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Adaptive Control of Active Dental Joint

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Abstract

In this paper, a PID model-based adaptive robust control method is proposed in order to design a high performance robust controller in the presence of structured (parametric) uncertainties and unstructured uncertainties. The approach improves performance by using the advantages of sliding mode control, adaptive control, and PID controller, while the disadvantages attributed to these methods are remedied by each other. This is achieved without increasing the complexities of the overall design and analysis of the control system (controller). The proposed controller attenuates the effect of model uncertainties from both structured uncertainties and unstructured uncertainties. Thus, transient performance and final tracking accuracy is guaranteed by proper design of the controller. Therefore, asymptotic tracking (or zero final tracking error) can be achieved without using high-gain feedback. The design is conceptually simple and is reliable in applications because of its high performance and strong robustness.

Keywords: *sliding mode controller, adaptive methodology, PID algorithm, active dental joint, robustness*

1. Introduction

Dental Automation: One of the best ways to maintenance of comprehensive oral health is Nanodentistry. It is employing nanomaterials, biotechnology, including tissue engineering and ultimately, dental nanorobotics. Nanodentistry can do oral health maintenance using mechanical dentifrobots, like local anesthesia, dentition renaturalization, permanent hypersensitivity cure, complete orthodontic realignments, covalently bonded diamond dised enamel and *etc.* Any product containing nano particles are Nano products that can be made by combining atomic elements to create mechanical nanoscale objects. Dentin hypersensitive of natural teeth have higher surface density of dentinal tubules and diameter and also larger than nonsensitive teeth. In dental nanorobots, we can use native biological materials, so it could selectively occlude specific tubules in a few minutes and offering patients a quick cure [1-3]. Even Orthodontic nanorobots could directly effect to the periodontal ligaments, and allowing rapid and painless tooth alignment in correct positioning within minutes to hours [2-4]. Nanorobotic manufacture of a biologically auto logous whole replacement tooth, that is, 'complete dentition replacement therapy' should become conveniently of a typical office visit with use of a desktop manufacturing facility, which would invent or fabricate the new tooth in the dentist's office not in the laboratory . In Nanorobotic analgesics, don't use needles, so there is a greater ability to control the analgesic effect, fast and reversible with avoid of side effects, to give patient comfort and also reduced nervousness [5]. Nanorobotic dentifrice (dentifrobots) take by mouthwash or toothpaste that could control all supragingival and sub gingival surfaces using once a day or more, metabolizing the

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organic matter into harmless and odorless vapors and prevent calculus debridement and plaque accumulation . With this kind of daily dental care available from an early age, we can prevent tooth decay and gingival diseases.

Active Dental Joint: Multi degrees of freedom actuator is a type of nonlinear joints. These actuators are finding wide use in a number of Industries such as aerospace, Industrial medical and automotive. For high precession trajectory planning and control, it is necessary to replace the actuator system made up of several single-DOF motors connected in series and/or parallel with a single multi-DOF actuator [1-3]. The spherical motor have potential contributions to a wide range of applications such as coordinate measuring, object tracking, material handling, automated assembling, welding, and laser cutting [4]. All these applications require high precision motion and fast dynamic response, which the spherical motor is capable of delivering [5-6]. The spherical motor exhibits coupled, nonlinear and very complex dynamics. The design and implementation of feedback controllers for the motor are complicated. The controller design is further complicated by the orientation-varying torque generated by the spherical motor [7].

Control Challenge: At its simplest, a controller (control system) is a device in which a sensed quantity is used to modify the behavior of a physical system through computation and actuation. The basic loop of sensing, computation, and actuation is the central concept in control and is called a feedback-loop. The feedback-loop operates with actions based on the deviation between measured and reference quantities. The key issues in designing control systems are ensuring that the dynamics of the closed-loop system (system to be controlled plus controller) are stable (bounded disturbances give bounded errors) and that dynamics has the desired performance (good disturbance rejection, small tracking error, and fast adaptation to changes in operating point, *etc*). It is a well known fact that real physical systems (engineering systems) are very often uncertain or vague, which generally makes it difficult to accurately model a complex system or process by a mathematical model. Uncertainty means the exact output of a real physical system cannot be predicted by a mathematical model that describes the physical system under investigation, even if the input to the system is known. Uncertainty arises from two sources: unknown or unpredictable inputs (*e.g.,* disturbance, noise) and unknown or unpredictable dynamics (Zhou, *et al.,* 1996). From a control point of view uncertainties can be classified into two major categories: structured uncertainties (*e.g.,* parametric uncertainties) and unstructured uncertainties (*e.g.,* external disturbances, unmodelled dynamics and measurement noise). To control of uncertainties nonlinear controller is introduced [8-11].

Sliding Mode Algorithm: Sliding mode controller is a powerful nonlinear robust controller under condition of partly uncertain dynamic parameters of system [7]. This controller is used to control of highly nonlinear systems especially for robot manipulators. This controller works very well in certain and partly uncertain condition [12-18]. This controller has two important subparts, switching part and equivalent part. Switching part of controller is used to design suitable tracking performance based on very fast switching. This part has essential role to have a good trajectory performance in all joints. However this part is very important in uncertain condition but it is caused to chattering phenomenon in system performance. Chattering phenomenon can cause some important mechanical problems [19-22]. The second subpart in sliding mode controller is equivalent part especially in uncertain condition. Sliding mod controller is a nonlinear model based controller and equivalent part is a dynamic formulation of active dental joint, which is used in control formulation to eliminate the decoupling and nonlinear term of dynamic parameters. However, this part is very essential to reliability but in uncertain condition or highly nonlinear dynamic systems it can cause some problem. However conventional sliding mode controller is a robust, stable and reliable controller but there are three main issues limiting; equivalent part related to dynamic equation of systems, computation of the bounds of uncertainties and chattering phenomenon [20-22].

Adaptive Algorithm: 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 [20-22]. 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. For nonlinear dynamic systems with various parameters, adaptive control technique can train the dynamic parameter to have an acceptable controller performance.

Problem Statements and Objectives: Active dental joint is three degrees of freedom, dynamics formulation is highly nonlinear, time variant, MIMO, uncertain and there exist strong coupling effects between joints. Design a linear behaviour controller to reduce or cancelling decoupling as well as stability, robustness and reliability are most important objectives. To control of this system conventional sliding mode controller (SMC) is introduced. Conventional sliding mode controller (SMC) is a nonlinear, model base, stable, robust and reliable controller. This controller is a strong candidate in order to design a controller using the uncertainties and external disturbance. However, this type of controller is worked in many applications but there are three main issues limiting the applications of conventional sliding mode controller.

- equivalent part related to dynamic equation of active dental joint
- chattering phenomenon
- computation the uncertainties problem in chattering free equivalent estimation sliding mode controller

The first challenge to design a robust sliding mode based controller is reduce or remove the chattering phenomenon, because this problem caused to heating and oscillation in mechanical part of system. Many researchers can reduce the chattering but they also lost the system stability based on methods. In this research reduce or eliminate the chattering according to maintain the robustness is the main objective. Switching function is caused to chattering but it is one of the main parts to design robust and high speed sliding mode controller. In sliding mode controller, sliding surface slope (λ) is the second factor to control the chattering, as a result the main task in the first objective is reduce or eliminate the chattering in sliding mode controller based on design parallel linear control methodology and discontinuous part. Sliding mode controller and linear control methodologies are robust based on Lyapunov theory, therefore; Lyapunov stability is proved in proposed chattering free sliding mode controller based on switching theory.

The second challenge to improve sliding mode controller for active dental joint is nonlinear dynamic sliding mode formulation related to highly nonlinear dynamic equation. This problem is not a simple mission, consequently; to solve this challenge PID controller is used as a parallel controller with chattering-free sliding mode controller as a model-base PID sliding mode controller. In model-base PID sliding mode controller, PID controller is used as an estimator to eliminate the dynamic uncertainties.

The third challenge in this research is the uncertainty problem. Uncertainties are very important challenges and caused to extremely high estimation of the bounds. To solve this problem, select the desired sliding surface and $sign$ function play a vital role and if the dynamic of active dental joint is derived to sliding surface then the linearization and decoupling through the use of feedback, not gears, can be realized.

This paper is organized as follows; section 2, is served as an introduction to the dynamic of three degrees of freedom spherical motor, sliding mode controller and PID algorithm. Part 3, introduces and describes the methodology algorithm. Section 4 presents the simulation results and discussion of this algorithm and the final section describe the conclusion.

2. THEORY

Active Dental Joint Kinematics and Dynamics: Dynamic modeling of spherical motors is used to describe the behavior of spherical motor such as linear or nonlinear dynamic behavior, design of model based controller such as pure sliding mode controller which design this controller is based on nonlinear dynamic equations, and for simulation. The dynamic modeling describes the relationship between motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (*e.g.,* inertia, coriolios, centrifugal, and the other parameters) to behavior of system. Spherical motor has nonlinear and uncertain dynamic parameters 3 degrees of freedom (DOF) motor.

The equation of a spherical motor governed by the following equation:

$$\boldsymbol{H}(\boldsymbol{q})\begin{bmatrix}\ddot{\alpha}\\ \ddot{\beta}\\ \ddot{\gamma}\end{bmatrix}+\mathbf{B}(\boldsymbol{q})\begin{bmatrix}\dot{\alpha}\dot{\beta}\\ \dot{\alpha}\dot{\gamma}\\ \dot{\beta}\dot{\gamma}\end{bmatrix}+\boldsymbol{C}(\boldsymbol{q})\begin{bmatrix}\dot{\alpha}^2\\ \dot{\beta}^2\\ \dot{\gamma}^2\end{bmatrix}=\begin{bmatrix}\tau_x\\ \tau_y\\ \tau_z\end{bmatrix} \quad (1)$$

Where τ is actuation torque, H (q) is a symmetric and positive define inertia matrix, B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques.

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 variableq_i, independently of the motion of the other parts. Therefore, the angular acceleration is found as to be:

$$\ddot{\boldsymbol{q}}=\boldsymbol{H}^{-1}(\boldsymbol{q}).\{\boldsymbol{\tau}-\{\boldsymbol{B}+\boldsymbol{C}\}\} \quad (2)$$

This technique is very attractive from a control point of view.

Study of spherical motor is classified into two main groups: kinematics and dynamics. Calculate the relationship between rigid bodies and final part without any forces is called Kinematics. Study of this part is pivotal to design with an acceptable performance controller, and in real situations and practical applications. As expected the study of kinematics is divided into two main parts: forward and inverse kinematics. Forward kinematics has been used to find the position and orientation of task frame when angles of joints are known. Inverse kinematics has been used to find possible joints variable (angles) when all position and orientation of task frame be active.

The main target in forward kinematics is calculating the following function:

$$\boldsymbol{\Psi}(\boldsymbol{X},\boldsymbol{q})=\boldsymbol{0} \quad (3)$$

Where $\Psi(.)\in R^n$ is a nonlinear vector function, $X=[X_1,X_2,\dots\dots,X_l]^T$ is the vector of task space variables which generally task frame has three task space variables, three orientation, $q=[q_1,q_2,\dots.,q_n]^T$ is a vector of angles or displacement, and finally n is the number of actuated joints. The Denavit-Hartenberg (D-H) convention is a method of drawing spherical motor free body diagrams. Denvit-Hartenberg (D-H) convention study is necessary to calculate forward kinematics in this motor.

A systematic Forward Kinematics solution is the main target of this part. The first step to compute Forward Kinematics (F.K) is finding the standard D-H parameters. The following steps show the systematic derivation of the standard D-H parameters.

1. Locate the spherical motor
2. Label joints
3. Determine joint rotation (θ)
4. Setup base coordinate frames.
5. Setup joints coordinate frames.
6. Determineα_i, thatα_i, link twist, is the angle between Z_i and Z_{i+1} about an X_i.
7. Determine d_i and a_i , that a_i, link length, is the distance between Z_i and Z_{i+1} along X_i. d_i, offset, is the distance between X_{i-1} and X_i along Z_i axis.
8. Fill up the D-H parameters table. The second step to compute Forward kinematics is finding the rotation matrix (R_n^0). The rotation matrix from$\{F_i\}$ to $\{F_{i-1}\}$ is given by the following equation;

$$\boldsymbol{R_i^{i-1} = U_{i(\theta_i)} V_{i(\alpha_i)}} \quad (4)$$

Where $U_{i(\theta_i)}$ is given by the following equation;

$$\boldsymbol{U_{i(\theta_i)}} = \begin{bmatrix} \boldsymbol{cos(\theta_i)} & \boldsymbol{-sin(\theta_i)} & \boldsymbol{0} \\ \boldsymbol{sin(\theta_i)} & \boldsymbol{cos(\theta_i)} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} \quad (5)$$

and $V_{i(\alpha_i)}$ is given by the following equation;

$$\boldsymbol{V_{i(\theta_i)}} = \begin{bmatrix} \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{cos(\alpha_i)} & \boldsymbol{-sin(\alpha_i)} \\ \boldsymbol{0} & \boldsymbol{sin(\alpha_i)} & \boldsymbol{cos(\alpha_i)} \end{bmatrix} \quad (6)$$

So (R_n^0) is given by

$$\boldsymbol{R_n^0 = (U_1 V_1)(U_2 V_2) \dots\dots\dots (U_n V_n)} \quad (7)$$

The final step to compute the forward kinematics is calculate the transformation ${}_n^0T$ by the following formulation [3]

$$\boldsymbol{{}_n^0T = {}_1^0T . {}_2^1T . {}_3^2T \dots\dots . {}_n^{n-1}T} = \begin{bmatrix} \boldsymbol{R_n^0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{1} \end{bmatrix} \quad (8)$$

Sliding Mode Algorithm: In this section a type of robust nonlinear feedback control methodology that has been proven very effective in a variety of practical control problems is analyzed. In this control methodology, the control law is allowed to change its structure, *i.e.*, the gains in each feedback path switch between two values according to some rules. Because during the control process, the structure of the control law switches/varies from one structure to another, this control methodology is called "variable structure control" (VSC). In variable structure control, the control is designed such that the states of a system (possibly nonlinear uncertain) are attracted to a prescribed (user defined) surface called a sliding/switching surface. The system dynamics restricted to the sliding/switching surface have desired properties such as convergence of the system states to the desired equilibrium point and robustness. The system dynamics on the sliding/switching surface represent a motion, called sliding mode. That is why this type of control methodology is often called "sliding mode control (SMC)." This control methodology can be found with both names "variable structure control" and "sliding mode control" in the literature. The sliding mode control is used as a framework to design a robust controller in this research. One of the underlying assumptions in the SMC is that the control input can be switched from one value to another infinitely fast. In practice switching is not instantaneous, because finite delays are inherent in all physical actuators. The uncertainties, imperfections in switching devices or delays, lead to high-frequency oscillations called chattering, which can cause a fast breakdown of mechanical elements in actuators, *e.g.*, high wear. It may also excite unmodelled high-frequency dynamics, which may lead to instability. The performance of a SMC is therefore measured by its robustness and severity of chattering. Thus, it is of primary importance to reduce or eliminate the chattering phenomenon, in order to make SMC to be practical. 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. Sliding mode control theory for control joint 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 [16-19];

$$\tau_{(q,t)} = \begin{cases} \tau_i^+(q,t) & if\ S_i > 0 \\ \tau_i^-(q,t) & if\ S_i < 0 \end{cases} \tag{9}$$

where S_i is sliding surface (switching surface), $i = 1, 2, \dots\dots, n$ for n-DOF joint, $\tau_i(q,t)$ is the i^{th} torque of joint. Sliding mode controller is divided into two main sub controllers:

- Corrective control(U_c)
- Equivalent controller(U_{eq}).

Discontinues controller causes an acceptable tracking performance at the expense of very fast switching. Conversely in this theory good trajectory following is based on fast switching, fast switching is caused to have system instability and chattering phenomenon. Fine tuning the sliding surface slope is based on nonlinear equivalent part [20]. However, this controller is used in many applications but, pure sliding mode controller has two most important challenges: chattering phenomenon and nonlinear equivalent dynamic formulation in uncertain parameters [21].

Design a robust controller for multi-DOF-joints is essential because these joints have highly nonlinear dynamic parameters. Consider a nonlinear single input dynamic system is defined by:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{10}$$

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 main goal to design this controller is train to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and trucking error vector is defined by:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \tag{11}$$

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

$$U_C = \hat{U} - K(\vec{x}, t) \cdot \mathbf{sgn}(s) \tag{12}$$

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

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{13}$$

and the $K(\vec{x}, t)$ is the positive constant.

Based on above discussion, the sliding mode control law for multi-DOF-joints is written as:

$$U = U_{eq} + U_c \tag{14}$$

where, the model-based component U_{eq} is the nominal dynamics of systems and calculated as follows:

$$U_{eq} = \left[H^{-1}(q) \left(\mathrm{B}(q) \begin{bmatrix} \dot{\alpha}\dot{\beta} \\ \dot{\alpha}\dot{\gamma} \\ \dot{\beta}\dot{\gamma} \end{bmatrix} + C(q) \begin{bmatrix} \dot{\alpha}^2 \\ \dot{\beta}^2 \\ \dot{\gamma}^2 \end{bmatrix} \right) + \dot{S} \right] H(q) \tag{15}$$

and U_c is computed as;

$$U_c = K \cdot \mathbf{sgn}(S) \tag{16}$$

The sliding mode control of multi-DOF-joint is calculated as;

$$\begin{bmatrix} \widehat{\tau_\alpha} \\ \widehat{\tau_\beta} \\ \widehat{\tau_\gamma} \end{bmatrix} = \left[H^{-1}(q) \left(\mathrm{B}(q) \begin{bmatrix} \dot{\alpha}\dot{\beta} \\ \dot{\alpha}\dot{\gamma} \\ \dot{\beta}\dot{\gamma} \end{bmatrix} + C(q) \begin{bmatrix} \dot{\alpha}^2 \\ \dot{\beta}^2 \\ \dot{\gamma}^2 \end{bmatrix} \right) + \dot{S} \right] H(q) + K \cdot \mathbf{sgn}(S) \tag{17}$$

The lyapunov formulation can be written as follows [22],

$$V = \frac{1}{2} S^T . H . S \tag{18}$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S^T . \dot{H} . S + S^T \, H\dot{S} \tag{19}$$

the dynamic equation of multi-DOF actuator can be written based on the sliding surface as

$$H\dot{S} = -VS + H\dot{S} + B + C \tag{20}$$

it is assumed that

$$S^T\big(\dot{H} - 2B + C\big)S = 0 \tag{21}$$

by substituting (20) in (21)

$$\dot{V} = \frac{1}{2} S^T \dot{H} S - S^T B + CS + S^T\big(H\dot{S} + B + CS\big) = S^T\big(H\dot{S} + B + CS\big) \tag{22}$$

suppose the control input is written as follows

$$\widehat{U} = U_{\widehat{Nonlinear}} + \widehat{U_c} = \big[\widehat{H^{-1}}(B + C) + \dot{S}\big]\widehat{H} + K.sgn(S) + B + CS \tag{23}$$

$$\dot{V} = S^T(H\dot{S} + B + C - \widehat{H}\dot{S} - \widehat{B + C}S - Ksgn(S) = S^T \left(\widetilde{H}\dot{S} + \widetilde{B + C}S - Ksgn(S)\right) \tag{24}$$

and

$$\big|\widetilde{H}\dot{S} + \widetilde{B + C}S\big| \le \big|\widetilde{H}\dot{S}\big| + \big|\widetilde{B + C}S\big| \tag{25}$$

$$K_u = \big[\big|\widetilde{H}\dot{S}\big| + |B + CS| + \eta\big]_i \, , i = 1, 2, 3, 4, \ldots \tag{26}$$

and finally;

$$\dot{V} \le -\sum_{i=1}^{n} \eta_i \, |S_i| \tag{27}$$

Linear Control Algorithm: Linear control theory is used in linear and nonlinear systems. This type of theory is used in industries, because design of this type of controller is simple than nonlinear controller. However this type of controller used in many applications but it cannot guarantee performance in complex systems. Simple linear controllers are including proportional algorithm, Proportional-Derivative algorithm, Integral algorithm, Proportional-Integral algorithm and Proportional-Integral-Derivative algorithm. The combination of proportional (P) component, integral (I) component with a derivative (D) controller offered advantages in each case. This type of controller has rapid response to the input deviation, the exact control at the desired input as well as fast response to the disturbances. The PID controller takes the error between the desired joint variables and the actual joint variables to control. A proportional-derivative integral control system can easily be implemented. This method does not provide sufficient control for systems with time-varying parameters or highly nonlinear systems. Figure 1 shows the block diagram of PID control. The formulation of PID controller calculated as follows;

$$U_{PID} = K_p \times e + K_i(\frac{1}{T} \int e.dt) + K_v(\frac{de}{dt}) = K_p \times e + K_i \sum e + K_v \dot{e} \tag{18}$$

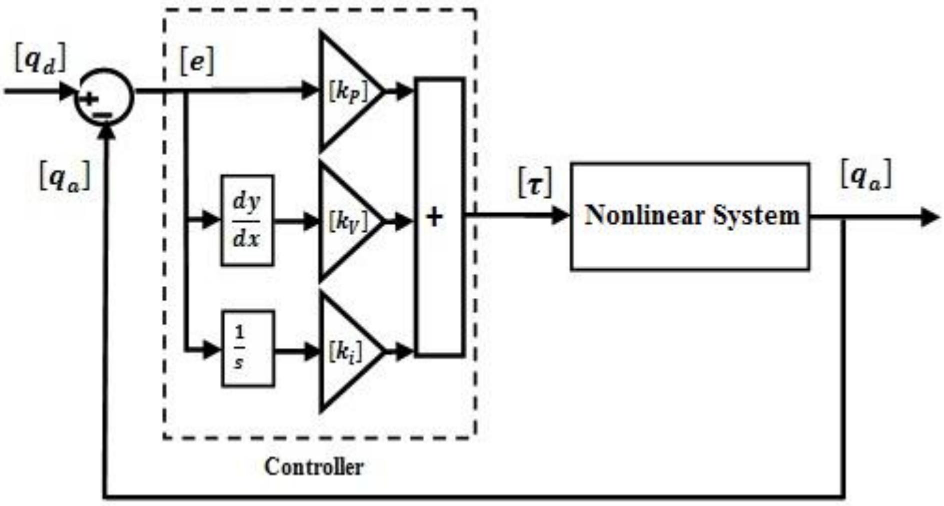

Figure 1. Block Diagram of PID Control of Robot Manipulator

3. Methodology

The main approach to reduce or eliminate the chattering in this research is based on the estimated uncertainties. In this approach, the control law consists of a continuous feedback control component and a component derived from the uncertainties estimator for compensation of the uncertainties that exist in the dynamic model of the system. If uncertainties are sufficiently compensated there is no need to use discontinuous control law to achieve sliding mode, thus the chattering can be reduced or eliminated if the uncertainties estimator is properly designed. In sliding mode controller select the desired sliding surface and $\boldsymbol{sign}$ function play a vital role to system performance and if the dynamic of active dental joint is derived to sliding surface then the linearization and decoupling through the use of feedback, not gears, can be realized. In this state, the derivative of sliding surface can help to decoupled and linearized closed-loop active dental joint dynamics that one expects in computed torque control. Linearization and decoupling by sliding mode controller can be obtained in spite of the quality of the active dental joint dynamic model. As a result, uncertainties are estimated by discontinuous feedback control but it can cause to chattering. To reduce the chattering in presence of switching functions; linear controller is added to discontinuous part of sliding mode controller. Linear controller is type of stable controller as well as conventional sliding mode controller. In proposed methodology PD, PI or PID linear controller is used in parallel with discontinuous part to reduce the role of sliding surface slope as a main coefficient. The formulation of new chattering free sliding mode controller for active dental joint is;

$$\boldsymbol{\tau} = \boldsymbol{\tau_{eq}} + \boldsymbol{\tau_{dis-new}} \tag{29}$$

In (29) $\boldsymbol{\tau_{eq}}$ is equivalent term of sliding mode controller and this term is related to the nonlinear dynamic formulation of active dental joint. The new switching discontinuous part is introduced by $\boldsymbol{\tau_{dis-new}}$ a6nd this item is the important factor to resistance and robust in this controller. In PD sliding surface, based on (3.26) the change of sliding surface calculated as;

$$\boldsymbol{S_{PD}} = \boldsymbol{\lambda e} + \boldsymbol{\dot{e}} \rightarrow \boldsymbol{\dot{S}_{PD}} = \boldsymbol{\lambda \dot{e}} + \boldsymbol{\ddot{e}} \tag{30}$$

The discontinuous switching term $(\boldsymbol{\tau_{dis}})$ is computed as

$$\boldsymbol{\tau_{dis-new}} = \boldsymbol{K_a} \cdot \mathbf{sgn}(\boldsymbol{S}) + \boldsymbol{K_b}.\boldsymbol{S} \tag{31}$$

$$\boldsymbol{\tau_{dis-PD-new}} = \boldsymbol{K_a} \cdot \mathbf{sgn}(\boldsymbol{\lambda e} + \boldsymbol{\dot{e}}) + \boldsymbol{K_b} \cdot (\boldsymbol{\lambda e} + \boldsymbol{\dot{e}}) \tag{32}$$

$$\boldsymbol{\tau_{dis-PI-new}} = \boldsymbol{K_a} \cdot \mathbf{sgn}\left(\boldsymbol{\lambda e} + (\tfrac{\lambda}{2})^2 \sum \boldsymbol{e}\right) + \boldsymbol{K_b} \cdot \left(\boldsymbol{\lambda e} + (\tfrac{\lambda}{2})^2 \sum \boldsymbol{e}\right) \tag{33}$$

$$\tau_{dis-PID-new} = K_a \cdot \mathrm{sgn}\left(\lambda e + \dot{e} + (\frac{\lambda}{2})^2 \sum e\right) + K_b \cdot \left(\lambda e + \dot{e} + (\frac{\lambda}{2})^2 \sum e\right) \quad (34)$$

$$\tau = \tau_{eq} + K_a . \mathrm{sgn}(S) + +K_b . S = \left[A^{-1}(q) \times (N(q,\dot{q})) + \dot{S}\right] \times A(q) + K_a . \mathrm{sgn}(S) \ + K_b . S \quad (35)$$

The formulation of PD-SMC is;

$$\tau_{PD-SMC-new} = K_a \cdot \mathrm{sgn}(\lambda e + \dot{e}) + K_b \cdot (\lambda e + \dot{e}) + \left[A^{-1}(q) \times (N(q,\dot{q})) + \dot{S}\right] \times A(q) \quad (36)$$

According to the dynamic formulation of active dental joint

$$\tau = A(q)\ddot{q} + V(q,\dot{q})\dot{q} \quad (37)$$

And the controller formulation

$$\tau = \hat{A}\ddot{q}_r + \hat{V}\dot{q}_r + K\, sgn\,(S) + K.S \quad (38)$$

$$A(q)\ddot{q} + V(q,\dot{q})\dot{q} = \hat{A}\ddot{q}_r + \hat{V}\dot{q}_r + K_a\, sgn(S) + K_b.S \quad (39)$$

Where $\hat{A}, \hat{V}$ are the estimation of $A(q), V(q,\dot{q})$ and in this formulation $K_a = \left[K_{a_1}, K_{a_2}, K_{a_3}, K_{a_4}, K_{a_5}, K_{a_6}\right]$ and $K_b = \left[K_{b_1}, K_{b_2}, K_{b_3}, K_{b_4}, K_{b_5}, K_{b_6}\right]$

Since $\dot{q}_d = \dot{q} - S$ and $\ddot{q}_d = \ddot{q} - \dot{S}$

$$A\dot{S} + (V + K_b)S = \Delta f - K_a\, sgn(S) \quad (40)$$

Where $\Delta f = \Delta A\ddot{q} + \Delta V\dot{q}$ and $\Delta A = \hat{A} - A, \Delta V = \hat{V} - V$

The dynamic equation of active dental joint can be written based on the sliding surface as

$$A\dot{S} = -VS + A\dot{S} + VS + G - \tau \quad (41)$$

Assuming that it can be expressed by the following equation:

$$S^T\left(\dot{A} - 2V\right)S = 0 \quad (42)$$

If the Lyaponuv function is written by;

$$V = \frac{1}{2}S^T A(q) S \quad (43)$$

We can written the derivative of Lyapunov functions as;

$$\dot{V} = S^T A\dot{S} + \frac{1}{2}S^T\, \dot{A}S \quad (44)$$

$$= S^T\left(A\dot{S} + VS\right)$$

$$= S^T[-k_{ab}S + \Delta f - k_a sgn(S)]$$

$$= \sum_{i=1}^{3}(S_i[\Delta f_i - k_{ai} sgn(S_i)]) - S^T k_b S.$$

$$\dot{V} = \frac{1}{2}S^T \dot{A}S - S^T VS + S^T\left(A\dot{S} + VS - \tau\right) = S^T\left(A\dot{S} + VS - \tau\right) \quad (45)$$

according to the sliding mode controller formulation;

$$\hat{\tau} = \widehat{\tau_{eq}} + \widehat{\tau_{dis}} = \left[\widehat{A^{-1}}(\hat{V}) + \dot{S}\right]\hat{A} + K_a\, sgn(S) + K_b.S \quad (46)$$

$$\dot{V} = S^T(A\dot{S} + VS - \hat{A}\dot{S} - \hat{V}S - K_a\, sgn(S) - K_b.S = S^T\left(\tilde{A}\dot{S} + \tilde{V}S - Ksgn(S) - K_b.S\right) \quad (47)$$

For $k_{ai} \geq \ |\Delta f_i|$ we always get $S_i[\Delta f_i - k_{ai} sgn(S_i)] \leq 0$ and we can write:

$$\dot{V} = \ \sum_{i=1}^{6}(S_i[\Delta f_i - k_{ai} sgn(S_i)]) - S^T k_{bi} S \leq -S^T k_{bi} S < 0 \quad (S \neq 0) \quad (48)$$

Conventional sliding mode controller is worked based on active joint dynamic model. Based on equivalent part in conventional nonlinear controllers, in complex and highly nonlinear systems these controllers have many problems for accurate responses because these type of controllers need to have accurate knowledge of dynamic formulation of system. The nonlinear dynamic formulation problem in highly nonlinear system can be solved by PID algorithm. This type of controller is free of mathematical dynamic parameters of plant. However, PID controller used in many applications, but pure PID controller has many challenges in nonlinear systems. To solve the equivalent challenge especially in uncertain system, PID sliding mode controller is recommended. Proportional-Integral-Derivative (PID) controller has rapid response to the input deviation, the exact control at the desired input as well as fast response to the disturbances. The PID controller takes the error between the desired joint variables and the actual joint variables to control the three dimension of joint. The equation of PID controller for control of 3 degrees of freedom joint is;

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \end{bmatrix} = \begin{bmatrix} K_{i1}\sum e_1 + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ K_{i2}\sum e_2 + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ K_{i3}\sum e_3 + K_{v3}\dot{e}_3 + K_{p3}e_3 \end{bmatrix} \quad (49)$$

Where $e = q_d - q_a$, q_d is desired joint variable and q_a is actual joint variable.

In PID controller the control law is given by the following equation;

$$\tau = K_p e + K_v \dot{e} + K_i \sum e \quad (50)$$

Where $e = q_{i_d} - q_{i_a}$

In this theory K_p, K_i **and** K_v are positive constant. To show this controller is stable and achieves zero steady state error, the Lyapunov function is introduced;

$$V = \frac{1}{2}\left[\dot{q}^T A(q)\dot{q} + e^T K_p e\right] = \quad (51)$$

$$\frac{1}{2}\frac{d}{dt}\left[\dot{q}^T A\dot{q}\right] = \dot{q}\,\tau$$

If the conversation energy is written by the following form:

$$\frac{1}{2}\frac{d}{dt}\left[\dot{q}^T A\dot{q}\right] = \dot{q}\,\tau$$

Where $(\dot{q}\,\tau)$ shows the power inputs from actuator and $\frac{1}{2}\frac{d}{dt}[\dot{q}^T A\dot{q}]$ is the derivative of the robot kinematic energy.

$$\dot{V} = \dot{q}^T\left[\tau + K_p e\right] \quad (52)$$

Based on $\tau = -K_{p_i} e - K_{v_i}\dot{e} - K_i \sum e$ **,** we can write:

$$\dot{V} = \dot{q}^T K_p \dot{q} \leq 0 \quad (53)$$

If $\dot{V} = 0$, we have

$$\dot{q} = 0 \rightarrow \ddot{q} = 0 \rightarrow \ddot{q} = A^{-1}K_p e \rightarrow e = 0 \quad (54)$$

In this state, the actual trajectories converge to the desired state. Figure 2 illustrates the uncertainty estimation based on linear PID controller.

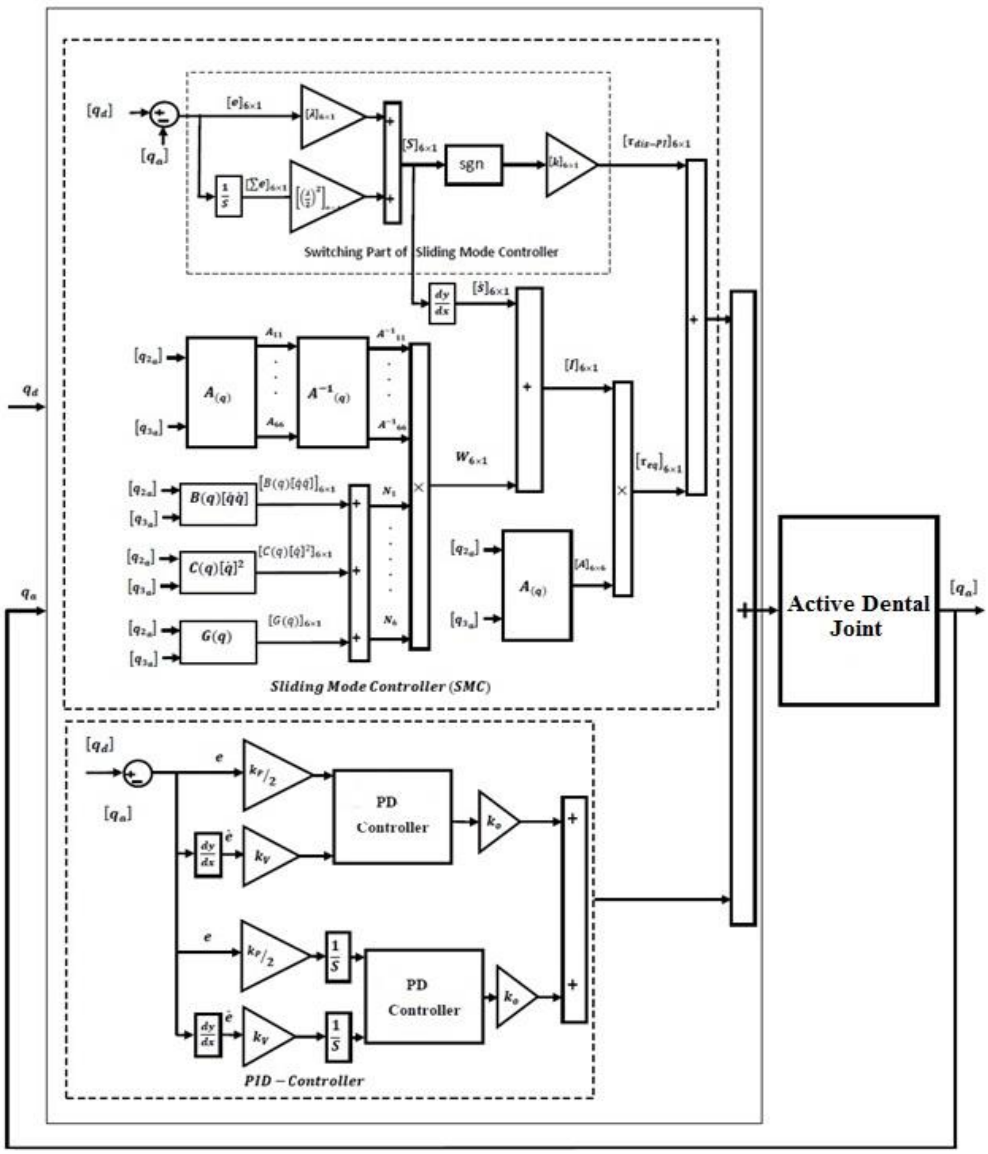

Figure 2. PID Chattering Free Sliding Mode Controller

Adaptive (on-line) control is used in systems whose dynamic parameters are varying and need to be training on line. PID sliding mode controller has difficulty in handling unstructured model uncertainties and this controller's performance is sensitive to sliding surface slope coefficient. It is possible to solve above challenge by combining PID tuning method and chattering free PID sliding mode controller, which this methodology can help to improve system,'s tracking performance by on-line tuning method. Compute the best value of sliding surface slope coefficient has played important role to improve system's tracking performance especially the system parameters are unknown or uncertain. This problem is solved by tuning the surface slope coefficient ($\boldsymbol{\lambda}$) of the chattering free PID sliding mode controller continuously in real-time. In this methodology, the system's performance is improved with respect to the classical sliding mode controller and chattering free PID sliding mode controller. Figure 3 shows the PID based tuning chattering free PID sliding mode controller. To adjust the sliding surface slope coefficient we define $\widehat{\boldsymbol{C}}(\boldsymbol{x}|\boldsymbol{\lambda})$ as the PID tuning.

$$\widehat{\boldsymbol{C}}(\boldsymbol{x}|\boldsymbol{\lambda}) = \boldsymbol{\lambda}^{\boldsymbol{T}}\boldsymbol{\zeta}(\boldsymbol{x}) \quad (55)$$

If minimum error ($\boldsymbol{\lambda}^*$) is defined by;

$$\boldsymbol{\lambda}^* = \boldsymbol{arg\ min}\ [\left(\boldsymbol{Sup}\left|\widehat{\boldsymbol{C}}(\boldsymbol{x}|\boldsymbol{\lambda}) - \boldsymbol{f}(\boldsymbol{PID})\right)\right] \quad (56)$$

where λ^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $\boldsymbol{\lambda} - \boldsymbol{\lambda}^*$. adaption law in PID-based tuning chattering free PID sliding mode controller is used to adjust the sliding surface slope coefficient.

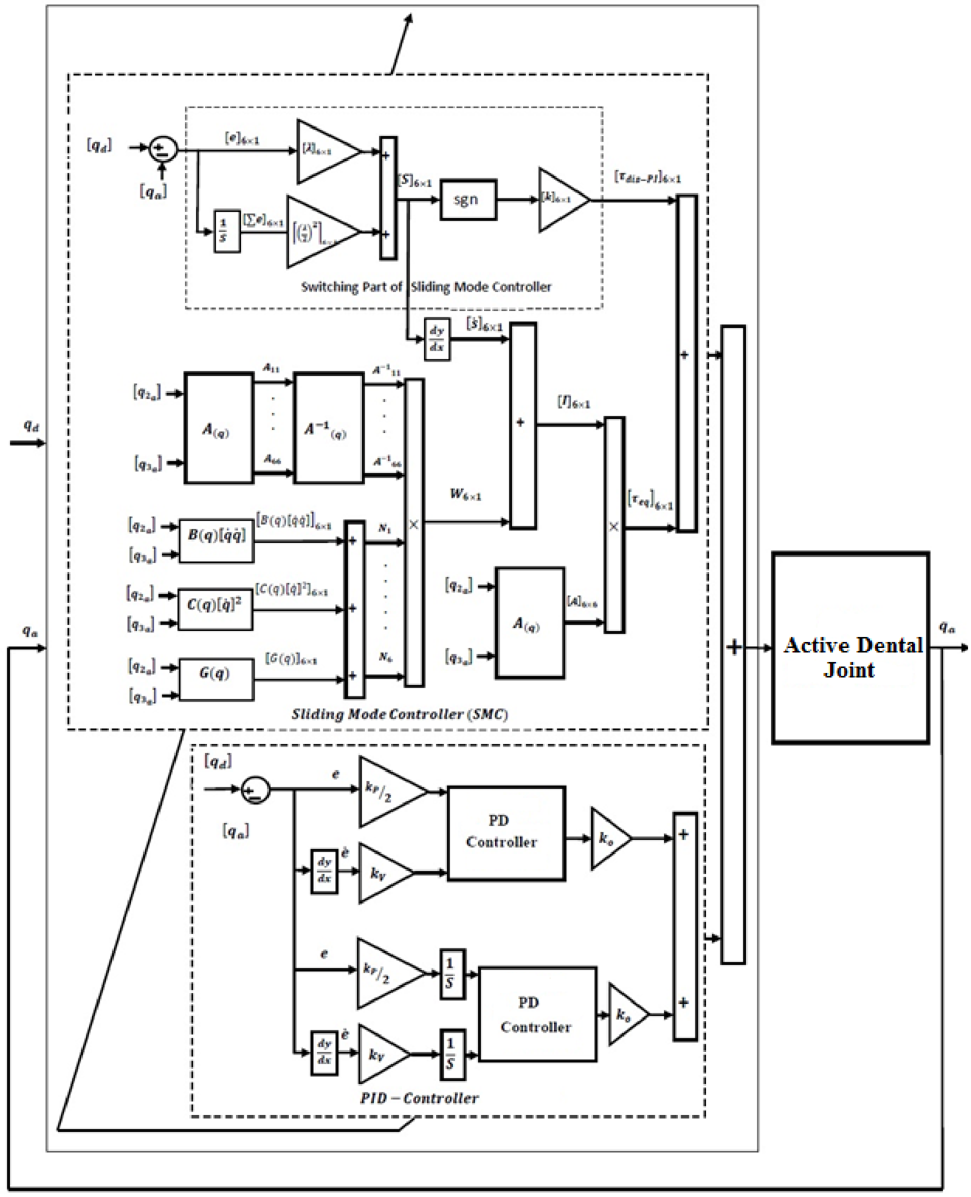

Figure 3. Adaptive Chattering Free PID Sliding Mode Controller

4. Results And Discussion

Comparison of the Tracking Data and Information: based on the formulation of PID sliding mode controller formulation, discontinuous controllers gain (K_a), linear controllers gain (K_b), PD gain updating factors $(K_{p_{PD}}, K_v\ and\ K_{o_{PD}})$, PI gain updating factors $(K_{p_{PI}}, K_i\ and\ K_{o_{PI}})$ and sliding surface slope (λ) are very important to quality of the system's performance. Sliding surface slope is the main coefficient to design conventional sliding mode controller, parallel linear chattering free sliding mode controller and PID sliding mode controller hence, to improve the controller's performance as well as increase the controller robustness online tuning sliding surface slope is recommended. In uncertain situations sliding surface slope can online tuning by PID controller. According to this theory, the performance in online tuning is better than offline tuning PID sliding mode controller. The trajectory following online sliding surface slope tuning PID sliding mode controller and off line tuning surface slope tuning PID sliding mode controller are compared in Figure 4. Based on the Figure 4, both of two controllers can eliminate the chattering and oscillation in certain situation. In rise time point of view, offline PID sliding mode controller is faster than online PID sliding mode controller because the rise time in offline PID sliding mode controller is 0.48 second and in online PID sliding mode controller is 0.50 second. In error point of view, online PID sliding mode controller is better than offline PID sliding mode controller. According to Figure 4, online PID sliding mode controller has accurate trajectory response and it can eliminate the chattering as well as reduce the error.

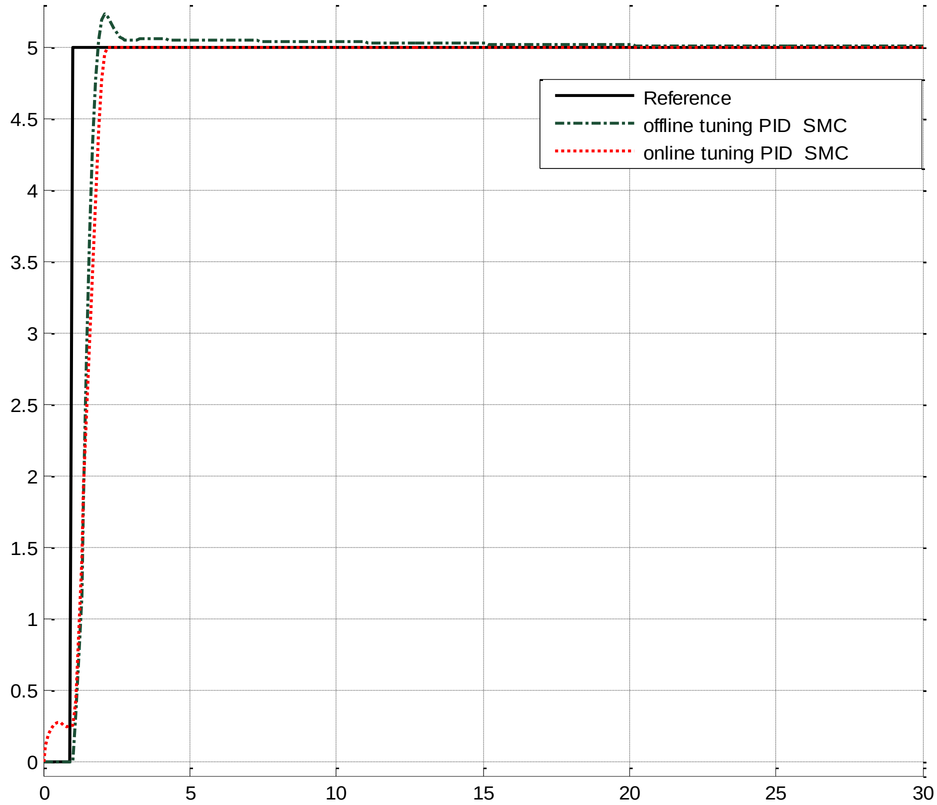

Figure 4. Trajectory Following, Offline PID SMC and Online PID SMC

Comparison of Sliding Surface(S): Figure 5 shows the sliding surface in offline sliding surface slope tuning PID sliding mode controller and online sliding surface slope tuning PID sliding mode controller. According to the following graph, all two methods have about the same sliding surface trajectories and these trajectories are zero.

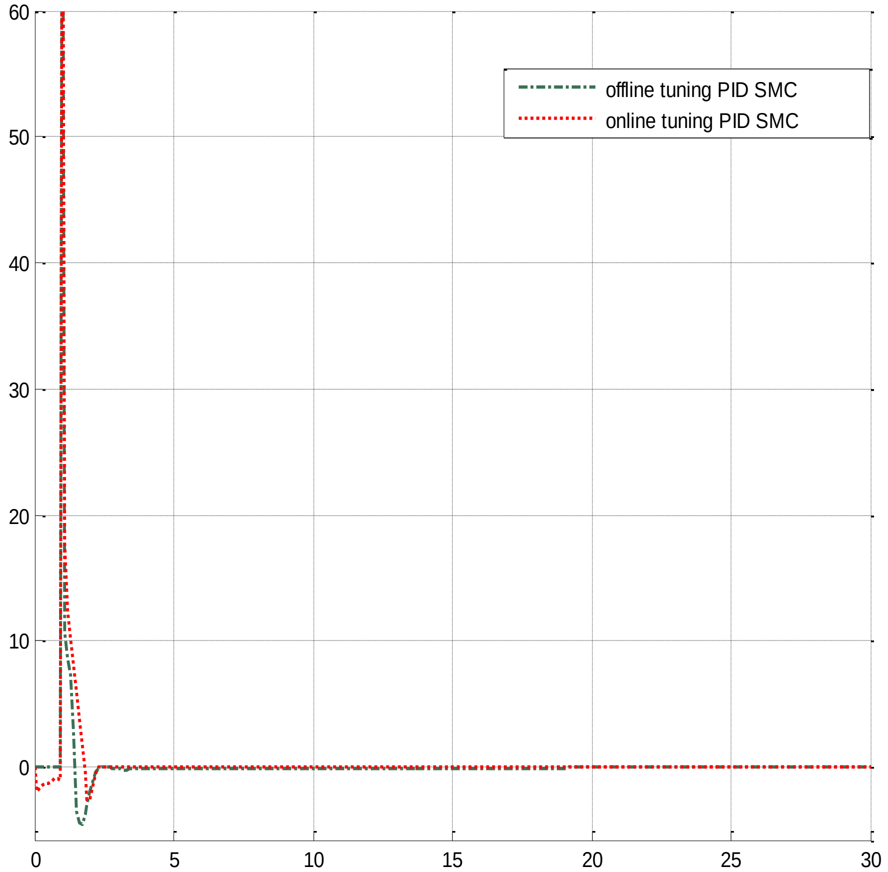

Figure 5. Comparison of Sliding Surface, Offline PID SMC and Online PID SMC

Based on Figure 5, sliding surface of offline sliding surface slope tuning PID sliding mode controller and online sliding surface slope tuning PID sliding mode controller are spike free, which caused to have stability.

Comparison the Actuation Torque(τ_i): the control input, forces the active dental joint to track the desired trajectories. Figure 6 shows the torque performance in offline sliding surface slope tuning PID sliding mode controller and online sliding surface slope tuning PID sliding mode controller. According to the following graph, both two controllers have steady stable torque performance.

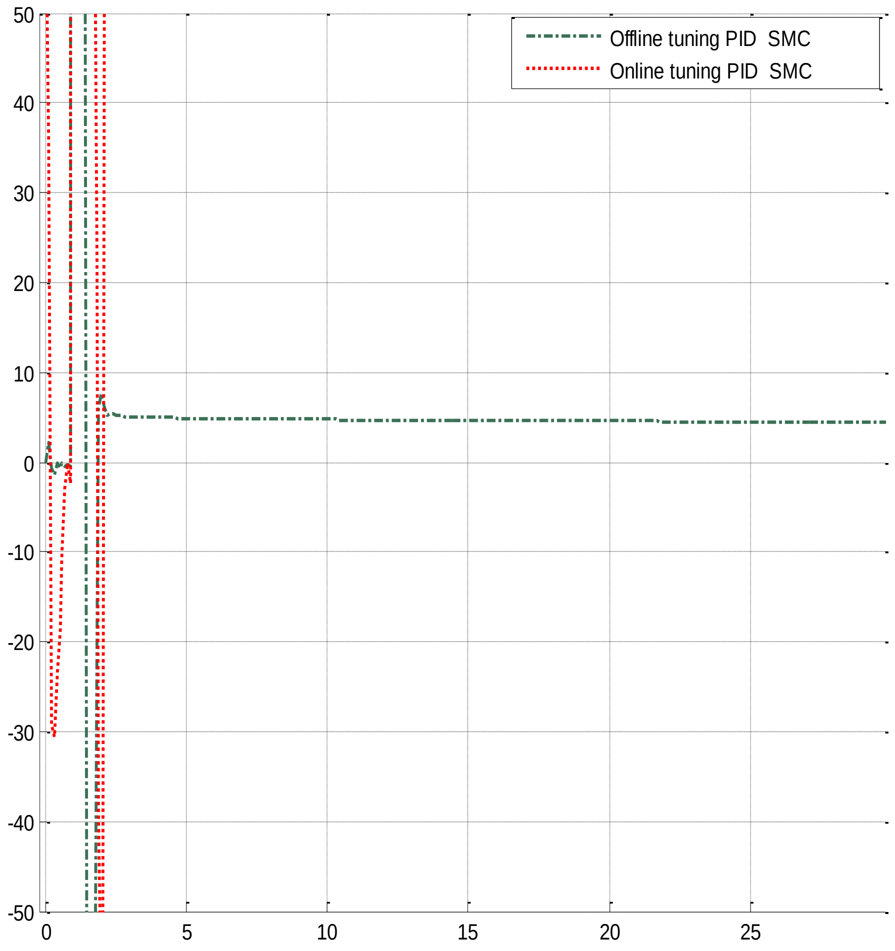

Figure 6: Comparison the Actuation Torque, Offline PID SMC and Online PID SMC

In the control forces, smaller amplitude means less energy. Therefore, online sliding surface slope tuning PID sliding mode controller require less energy than the offline sliding surface slope tuning PID sliding mode controller.

Comparison the Disturbance Rejection: the power of disturbance rejection is very important to robust checking in these two types of controllers. In this section trajectory accuracy, sliding surface and torque performances are test under uncertainty condition. To test the disturbance rejection band limited white noise with 30% amplitude is applied to offline sliding surface slope tuning PID sliding mode controller and online sliding surface slope tuning PID sliding mode controller. In Figures 7 to 9, trajectory accuracy, sliding surface and torque performance are shown.

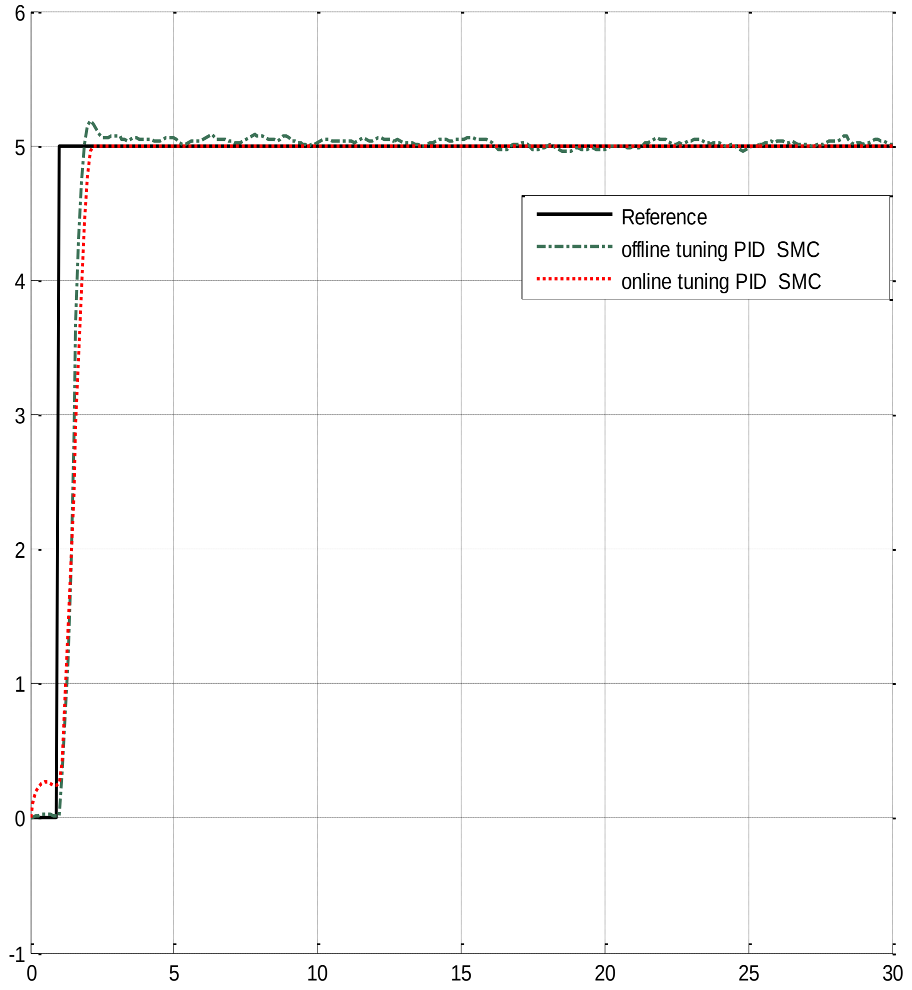

Figure 7. Comparison of Disturbance Rejection, Offline PID SMC and Online PID SMC in Presence of Uncertainty

According to above graph, online tuning sliding surface slope tuning PID sliding mode controller is more stable than off-line tuning sliding surface slope tuning PID sliding mode controller because in presence of uncertainty online tuning estimate the sliding surface slope using PID controller. In presence of uncertainty offline sliding surface slope tuning PID sliding mode controller has moderate fluctuations. Figure 8 shows the sliding surface in presence of uncertainty.

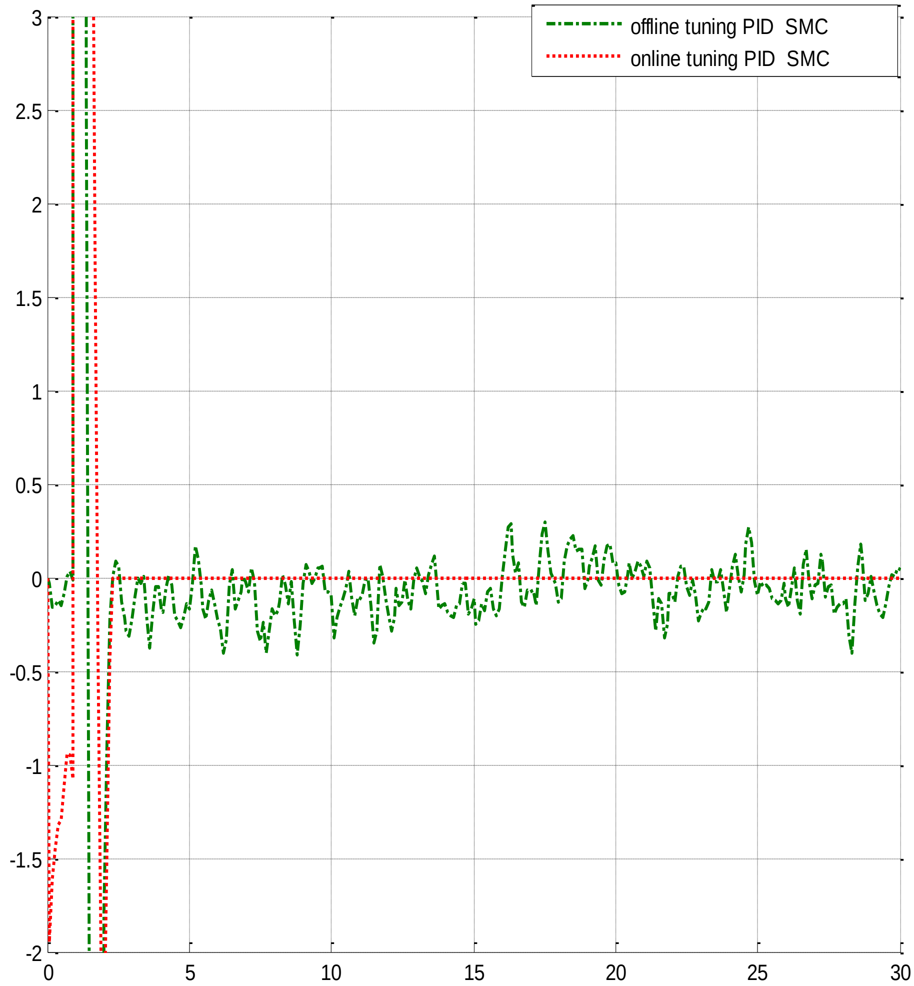

Figure 8. Comparison of Sliding Surface, Offline PID SMC and Online PID SMC in Presence of Uncertainty

According to above graph, however offline tuning sliding surface slope tuning PID sliding mode controller can eliminate the chattering but it has fluctuations in presence of uncertainties. This is the main challenge in offline tuning sliding surface slope tuning PID sliding mode controller, when sliding surface slope cannot adjust the sliding surface in presence of uncertainty. According to above graph, online tuning sliding surface slope tuning PID sliding mode controller is more robust than offline tuning sliding surface slope tuning fuzzy sliding mode controller and the amplitude of fluctuation is near to the zero. Figure 9 shows the torque performance in presence of uncertainty.

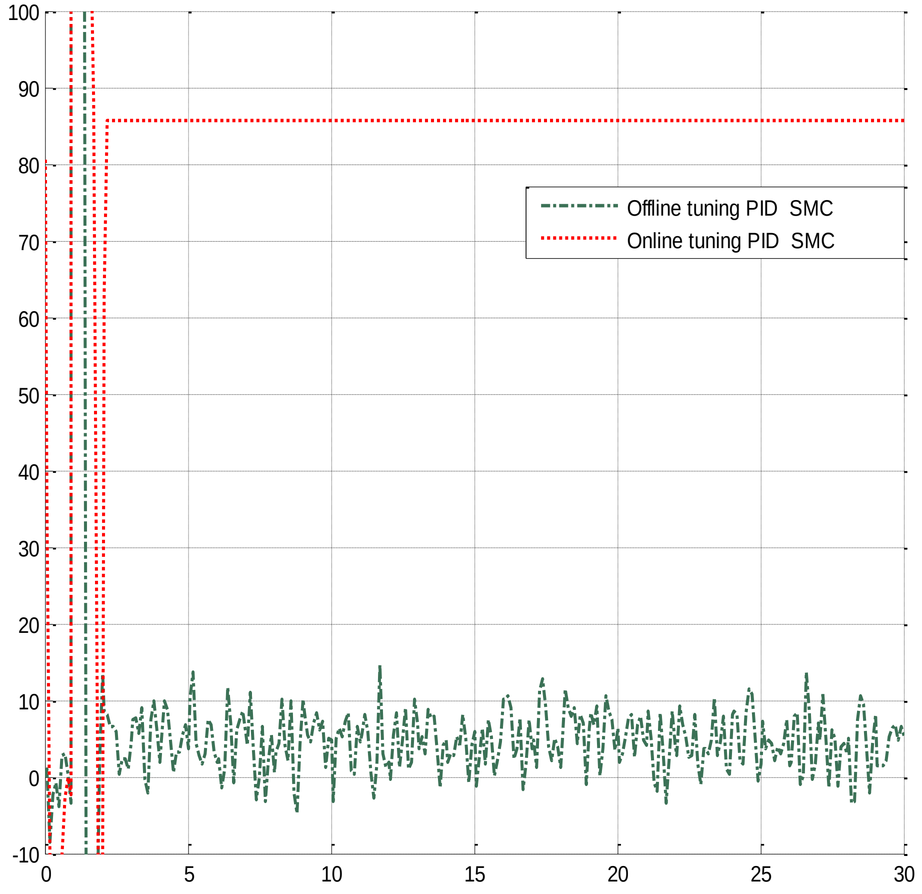

Figure 9. Comparison the Actuation Torque: Offline PID SMC and Online PID SMC in Presence of Uncertainty

Based on above graph, offline tuning sliding surface slope tuning PID sliding mode controller has moderate oscillation in presence of uncertainty. According to above three graphs, online tuning sliding surface slope tuning PID sliding mode controller is more stable than offline tuning sliding surface slope tuning PID sliding mode controller because it has online tunable gain.

Tracking Error Comparison: this part is used to test the controller joint variable accuracy. Figure 10 shows the steady state error in online tuning sliding surface slope tuning PID sliding mode controller and offline tuning sliding surface slope tuning PID sliding mode controller. According to this Figure, offline tuning sliding surface slope tuning PID sliding mode controller has irregular fluctuations but online tuning sliding surface slope tuning PID sliding mode controller has steady stable.

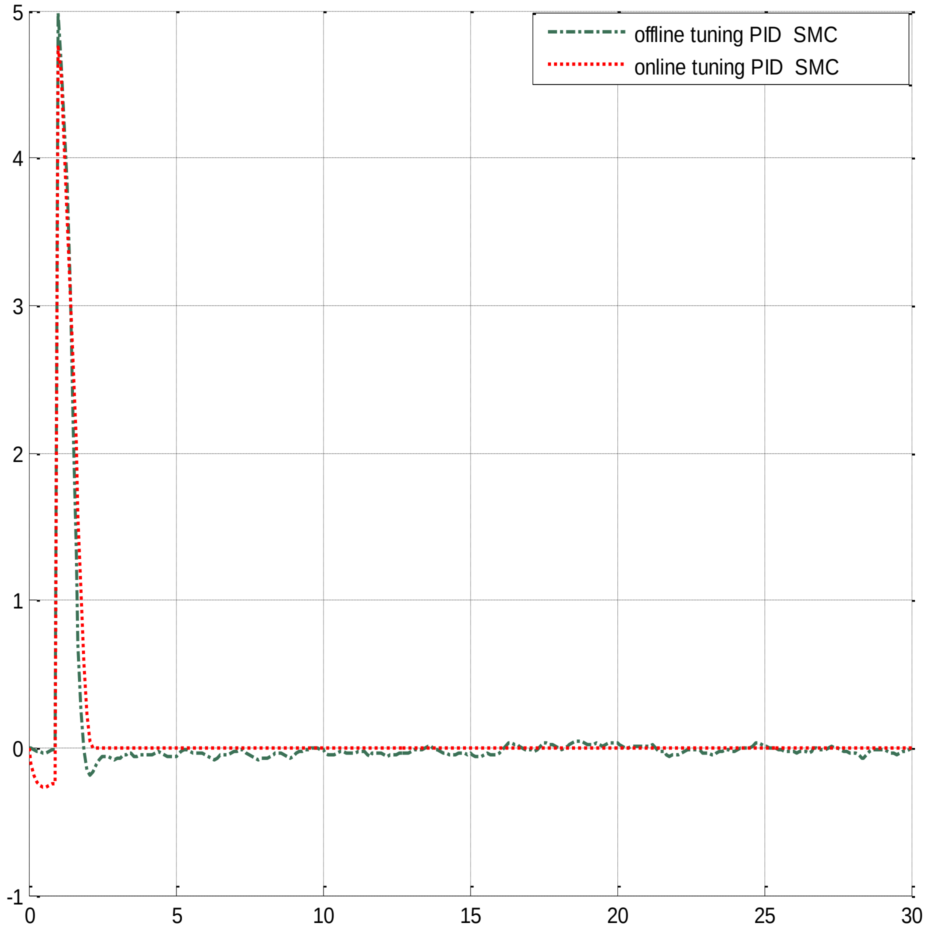

Figure 10. Comparison the Steady State Error: Offline PID SMC and Online PID SMC in Presence of Uncertainty

According to above Figure, online tuning sliding surface slope tuning PID sliding mode controller has more robust than offline tuning sliding surface slope tuning PID sliding mode controller. Figure 11 shows root means square (RMS) error in presence of uncertainty for online tuning sliding surface slope tuning PID sliding mode controller and offline tuning sliding surface slope tuning PID sliding mode controller.

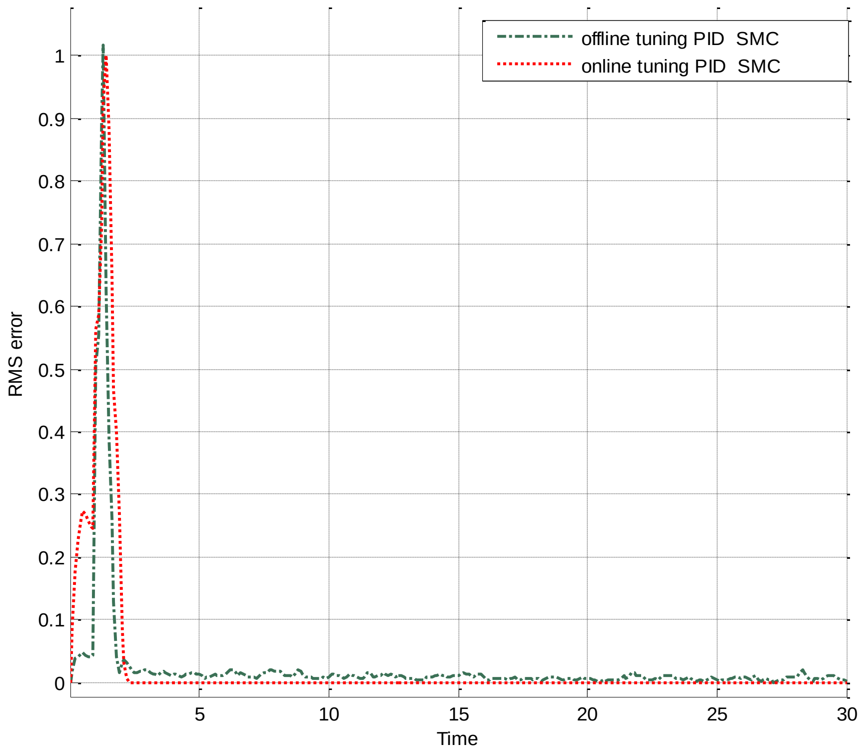

Figure 11. Comparison the RMS Error, Offline PID SMC and Online PID SMC in Presence of Uncertainty

Based on Figure 11, offline tuning sliding surface slope tuning PID sliding mode controller has more position deviation than online tuning sliding surface slope tuning PID sliding mode controller.

5. Conclusion

The work presented in this paper is a new approach to the systematical design of an adaptive robust control using an online estimation of lumped uncertainty. It was hypothesized and demonstrated that by combining the different techniques, based on a rigorous theoretical framework, high performance and high accuracy can be achieved in comparison to what a single control technique offers, without sacrificing the simplicity and applicability. The validity of the proposed method was verified in active dental joint. Results from simulations verified that the proposed controller outperforms existing methods and achieves better performance in terms of tracking accuracy and suppressing the uncertainties. Regarding to results and discussion in uncertainty, proposed method improve the data tracking, eliminate the oscillation, overshoot, reduce the steady state error and RMS error.

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Iranian center of Advance Science and Technology (IRAN SSP) is one of the independent research centers specializing in research and training across of Control and Automation, Electrical and Electronic Engineering, and Mechatronics & Robotics in Iran. At IRAN SSP research center, we are united and energized by one mission to discover and develop innovative engineering methodology that solve the most important challenges in field of advance science and technology. The IRAN SSP Center is instead to fill a long-standing void in applied engineering by linking the training a development function one side and policy research on the other. This center divided into two main units:

- Education unit
- Research and Development unit

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Farzin Piltan is an outstanding scientist in the field of Electronics and Control engineering with expertise in the areas of nonlinear systems, robotics, and microelectronic control. Mr. Piltan is an advanced degree holder in his field. Currently, Mr. Piltan is the Head of Mechatronics, Intelligent System, and Robotics Laboratory at the Iranian Institute of Advanced Science and Technology (IRAN SSP). Mr. Piltan led several high impact projects involving more than 150 researchers from countries around the world including Iran, Finland, Italy, Germany, South Korea, Australia, and the United States. Mr. Piltan has authored or co-authored more than 140 papers in academic journals, conference papers and book chapters. His papers have been cited at least 3900 times by independent and dependent researchers from around the world including Iran, Algeria, Pakistan, India, China, Malaysia, Egypt, Columbia, Canada, United Kingdom, Turkey, Taiwan, Japan, South Korea, Italy, France, Thailand, Brazil and more. Moreover, Mr. Piltan has peer-reviewed at least 23 manuscripts for respected international journals in his field. Mr. Piltan will also serve as a technical committee member of the upcoming EECSI 2015 Conference in Indonesia. Mr. Piltan has served as an editorial board member or journal reviewer of several international journals in his field as follows: International Journal Of Control And Automation (IJCA), Australia, ISSN: 2005-4297, International Journal of Intelligent System and Applications (IJISA), Hong Kong, ISSN:2074-9058, IAES International Journal Of Robotics And Automation, Malaysia, ISSN:2089-4856, International Journal of Reconfigurable and Embedded Systems, Malaysia, ISSN:2089-4864.

Mr. Piltan has acquired a formidable repertoire of knowledge and skills and established himself as one of the leading young scientists in his field. Specifically, he has accrued expertise in the design and implementation of intelligent controls in nonlinear systems. Mr.

Piltan has employed his remarkable expertise in these areas to make outstanding contributions as detailed follows:Nonlinear control for industrial robot manipulator (2010-IRAN SSP), Intelligent Tuning The Rate Of Fuel Ratio In Internal Combustion Engine (2011-IRANSSP), Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator (2013-IRANSSP), Research on Full Digital Control for Nonlinear Systems (2011-IRANSSP), Micro-Electronic Based Intelligent Nonlinear Controller (2015-IRANSSP), Active Robot Controller for Dental Automation (2015-IRANSSP), Design a Micro-Electronic Based Nonlinear Controller for First Order Delay System (2015-IRANSSP).

The above original accomplishments clearly demonstrate that Mr. Piltan has performed original research and that he has gained a distinguished reputation as an outstanding scientist in the field of electronics and control engineering. Mr. Piltan has a tremendous and unique set of skills, knowledge and background for his current and future work. He possesses a rare combination of academic knowledge and practical skills that are highly valuable for his work. In 2011, he published 28 first author papers, which constitute about 30% of papers published by the Department of Electrical and Electronic Engineering at University Putra Malaysia. Additionally, his 28 papers represent about 6.25% and 4.13% of all control and system papers published in Malaysia and Iran, respectively, in 2011.

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Dr. Nasri Sulaiman advisor and supervisor of several high impact projects involving more than 150 researchers from countries around the world including Iran, Malaysia, Finland, Italy, Germany, South Korea, Australia, and the United States. Dr. Nasri Sulaiman has authored or co-authored more than 80 papers in academic journals, conference papers and book chapters. His papers have been cited at least 3000 times by independent and dependent researchers from around the world including Iran, Algeria, Pakistan, India, China, Malaysia, Egypt, Columbia, Canada, United Kingdom, Turkey, Taiwan, Japan, South Korea, Italy, France, Thailand, Brazil and more**.**

Dr. Nasri Sulaiman has employed his remarkable expertise in these areas to make outstanding contributions as detailed below:

- Design of a reconfigurable Fast Fourier Transform (FFT) Processor using multi-objective Genetic Algorithms (2008-UPM)
- Power consumption investigation in reconfigurable Fast Fourier Transform (FFT) processor (2010-UPM)
- Crest factor reduction And digital predistortion Implementation in Orthogonal frequency Division multiplexing (ofdm) systems (2011-UPM)
- High Performance Hardware Implementation of a Multi-Objective Genetic Algorithm, (RUGS), Grant amount RM42,000.00, September (2012-UPM)
- Nonlinear control for industrial robot manipulator (2010-IRAN SSP)
- Intelligent Tuning The Rate Of Fuel Ratio In Internal Combustion Engine (2011-IRANSSP)
- Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator (2013-IRANSSP)
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- Active Robot Controller for Dental Automation (2015-IRANSSP)
- Design a Micro-Electronic Based Nonlinear Controller for First Order Delay System (2015-IRANSSP)

