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Real-Time Implementation of Sliding Mode Control Technique for Two-DOF Industrial Robotic Arm

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ABSTRACT: This study presents a real-time implementation of the angle trajectory tracking control for the two DOF industrial robotic manipulators. For real-time trajectory tracking control, the classical proportional–integral–derivative (PID) control and the nonlinear Sliding Mode Control techniques have been considered. The SMC technique takes into account the complete dynamic model of the two DOF robot to increase the trajectory tracking performance of the manipulator. The experimental results demonstrate that the nonlinear SMC method has improved the trajectory tracking performance compared with the PID method.

Keywords: PID control, robot control, sliding mode control, trajectory control.

İki Serbestlik Derecesine Sahip Endüstriyel Bir Robotun Kayan Kipli Kontrol Yöntemi ile Kontrolünün Gerçek Zamanlı Uygulaması

ÖZET: Bu çalışmada, iki serbestlik derecesine sahip bir endüstriyel robot kolunun analizi, tasarımı ve gerçek zamanlı açısal yörünge takip kontrolü gerçekleştirilmiştir. Sistemin tanımlanan yörüngeyi en iyi doğrulukta takip edebilmesi için klasik oransal-integral-türev denetleyicisi (PID) ile doğrusal olmayan Kayan Kipli Kontrol (SMC) yöntemlerinden yararlanılmıştır. Doğrusal olmayan Kayan Kipli Kontrol tekniği, robotun tam dinamik modelini göz önüne aldığından dolayı, manipülatörün yörünge izleme performansını arttırabilmektedir. Önerilen sistem için iki farklı kontrol yöntemi gerçek zamanlı olarak uygulanmıştır. Yapılan gerçek zamanlı yörünge izleme performans deneylerinden elde edilen sonuçlara göre, Kayan Kipli Kontrol yönteminin sistemdeki belirsizliklere ve bozucu etkilere karşı gürbüz bir kontrol yöntemi olmasından dolayı bu kontrol tekniğinin klasik bir PID denetleyicisine göre, robotik manipülatörün yörünge izleme performansını arttırdığı kanıtlanmıştır.

Anahtar Kelimeler: Kayan kipli kontrol, PID kontrol, robot kontrol, yörünge kontrol.

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INTRODUCTION

The purpose of robotic manipulators used in today's modern industrial world is to improve the quality of products, to improve industrial productivity, correctness, speed and flexibility. Although the requirements of industrial applications are complex and difficult, robotic manipulators are increasingly being used more and more dangerous, tedious or repetitive industrial processes, where people do not want to work. More efficient and quality manufacturing is an important issue of the industry, and this demand has led to the development of more skilled and modern robotic manipulators. These skilled systems are usually autonomous and required initial actions, such as calibration, trajectory planning in order to fulfil their assigned tasks. For this reason, it is a very important step to accurately and precisely control the manipulator in the working environment in order to be able to fulfil the assigned tasks successfully. The main areas of research in the field of robotics manipulators can be summarized as robotic manipulator design, trajectory planning, trajectory optimization, and robot manipulator control. Among these scientific research areas, the control of robotic manipulators has a crucial place to follow a precise and reliable trajectory between the initial and final position of the robot (Dasgupta et al., 2009). Accurate trajectory control is a vital issue for the efficient operation of a given robotic application. For this reason, a large number of control methods have been applied in the literature for various types of robotic systems, such as, H infinity control (Makarov et al., 2016), neural network control (Li et al., 2017; Zhang et al., 2018), adaptive fuzzy control (Li et al., 2013; Chu et al., 2014) and fractional order control (Monje et al., 2007; Efe et al., 2008; Nikdel et al., 2016). Among the above mentioned control techniques, the sliding mode controller is an effective and robust control technique and is a variable structure for the unknown dynamics of unknown loads and nonlinear systems in the system. In many nonlinear systems, a sliding-mode control technique is used to improve system performance and system stability against external disturbances. In addition, this method is also used to simplify the design, increase the trajectory tracking accuracy and reduce model complexity (Utkin, 1977; Edwards and Spurgeon, 1998). The sliding modal control technique provides a systematic approach that improves system capability to eliminate the problem of stability preservation. In addition, it improves the system's performance for modelling instabilities (Slotine and Li, 1991). Therefore, due to the characteristics of the sliding mode controller, many researchers have used this control method to overcome the control problem in their systems (Capisani and Ferrara, 2012; Baek et al., 2016; Zhang, 2017; Lee et al., 2017; Van et al., 2017).

According to the abovementioned, SMC control method was applied to improve the trajectory tracking performance of an industrial robotic manipulator. To demonstrate the effectiveness of the SMC technique, the given trajectory was also operated by a PID controller. Angular position and error values are given experimentally in order to compare the performance of two controllers. However, during the implementation of the PID controller, the un-modelled dynamics of the robot are taken into account. However, In the SMC method, the full dynamic model of the robot is taken into account. The most important feature of SMC is that it adjusts itself according to the uncertainties in the system. As a result of this study, it has been shown that SMC technique is a robust control method against unknown uncertainty and un-modelled dynamics.

SYSTEM DESCRIPTION

This section focuses on the mathematical analysis of an industrial robot with two degrees of freedom, and the implementation of a sliding-mode control method for precise position control of the robot.

Mathematical analysis of robot with two degrees of freedom

Figure 1 shows a schematic representation of a planar robot arm with two degrees of freedom.

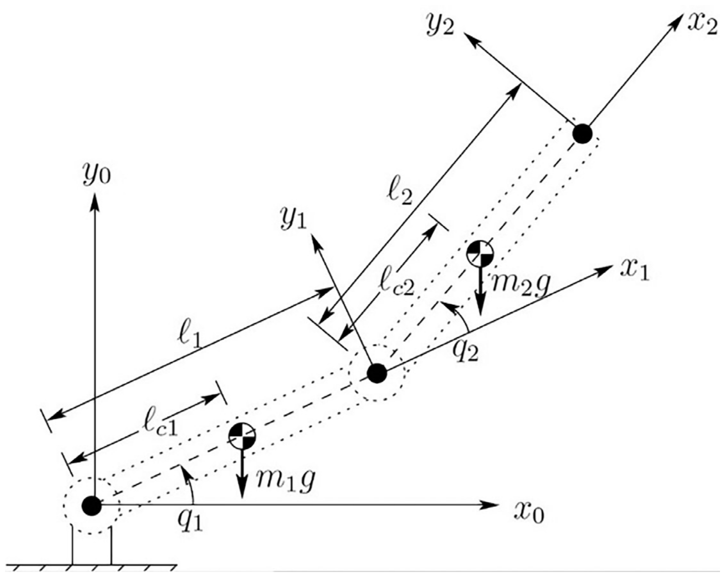

Figure 1. Schematic presentation of two-DOF robot

The parameters related to the robot are given in Table 1.

Table 1. 2-DOF robot specification

x_0, y_0	Fixed Cartesian coordinate system
x_1, y_1	First-link moving coordinate system
x_2, y_2	Second-link moving coordinate system
q_1, q_2	Joint angles of the robot
m_1, m_2	Mass of robotic arms (2.45 kg, 6.55 kg)
I_1, I_2	Inertia of Robotic arms (0.024, 0.0365)
l_1, l_2	Length of link 1 and 2 (0.21m, 0.32m)
l_{c1}, l_{c2}	The length of mass centres of the links (0.105m, 0.19m)
g	Gravitational acceleration (9.81 kg/m^2)

The forward kinematic equations of this robot arm can be calculated by Equations 1 and 2 as follows;

$$p_x = l_1 \cos(q_1) + l_2 \cos(q_1 + q_2) \tag{1}$$

$$p_y = l_1 \sin(q_1) + l_2 \sin(q_1 + q_2) \tag{2}$$

Equation 4 demonstrates the inverse kinematic equations as follows:

$$q_2 = tan^{-1}(\frac{\pm\sqrt{1-D^2}}{D}) \tag{3}$$

$$q_1 = tan^{-1}\left(\frac{p_y}{p_x}\right) - tan^{-1}(\frac{l_2 \sin(\theta_2)}{l_1 + l_2 \cos(\theta_2)}) \tag{4}$$

where $D = \frac{p_x^2 + p_y^2 - l_1^2 - l_2^2}{2 l_1 l_2}$. Equation of motion of the robot is given in Equation 5 as follows;

$$\tau = M(q)\ddot{q} + N(q, \dot{q}) + \tau_d \tag{5}$$

In this equation, τ_d is the disturbance effects such as friction, q is the position of the joints of the robot joint, and finally τ is the motor output torque. $M(q)$ is a mass matrix and is given by Equation 6 as follows;

$$\begin{bmatrix} m_1 l_{c1}^2 + m_2(l_1^2 + l_{c2}^2 + 2l_1 l_{c2}^2 + 2l_1 l_{c2} cosq_2) + I_1 + I_2 & m_2(l_{c2}^2 + l_1 l_{c2} cosq_2) + I_2 \\ m_2(l_{c2}^2 + l_1 l_{c2} cosq_2) + I_2 & m_2 l_{c2}^2 + I_2 \end{bmatrix} \tag{6}$$

$$N(q, \dot{q}) = \begin{bmatrix} -m_2 l_1 l_{c2} sinq_2 \dot{q}_2 & -m_2 l_1 l_{c2} sinq_2 \dot{q}_2 + -m_2 l_1 l_{c2} sinq_2 \dot{q}_1 \\ m_2 l_1 l_{c2} sinq_2 \dot{q}_1 & 0 \end{bmatrix} +$$

$$\begin{bmatrix} (m_1 l_{c1} + m_2 l_1) g cosq_1 + m_2 l_{c2} g cos(q_1 + q_2) \\ m_2 l_{c2} g cos(q_1 + q_2) \end{bmatrix} \tag{7}$$

In Equation 7, $N(q, \dot{q})$ shows the centrifugal and coriolis terms.

Sliding mode control technique

In order to use the equation of motion expressed by Eq. (5) in the sliding mode control, it is necessary to leave the q output variables in the equation alone. For this, if both sides of Eq. (5) are multiplied by , $M(q)^{-1}$, $\ddot{q}$ is expressed as in Eq. (8).

$$\ddot{q} = f(q, \dot{q}, t) + g(q, t)u(t) + \xi(t, u(t)) \tag{8}$$

where $f(q, \dot{q}, t) = -M(q)^{-1} N(q, \dot{q})$, $g(q, t) = M(q)^{-1}$, $u(t) = \tau$ and $\xi(t, u(t))$ defines the limited uncertainty of the system. The sliding mode control method is a variable structure control and it has a robust structure against the uncertainties in the system and disturbance effects. The control signal used in the sliding mode control method consists of two components. The first component is the equivalent control component that is used to at least reduce the error values. The second component is a switched control component that can make the system susceptible to disruptive effects resulting from unknown uncertainties. In this proposed method, a sliding surface *s(t)* is selected as follows;

$$\boldsymbol{s} = \boldsymbol{\lambda e} + \dot{\boldsymbol{e}} \tag{9}$$

where, λ is a positive constant matrix, *e* is a tracking error matrix and it can be given as $\boldsymbol{e} = [\boldsymbol{q_d} - \boldsymbol{q}]$. Differentiating Equation (9) with respect to time, the following equation is obtained

$$\dot{\boldsymbol{s}} = \boldsymbol{\lambda}\dot{\boldsymbol{e}} + \ddot{\boldsymbol{e}} \tag{10}$$

This can be further written as,

$$\dot{\boldsymbol{s}} = \boldsymbol{\lambda}\dot{\boldsymbol{e}} + (\ddot{\boldsymbol{q}}_{\boldsymbol{d}} - \ddot{\boldsymbol{q}}) \tag{11}$$

Substituting $\ddot{\boldsymbol{q}}$ from Equation (8) into Equation (11) yields;

$$\dot{\boldsymbol{s}} = \boldsymbol{\lambda}\dot{\boldsymbol{e}} + \ddot{\boldsymbol{q}}_{\boldsymbol{d}} - \boldsymbol{f}(\boldsymbol{q}) - \boldsymbol{g}(\boldsymbol{q})\boldsymbol{u} \tag{12}$$

It is well known that, in the second order sliding surface condition, if, $\boldsymbol{s(t)}$ and $\dot{\boldsymbol{s}}\boldsymbol{(t)}$ equal to null then the tracking error $\boldsymbol{e}$ reaches to zero. Hence, the reaching phase control law $\boldsymbol{u_{eq}}$ can be obtained by using the $\dot{\boldsymbol{s}}\boldsymbol{(t)} = \boldsymbol{0}$ as follows;

$$\boldsymbol{u_{eq}} = \frac{-\boldsymbol{f}(\boldsymbol{q})}{\boldsymbol{g}(q)} + \frac{\boldsymbol{\lambda}\dot{\boldsymbol{e}}}{\boldsymbol{g}(q)} + \frac{\ddot{\boldsymbol{q}}_{\boldsymbol{d}}}{\boldsymbol{g}(q)} \tag{13}$$

However, it is not possible to control the system using only the reaching phase control law. As previously mentioned, the effect of constrained but unknown uncertainties during the operation of the system may be serious. Therefore, by adding the switching control law, $\boldsymbol{u_{sc}}$, to the Equation (14), it can be ensured that the system is more robust against the external or system uncertainties during the motion.

$$\boldsymbol{u_{sc}} = \boldsymbol{k_x} sgn(\boldsymbol{s}) \tag{14}$$

where, $\boldsymbol{k_x}$ is the switching gain matrix and $sgn(\boldsymbol{s})$ can be expressed given as below.

$$sgn(\boldsymbol{s}) = \begin{Bmatrix} 1 \rightarrow \boldsymbol{s} > 0 \\ 0 \rightarrow \boldsymbol{s} = 0 \\ -1 \rightarrow \boldsymbol{s} < 0 \end{Bmatrix} \tag{15}$$

Thus, the total feedback SMC control law ***(u)*** for the system is written as follows;

$$\boldsymbol{u} = \boldsymbol{u_{eq}} + \boldsymbol{u_{sc}} = \frac{-\boldsymbol{f}(\boldsymbol{q})}{\boldsymbol{g}(\boldsymbol{q})} + \frac{\boldsymbol{\lambda}\dot{\boldsymbol{e}}}{\boldsymbol{g}(\boldsymbol{q})} + \frac{\ddot{\boldsymbol{q}}_{\boldsymbol{d}}}{\boldsymbol{g}(\boldsymbol{q})} + \boldsymbol{k_x} sgn(\boldsymbol{s}) \tag{16}$$

Practically, the control law given in Eq. (16) can result in oscillations due to the high-frequency switching and this oscillation is called chattering effect. To overcome the control-chattering during the implementation, the *sgn* (high-frequency switching function), can be approximated to the ***sat*** function, which is called the smooth limited function. The SMC implementation block diagram is shown in Figure 2.

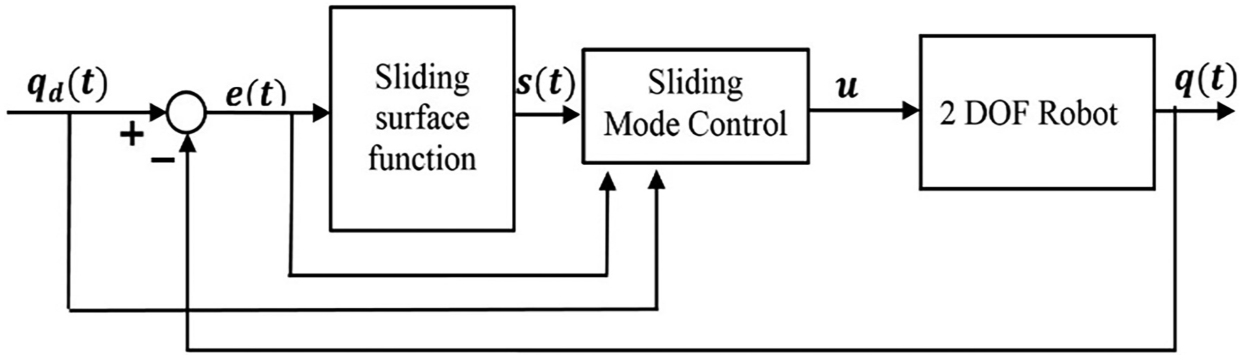

Figure 2. The block diagram of SMC

EXPERIMENTAL RESULTS AND DISCUSSIONS

The proposed sliding mode control method has been experimentally performed on a Denso VP-6242G industrial robot manipulator, as shown in Fig. 3. The Denso VP-6242G robot consists of six rotary joints driven by six servo motors. The sampling frequency of the system is given as 1KHz. In this study, to show the applicability of the sliding-mode control method to a robotic system with two proposed degrees of freedom, the second and third joints of the robot are considered while the other joints are locked, as shown in Fig. 3. In order to prove the proposed control method can perform well, the third degrees of polynomial trajectories have been defined in this work. For the experimental application, the initial joints positions are starting form -45º and -45º for q_1 and q_2, respectively. The manipulator task consists of moving the joints from an initial point (q_1=-45º and q_2=-45º) to final point (q_1=0º and q_2=45º). For the first 4 seconds, the joints angles, q_1 and q_2, have to move to 45º and 0º, respectively and last 4 seconds, the angles of q_1 and q_2 have to move to 0º and 45º. The initial and final velocities and accelerations are zero for all joints.

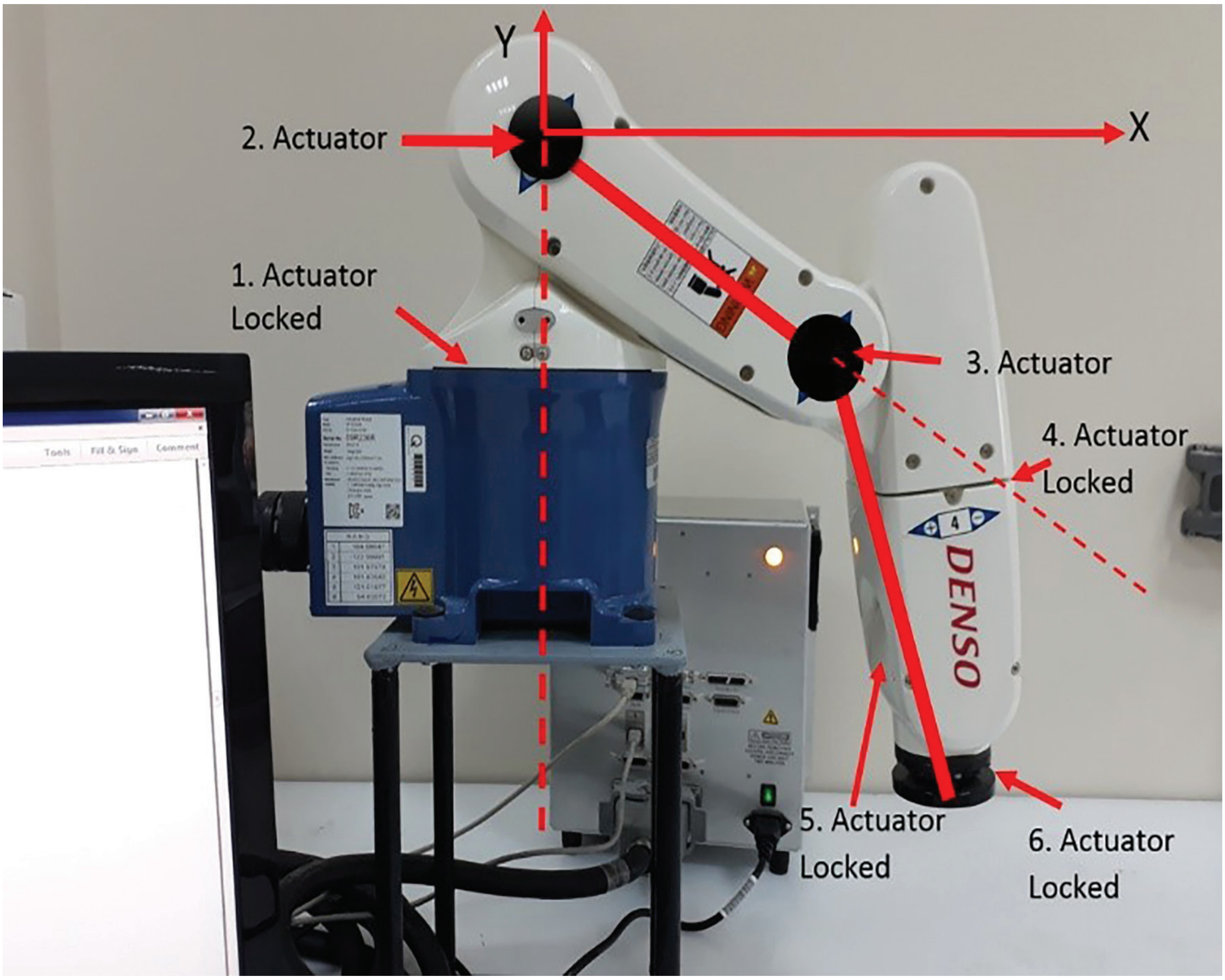

Figure 3. Experimental platform

In order to demonstrate the effectiveness of the proposed method, the comparison has been made between PID and Sliding mode control techniques. As it can be seen from Figure 4, the proposed SMC technique follows the reference trajectory more accurately than the PID control technique. According to the trajectory tracking response for both controllers in Figure 4 and 5, PID controller causes overshoot values at the beginning of the motion for joint 1 (q_1) and joint 2 (q_2). However, as can be seen from Figures 4 and 5, overshoot values are eliminated completely for the proposed SMC controller case due to the SMC technique is a robust and an efficient control technique for un-modelled dynamics and un-known loads of the robotic system. Also, both transient and steady-state error values are reduced by using the proposed SMC controller as shown in Figures 6 and 7.

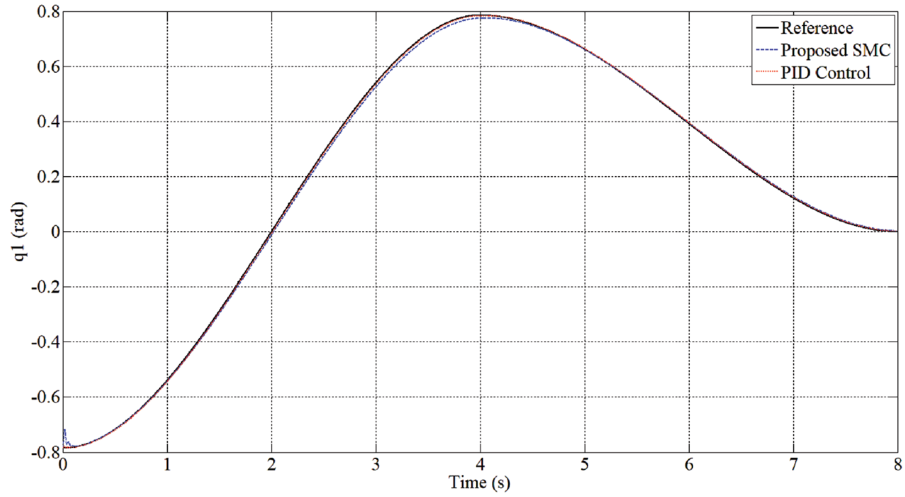

Figure 4. Trajectory tracking for joint 1 (q_1)

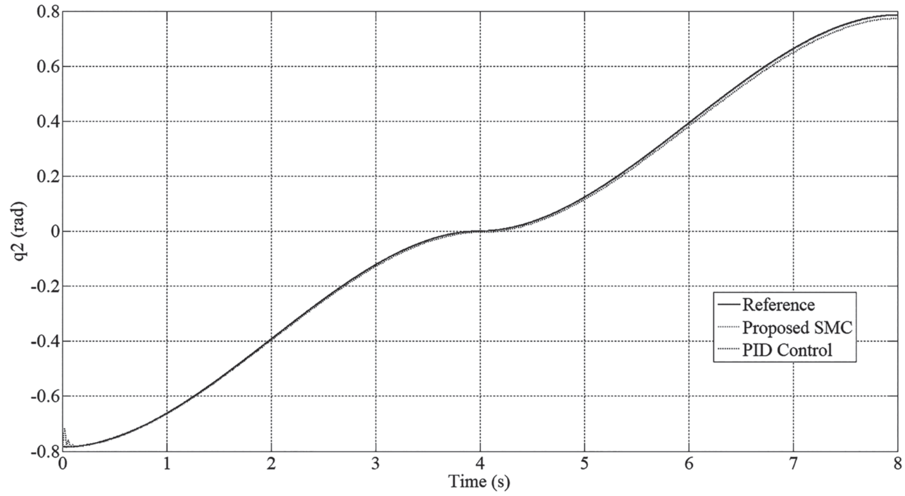

Figure 5. Trajectory tracking for joint 2 (q_2)

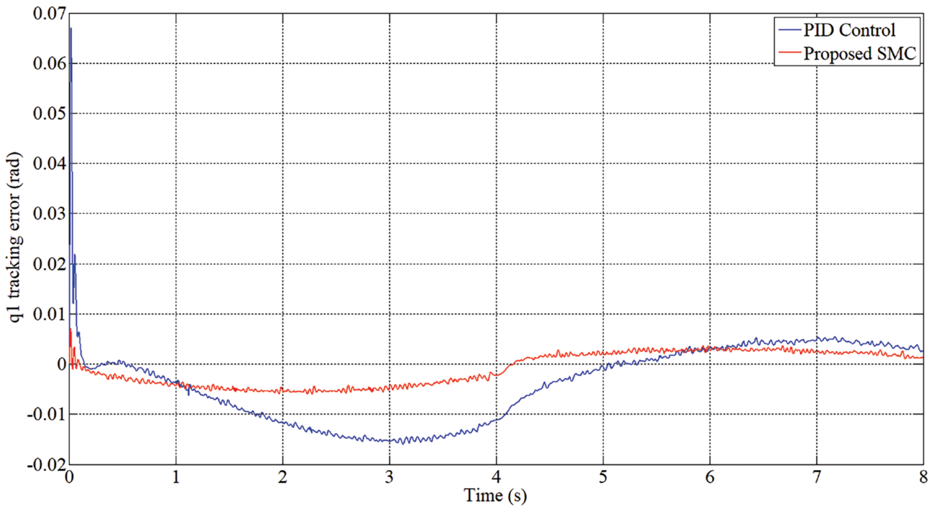

Figure 6. Tracking error for joint 1 (q_1)

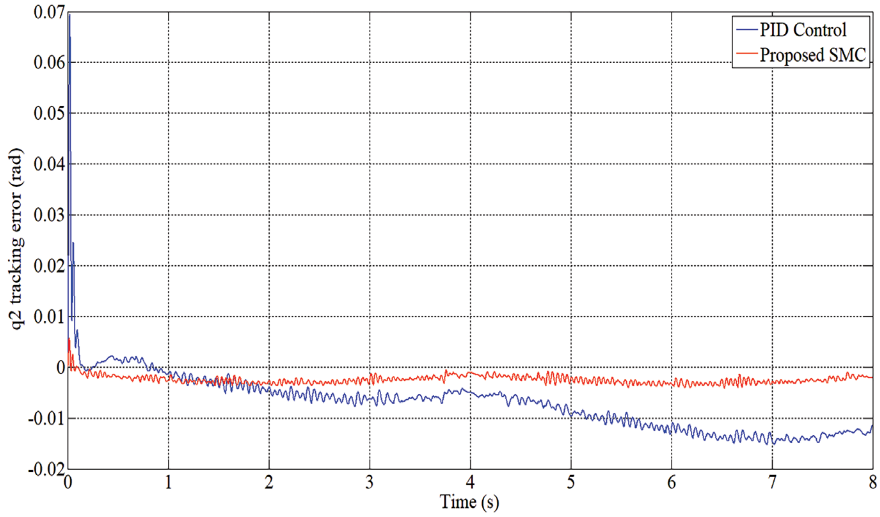

Figure 7. Tracking error for joint 2 (q_2)

CONCLUSION

In this study, 6 DOF was transformed into an industrial robot 2 DOF robot manipulator. First, mathematical modelling of two DOF robotic systems was performed. Two different control techniques such as PID and SMC were used for experimental study. System dynamics are not taken into consideration in PID method. In the SMC method, the full dynamic model of the system is considered. In the experimental study, the performances of the controllers were compared for the given trajectory. According to the results, SMC method was found to be a powerful control against uncertainty and un-modelled dynamics in the system.

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