d2}$. From equations (17), (18) and (20), the dynamic surfaces can be rewritten as follows,

$$\dot{S}_1 = S_2 + y_2 - K_1S_1$$

$$\dot{S}_2 = -K_2S_2 + U(x_R) \tag{21}$$

B. Proposed Fuzzy Gain Dynamic Surface Method

The main proposed idea in this research is tracking desired trajectory using fuzzy gain dynamic surface. To remove the effects of uncertainty and disturbance term U in (21), the fuzzy gain dynamic surface method is proposed to tune K_2 and K_1 gains. However, high value gains produce jerky response especially in transient phase of the system. To prevent abrupt variations of control torques, the gains of the controller K_1 is selected by the following fuzzy rules.

$\mathbf{R_1}$: **IF** S_1 is Big Positive and $\dot{S}_1$ is Big Positive **THEN** K_1 is Very Large

⋮

$\mathbf{R_n}$: **IF** S_1 is Negative and $\dot{S}_1$ is Big Positive **THEN** K_1 is Very Small.

Very Small , Big Positive, Medium, Negative, Very Large are the linguistic terms. The membership functions of their corresponding fuzzy sets are selected as a Gaussian function. S_1 and $\dot{S}_1$ are obtained from (8) and (12) and K_1 is the fuzzy gain and output rules. Note that, because of difficulty in measuring acceleration feedback in practice, $\dot{S}_2$ is not available. Therefore, K_2 is not directly tuned by the fuzzy rules and is proposed to consider by $K_2 = \epsilon K_1$ and $\epsilon > 0$. Additionally, ϵ is chosen by the designer based on the knowledge of the system so that the magnitude of the control signal is acceptable.

C. Satbility Analysis

As mentioned in the previous sections, the controller in Fig. 1 is proposed to force the robot to track the desired trajectory and remove the uncertainty and disturbance (7). In the following Theorems are presented to guarantee the stability of the closed-loop system.

Theorem 1: Consider the system illustrated in Fig.1. The closed loop system is uniformly ultimately bounded (UUB) by the command (15) with the following conditions,

$$K_1 \geq 2 + K_1^*(t),\ K_2 \geq \frac{5}{4} + K_2^*(t),\ \frac{1}{\tau_2} \geq \frac{5}{4} + \lambda_2 \tag{22}$$

where $K_1^*(t) > 0$, $K_2^*(t) > 0$ and $\lambda_2 > 0$.

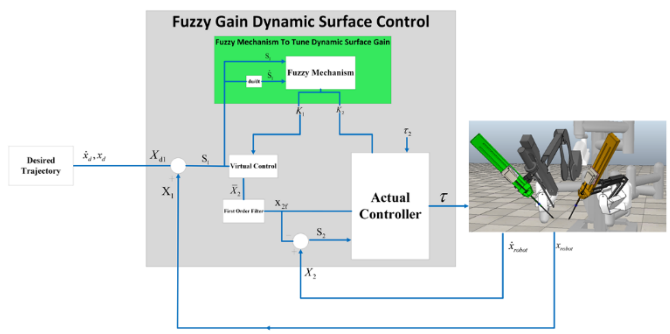

Fig. 1. Block diagram of the proposed controller for PSM robot manipulator. In this figure, desired trajectory block is responsible for determining the desired state vector x_d as position of the reference trajectory. Fuzzy gain block, determines K_1 and K_2 to remove uncertainty and disturbance term U.

Proof: To prove the stability of the closed loop system, it is necessary to consider fuzzy gain dynamic surface in the stability procedure. Proving the stability of the dynamic surface with time varying gain in (20) and (21) is required because the proposed fuzzy gain dynamic surface is applied to force the robot tracks the desired trajectory. Lyapunov function is chosen as

$$V_1 = \frac{1}{2}[S_1^TS_1 + S_2^TS_2 + y_2^Ty_2] \tag{23}$$

Differentiating (23) with respect to time and substituting (21) yields

$$\dot{V}_1 = S_1^T\dot{S}_1 + S_2^T\dot{S}_2 + y_2^T\dot{y}_2 = S_1^T(S_2 + y_2 - K_1S_1) + S_2^T(-K_2S_2 + U) + y_2^T\left(-\frac{y_2}{\tau_2} + R_2\right) \quad (24)$$

It is obvious that,

$$\dot{V}_1 \le \|S_1\|\|S_2\| + \|S_1\|\|y_2\| - K_1\|S_1\|^2 - K_2\|S_2\|^2 + \|S_2\|U - \frac{\|y_2\|^2}{\tau_2} + \left|y_2^TR_2\right| \quad (25)$$

For any finite workspace Ω, considering assumption 1 and boundedness of X_d, there exists a positive constant P_2 such that $\|R_2\| \le P_2$. Using the fact that $2a_1a_2 \le a_1^2 + a_2^2$, (i.e. $\|S_1\|\|S_2\| = 2\|S_1\|\frac{\|S_2\|}{2} \le \|S_1\|^2 + \frac{\|S_2\|^2}{4}$)

$$\dot{V}_1 \le \|S_1\|^2 + \frac{1}{4}\|S_2\|^2 + \|S_1\|^2 + \frac{1}{4}\|y_2\|^2 - K_1\|S_1\|^2 - K_2\|S_2\| + \|S_2\|^2 + \frac{1}{4}(\delta^2) - \frac{\|y_2\|^2}{\tau_2} + \|y_2\|^2 + \frac{1}{4}(P_2^2) \quad (26)$$

In order to make $\dot{V}_1 \le 0$, we choose $K_1(t) = 2 + K_1^*(t)$, $K_2(t) = \frac{5}{4} + K_2^*(t)$ and $\frac{1}{\tau_2} = \frac{5}{4} + \lambda_2$. Substituting into (26)

$$\dot{V}_1 \le -K_1^*\|S_1\|^2 - K_2^*\|S_2\|^2 - \lambda_2\|y_2\|^2 + \frac{1}{4}(\delta^2 + P_2^2)$$
$$\le -K_1^*\|S_1\|^2 - K_2^*\|S_2\|^2 - \lambda_2\|y_2\|^2 + O \quad (27)$$

where $K_1^*(t) > \bar{K}_1^* > 0$, $K_2^*(t) > \bar{K}_2^* > 0$. High order terms which introduces the uncertainty are illustrated by O.

Let us choose constant ζ satisfying the condition as follows,

$$0 < \zeta < \min[\bar{K}_1^*, \bar{K}_2^*, \lambda_2] \quad (28)$$

Hence, we obtain:

$$\dot{V}_1 \le -2\zeta(\|S_1\|^2 + \|S_2\|^2 + \|y_2\|^2) + O = -2\zeta V_1 + O \quad (29)$$

Equation (29) implies that $\dot{V}_1 < 0$ when $V_1 > \frac{O}{2\zeta}$. The surface errors (S_1 and S_2) and the boundary layer error y_2 are all uniformly ultimately bounded in a compact set as shown by Theorem 2.

Theorem 2: According to (21) and considering V_1 as in Theorem 1, the error vectors including surface errors, boundary layer errors and estimation errors are defined as follows:

$$N = [S_1^T \quad S_2^T \quad y_2^T]^T \quad (30)$$

N converges asymptotically to the compact set

$$\Omega_N \coloneqq \left\{N \in \mathbb{R}^{l_N \times 1} \,\middle|\, \|N\| \le \sqrt{M}\right\} \quad (31)$$

where $M = 2(V_1(0)e^{-2\zeta t} + \frac{O}{2\zeta})$ with ζ and O are given in (27) and (28).

Proof: Multiplying (31) by $e^{2\zeta t}$ and then integrating yields

$$V_1(t) \le V_1(0)e^{-2\zeta t} - \frac{O}{2\zeta}e^{-2\zeta t} + \frac{O}{2\zeta} \quad (32)$$

and $\frac{O}{2\zeta}e^{-2\zeta t} \to 0$ and then

$$V_1(t) \le V_1(0)e^{-2\zeta t} + \frac{O}{2\zeta} \quad (33)$$

According to (23) and (30), we have:

$$\frac{1}{2}N^TN \le V_1(0)e^{-2\zeta t} + \frac{O}{2\zeta} \quad (34)$$

Now, we can obtain,

$$\|N\| \le \sqrt{M} \quad (35)$$

where $M = 2(V_1(0)e^{-2\zeta t} + \frac{O}{2\zeta})$. If $t \to \infty$ the then $V_1(0)e^{-2\zeta t} \to 0$ and consequently, the compact set introduced as follows,

$$\mathcal{F} = \{S_1, S_2, y_2 \mid \|S_1\|^2 + \|S_2\|^2 + \|y_2\|^2 \le \frac{O}{\zeta}\} \quad (36)$$

Compact set $\mathcal{F}$ can be kept arbitrarily small choosing $\bar{K}_1^*, \bar{K}_2^*$ and λ_2.

IV. Experimental Evaluation

To verify the proposed methods in Section.3, we used the da Vinci Research Kit [3], a research platform including the first-generation of da Vinci robotic surgery system and embedded systems consisting of electronics hardware and software from WPI and Johns Hopkins University. We consider two cases to demonstrate the performance of the proposed methods. In Case I, we evaluate the performance of Computed Torque Method (CTM). In Case II, the fuzzy gain dynamic surface is considered and results are reported. It is worth mentioning that the model dynamic of da Vinci is available in [3]. Because of the uncertainty of the friction model of the prismatic joint depicted in Fig. 2, we only consider the first three joints of the da Vinci including RRP. In Fig.2, the prismatic joint of the da Vinci system is depicted. The cables used to drive the joint lead to an unknown friction that cannot be easily identified.

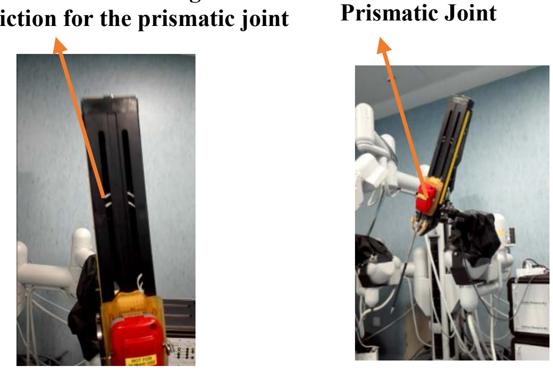

Fig. 2. The PSM of the daVinci robot used to track the desired trajectory.

A. *Case I: Computed Torque Method (CTM)*

CTM is an effective control strategy which can guarantee the globally asymptotic stability of robotic manipulators. However, this method cannot be considered as robust method because it is sensitive to modeling errors. CTM parameters are considered as $K_p = [10 \;\, 8 \;\, 50]^T$ and $K_d = [5 \; 5 \; 25]^T$ which are the gain of error and rate of the error, respectively. From Fig.3, it can be observed that the CTM approach is sensitive to the error in the dynamic model due to friction, thus the prismatic joint tracks the desired trajectory with large error. Fig.4 depicts that the position tracking is not satisfied by CTM algorithm. The control signal is illustrated in Fig.5.

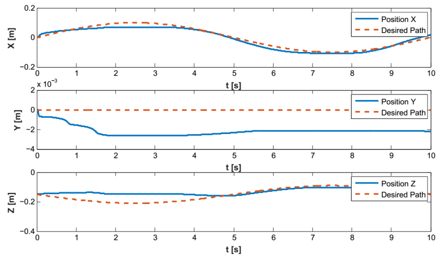

Fig. 3. Position Tracking for CTM approach

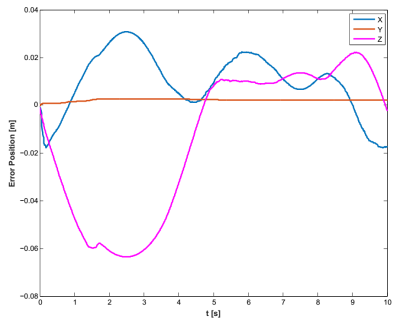

Fig. 4. Error Position Tracking for CTM approach

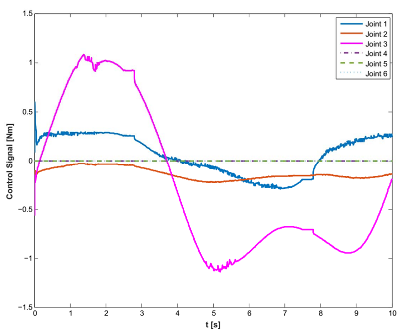

Fig. 5. Torque Control Signals for CTM approach

B. *Case II: Fuzzy Gain Dynamic Surface*

To demonstrate the proposed controller effectiveness to remove and handle the uncertainties effects, the proposed fuzzy gain dynamic surface is used for the PSM. According to fuzzy set rules, the fuzzy rules designed for K_1 are depicted in Tables 1. In addition, $K_2 = K_1$ is selected in the simulation.

TABLE I. FUZZY RULES FOR K_1

K_1 Output		**S_1 (Input)**				
		BN	**SN**	**Z**	**SP**	**BP**
$\dot{S}_1$ (Input)	**BN**	K_1 =VL	K_1 =L	K_1 = M	K_1 = VS	K_1 = S
	SN	K_1 =L	K_1 =M	K_1 =S	K_1 = S	K_1 = L
	Z	K_1 =M	K_1 =S	K_1 =VS	K_1 =VS	K_1 = M
	SP	K_1 =L	K_1 = S	K_1 =S	K_1 = M	K_1 = L
	BP	K_1 =S	K_1 = VS	K_1 = M	K_1 = L	

where BP, SP, Z, SN, and BN are Big Positive, Small positive, Zero, Small Negative and Big Negative, respectively. Position tracking and error position tracking are depicted in Fig. 6 and Fig. 7, respectively. From Fig. 8, the control torque signals are limited. From Fig.9, K_1 as a fuzzy dynamic surface gain is changed to improve the performance of the manipulator. Table II compares the value of RMS position errors between Case I and Case II.

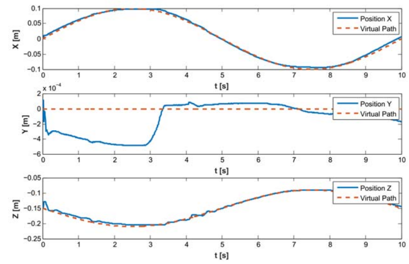

Fig. 6. Position Tracking for proposed FGDC

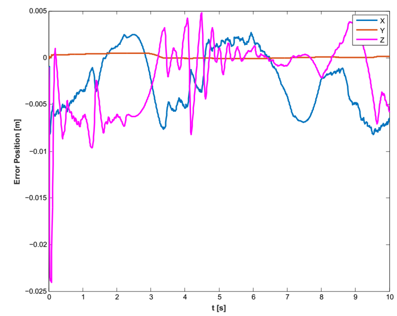

Fig. 7. Error Position Tracking for proposed FGDC

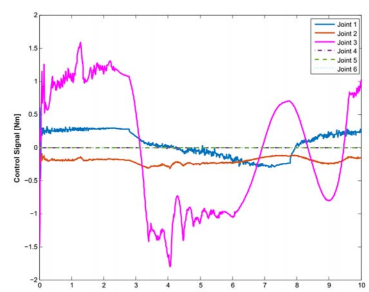

Fig. 8. Toque Control Signal for DSC

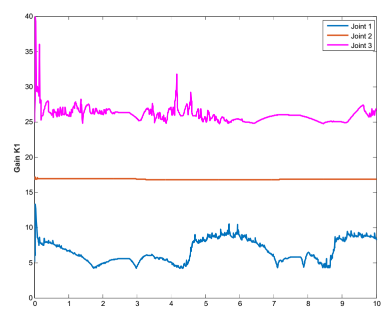

Fig. 9. Gain K_1 for the proposed FGDS control

TABLE II. RMS ERROR OF POSITION ERROR SIGNALS

Method	***Error X (m) RMS***	***Error Y (m) RMS***	***Error Z (m) RMS***
CTM	0.0160	0.0022	0.0342
FGDC	0.0041	0.0002	0.0044

V. Conclusion

In this paper, we have considered the combination of the dynamic surface and fuzzy approach to handle uncertainties in the model of the da Vinci manipulator. Fuzzy gain dynamic surface is used to make a robust control system overcoming uncertainties effect of the system. By definition fuzzy set rules, the gains of the defined dynamic surface are tuned to observe uncertainties. Sstability of the closed-loop systems is guaranteed using Lyapunov's direct method. Finally, the proposed method is verified experimentally using da Vinci robot.

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