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Design of PID, FLC and Sliding Mode Controller for 2-DOF Robotic Manipulator: A Comparative Study

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Abstract
Controlling the manipulators in a precise manner is a challenging task. To overcome this difficulty around the world, many researchers have developed various control algorithms but are not providing optimal results. To obtain the optimal results in the current research the authors designed a proportional, integral, and derivative (PID) controller, fuzzy logic controller (FLC), and sliding mode controller (SMC) for a 2-DOF manipulator. The concept of forward and inverse kinematics was initially solved after assigning the D-H parameters for each joint. The purpose of forward or direct kinematics is to obtain the position and orientation of the end effector. Further, the concept of inverse kinematics is used to estimate the joint angles. Later on, the Lagrange-Euler formulation was used to calculate the dynamics of the 2-DOF manipulator, which is required to estimate the torque required for each joint of the robotics arm. The main goal of this research problem is to optimize the angular error between the two successive events. Finally, the developed algorithm is compared with the existing algorithms such as PID and Fuzzy logic controller.

Keywords- 2-DOF manipulator, SMC, Dynamics, Lagrange-Euler formulation, PID, FLC.

1. Introduction
Day by day, the importance of manipulators increases in all industrial applications because manipulators will help increase productivity, quality, and time. Due to the huge demand, many industries produced various configurations of industrial robots. But most industries are facing the controlling manipulator precisely, which is a challenging task. Around the world, many researchers developed different control

algorithms such as PID, SMC, versatile control, fuzzy control, and neural network control for achieving the task in a precise manner (Bao et al., 2021). Later on, researchers developed a fuzzy PID controller for the 2-DOF manipulator, and they compared it with the SMC controllers using sim mechanics. The results show that SMC performs better results other than the fuzzy PID controller (Naik et al., 2015). Moreover, tuning of conventional PID controllers for uneven transient features. The outcomes deliver that the developed tuning procedure is a novel procedure that can help tune an uneven fractional-order system by interpolation (Tin et al., 2019).

In recent years, most of the manipulators have been used in high-precision applications like medical to achieve high accuracy. Therefore, to achieve high accuracy, all the robot joints are controlled by various controllers like FLC, PID, SMC, and adaptive controllers (Lochan and Roy, 2015). A PSO tuning strategy is used for FLC (Fuzzy Logic Controller) and PID regulator to control the prearranged robot direction. The result shows that the boundaries about the fuzzy regulator and the PID regulator were calculated with PSO (Bingül and Karahan, 2011). An adaptive neuro-fuzzy inference system (ANFIS) to calculate the inverse kinematics solution for 3-DOF planar robot. Therefore, ANFIS can recognize and control 2-DOF and 3-DOF manipulators and can also provide quick and adequate inverse kinematics for the manipulators. Woo and Hu presented a control framework for joining SMC and Neural-Network (NN) controllers with various weights. Later on, the weights of the controller were calculated by using the fuzzy framework (Alavandar and Nigam, 2008). Further, an adaptive neural network controller for tracking the end effector. They used the Lyapunov approach to control the manipulator torque at each joint (Cheng et al., 2009). A new adaptive Jacobian controller using uncertain kinematics and dynamics for trajectory tracking. The obtained results indicates that the end effector can converge to the desired trajectory using uncertain kinematics and dynamics. Moreover, the recommended controller can also be helpful in determining the camera parameters in visual tracking (Cheah et al., 2006). A new neutral Kalman filter for a manipulator with the support of a non-singular terminal sliding mode controller (NTSMC). An NN model has been applied to enhance the performance of the NTSMC (Asl et al., 2017). A limited time-persistent sliding mode regulator for a Stewart stage which was planned to make up for time-changing outside unsettling influences and unmodeled elements. The results show that the change in model boundary and time-differing outer unsettling influences (Luong et., 2017).

Later on, researchers developed a novel robust adaptive SMC for the parallel manipulator. The developed controller helped to improve the accuracy and performance of the manipulator while under operating conditions (Bennehar et al., 2017). A controller for a 6-DOF parallel robot running in continuous terminal sliding mode will follow. The created continuous terminal SMC is intended to increase the moving platform's control accuracy. For stability, the author simulated on a sinusoidal 3-DOF and 2-DOF platform using the Lyapunov function (Jun et al., 2017). Further, researchers developed a NTSMC for 2-DoF manipulator (Rsetam et al., 2017). A high-speed nonsingular terminal switched sliding mode control scheme for the manipulators is also included. The suggested method aids in improving control performance under working circumstances. Artificial intelligence technologies like neural networks and fuzzy logic controllers are becoming increasingly important in recent years as a result (Zhang, 2016). To become proficient with a nonlinear ability in the ideal control law, a fuzzy neural network (FNN) is used. The produced control regulator is divided into three groups: one is an intelligence regulator (fuzzy neural network), second is an adaptive regulator to reduce mistake, and third is a conventional regulator (Wai, 2007), a comparison between fuzzy controllers and versatile fuzzy. They discovered that the suggested FLC and self-tuning fuzzy logic regulator offered the greatest performance (Mohan and Bhanot, 200).

The other part of the article is categorized in following manner: Section 2 discusses the mathematical formulation of the problem. Later on, design of the SMC is discussed in Section 3. Moreover, the results and discussions related to the current research work is discussed in Section 4. Finally, the conclusions of the current research article are discussed in Section 5.

2. Mathematical Formulation of the Problem

In this section, the authors discussed the mathematical equations which are helpful for solving the, kinematics and dynamics of the 2-DOF manipulator. The developed kinematics are helpful for designing the controller.

2.1 Kinematics of the Two-link Manipulator

The forward and inverse kinematics of the 2-DOF manipulator (Figure 1) are deliberated in this section. For solving the forward kinematics, the authors used a systematic procedure. Initially, the coordinate frames are attached to each joint of the manipulator, and identifying the D-H parameters are given in Table 1. The D-H notations are helped to achieve the required position and orientation of the end effector.

Table 1. D-H parameters of the 2-DOF manipulator.

Link	θ_i	d_i	a_i	α_i
1.	θ_1	0	L_1	0
2.	θ_2	0	L_2	0

where, θ_i represents the joint angle, d_i denotes the prismatic distance, a_i indicates the link length and α_i represents the link twist angle.

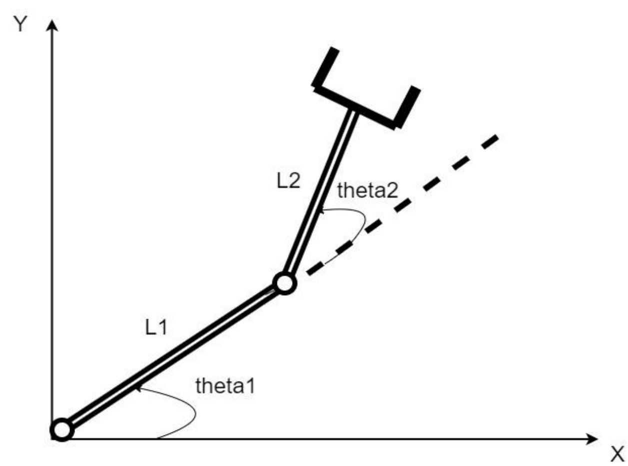


Figure 1. 2-DOF serial manipulator.

The homogeneous transformation matrix of the 2-DOF serial manipulator is as follows.

$$ {}^0_2T = \begin{bmatrix} C\theta_{12} & -S\theta_{12} & 0 & L_1C\theta_1 + L_2C\theta_{12} \\ S\theta_{12} & C\theta_{12} & 0 & L_1S\theta_1 + L_2S\theta_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Using inverse kinematics, the individual joint angles for 2 DOF robotic manipulator are computed. Eqn. (1) and Eqn. (2) equations are used in determining the angles at various joints.

$$\theta_1 = Atan2\left(\sqrt{1-\left[\frac{d_1C_2+d_2L_2S_2}{d_1^2+d_2^2}\right]^2}\cdot\frac{d_1C_2+d_2L_2S_2}{d_1^2+d_2^2}\right) \quad (2)$$

$$\theta_2 = Atan2\left(\sqrt{1-[\frac{(d_1^2+d_2^2)-(L_1^2+L_1^2)}{2L_1L_2}]^2}\cdot\frac{(d_1^2+d_2^2)-(L_1^2+L_1^2)}{2L_1L_2}\right) \quad (3)$$

2.2 Dynamics of the Two-link Manipulator

The dynamics of the 2-DOF manipulator have been solved after the determination of the forward and inverse kinematics. These dynamics are useful for calculating the torque needed at each manipulator joint. The torque needed for each joint of the manipulator provided in equation (4) was calculated using Lagrangian-Euler (L-E) formulation in the current study work.

$$\tau_i = \sum_{j=1}^{n} M_{ij}\,(\theta)\ddot{\theta_j} + \sum_{j=1}^{n}\sum_{k}^{n} C_{ijk}\dot{\theta}_j\dot{\theta}_k + G_i(\theta) \quad (4)$$

where, τ_i= Torque required at joint i due to motion of various links
q = Joint displacement.
$\dot{q}_j$= jth Joint velocity.
$\dot{q}_k$= jth Joint acceleration.

where the inertia factor is M_{ij} is

$$M_{ij} = \sum_{p=\max(i,j)}^{n} Tr[d_{pj}\, I_p d_{pi}^T] \qquad i,j = 1,2,\ldots\ldots\ldots n.$$

The Coriolis force factor is

$$C_{ijk} = \sum_{p=\max(i,j,k)}^{n} Tr\left[\frac{\partial(d_{pk})}{\partial q_p} I_p d_{pi}^T\right] \qquad i,j = 1,2,\ldots\ldots\ldots n.$$

The gravity factor is

$$G_i = -\sum_{p=i}^{n} m_p\, g d_{pi}\, {}_e^p\bar{r}_p \qquad i,j = 1,2,\ldots\ldots\ldots n.$$

3. Design of Controllers for 2-DOF Manipulator

To move the manipulator from one location to another location in a smooth manner proper controller is necessary for each joint of the robotic arm. In the current research article, the authors established a novel control algorithm, that is, a Sliding Mode Controller for 2-DOF manipulator. Later the designed control algorithm is compared with the PID and fuzzy logic controller.

3.1 PID Controller

PID controllers are among the controllers that will aid in easily achieving the aim out of all the controllers. It is significant to highlight that tuning the PID controller's gains is difficult. The error signal affects the controller gains *Kp*, *Kd*, and *Ki*. Based on the location of the end effector, the PID controller's advantage is utilized to regulate different joints in the manipulator. It is significant to remember that the PID controller has a comparatively straightforward design when compared to the other controllers. Additionally, the *Kp*, *Kd*, and *Ki* gains as well as the strength of the error signal are used to manipulate the PID controller. Therefore, the following equation is used to compute the torque needed at various manipulator joints to move from the starting to ending position.

$$f_i = K_{Pi}e + K_{Di}\dot{e} + K_{Ii}\int e\,dt \quad (5)$$

3.2 Sliding Mode Controller

The performance of a SMC may be optimized by modifying its structure. It is a flexible state feedback controller for nonlinear frameworks. It is a distinctive variable structure system (VSS) with strong defenses against framework deteriorations and parameter weaknesses. SMC can establish connections with feedback regulators in the framework state space that are monitoring the opposing sides of a sliding surface that has been specified. Chattering is also known as interference among switches, which consequences in finite-amplitude, high-recurrence changes. The chattering might cause immersion and heat the framework's mechanical components. Essential concerns including minimizing chattering, lowering unmodeled dynamics, the flexibility provided in uncertain frameworks, and enhancing the dynamic performance of closed-loop systems are the main areas of attention in SMC design. Designing the switching surface that complies with the design requirements in order for the framework to transfer on the sliding surface is the first stage in creating this controller. The right control law selection also enables the system to maintain a sliding surface in the presence of both internal and external disturbances. However, the standard SMC design results in chattering, which cannot be used in actual applications (Bao et al., 2021). Under the cover of susceptibilities, SMC may produce an unexpected strength with complete evidence about the asymptotic soundness of the framework. A nonlinear function is included into the sliding surface as a SMC. Here, maintaining the stability of the framework is the control goal. Figure 2 shows the working procedure of SMC.

$$\ddot{x} = f(x,t) + d(t) + u \tag{6}$$

If u is shown as the control input, d(t) is referred to as a time-varying disturbance, and f (x, t) is shown as a nonlinear function.

The following equations can be used to find the two unknown components of the variables f and d.

$$f(x,t) = f_M(x,t) + \Delta f(x,t) \tag{7}$$

$$d(t) = d_M(t) + \Delta f(x,t) \tag{8}$$

The system's state can be expressed in the following way.

$$\vec{x} = \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \tag{9}$$

The objective here is to find an equation in terms of x so that as $x \to \infty$,$x \to x_d(t)$ Asymptotically.

The expression for sliding mode control can be written as

$$\ddot{x} = f_M(x,t) + d_M(t) + \Delta f(x\ ,t) + \Delta\, d(t) + u \tag{10}$$

As a result, sliding surfaces just need a specific set of instructions to be followed rather than a formula.

$$s = \dot{\varepsilon} + \lambda\varepsilon \tag{11}$$

If s = 0, then $\boldsymbol{\varepsilon} = -\boldsymbol{\lambda\varepsilon}$ and

$$\varepsilon(t) = e^{-\lambda(t-t_0)}\varepsilon(to) \tag{12}$$

Therefore $\varepsilon(t) \to 0$, as $t \to \infty$ at every positive value of λ .

After differentiating Eqn. (11) by s, we get

$$\dot{s} = \ddot{\varepsilon} + \lambda\varepsilon^{\cdot} \tag{13}$$

Substitute $\ddot{\varepsilon} = \ddot{x} - \ddot{x}_d$ in equation (13),

$$\dot{s} = \ddot{x} - \ddot{x}_d + \lambda\dot{\varepsilon} \quad (14)$$

After first derivative of the sliding surface, the control input (u) is

$$\dot{s} = f_M(x,t) + d_M(t) + \Delta f(x,t) + \Delta\, d(t) + u - \ddot{x}_d + \lambda\dot{\varepsilon} \quad (15)$$

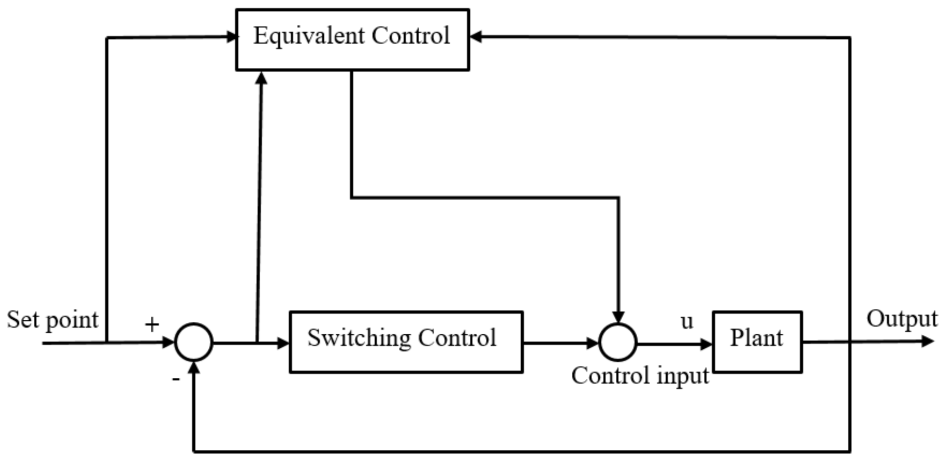


Figure 2. Block diagram of SMC controller.

3.2.1 Chattering in SMC

It is essential to determine the accurate sliding surface to design the sliding mode controller in real-time applications. It has been observed that the error and disturbance obtained from trajectory is to minimize the optimal level. The classical sliding mode controller is simple and robust and faces small issues which is called as chattering. The chattering is a very high-recurrence switching of the sliding variable around the sliding surface and is highly undesirable for practical applications. Moreover, chattering is dangerous because it leads to low precision, damage to dynamic mechanical elements and large heat losses in electrical circuits. The chattering can be obtained due to fast dynamics, which was not considered during modelling. These unmodeled dynamics are generally ignored. Ideally, the sliding mode entails infinite switching disturbances. Further, the control is bounded by sampling interval, frequency cannot exceed that of sampling, which leads to chattering in the system.

To tackle the above issue ("chattering phenomenon"), approximate executions of sliding mode control strategies have been recommended the intermittent "signum" term is replaced by a persistent smooth approximation. But, in real-time applications, it is not sensible to expect that the control sign can switch at endless recurrence. Because of the presence of dormancy in actuators, sensors, encompassing clamour, and unsettling exogenous influences, the control signal drives at an extremely high but limited recurrence (Perruquetti and Barbot, 2002; Yan et al., 2003; Utkin, 1992). The ideas of ideal and genuine sliding mode are embraced here to recognize the sliding movement that happens in a perfect world on the sliding surface from a sliding movement that, because of the non-idealities of the control law execution, happens in an area of the sliding boundary, which is known as the limit layer is shown in Figure 3 (Fridman, 2001; Boiko et al., 2004; Lee and Utkin, 2007).

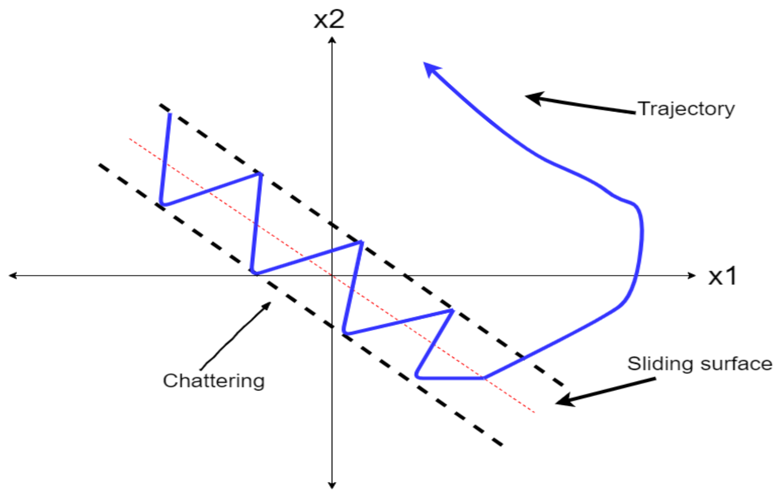


Figure 3. Chattering in SMC controller.

3.3 Fuzzy Logic Controller

FLC is also an adaptive controller used in real-time control applications (Sanchez et al., 1997). FLC incorporates linguistic variables for solving the real-time problems. The key benefit of the fuzzy logic controller is its capability to integrate professional knowledge into the control process without the use of a numerical model. The program will also assist in controlling nonlinear frameworks. The suggested approach properly develops the framework execution and sufficiently eliminates noise. Figure 4 illustrates the many functional challenges in developing an accurate numerical model of the real-world system. Linguistic factors are used by human experts to include FLC and lessen the complications in this method. These clever control techniques are applied with the intention of performing clever actions. The suggested control structure also supports the performance of a series of challenging tasks in an uncertain or hostile environment.

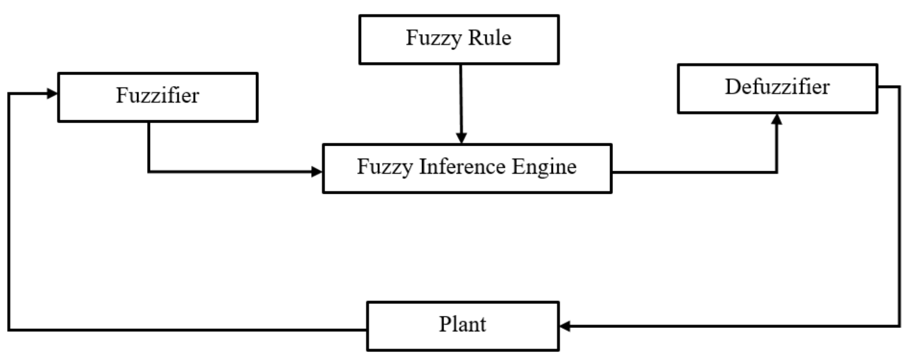
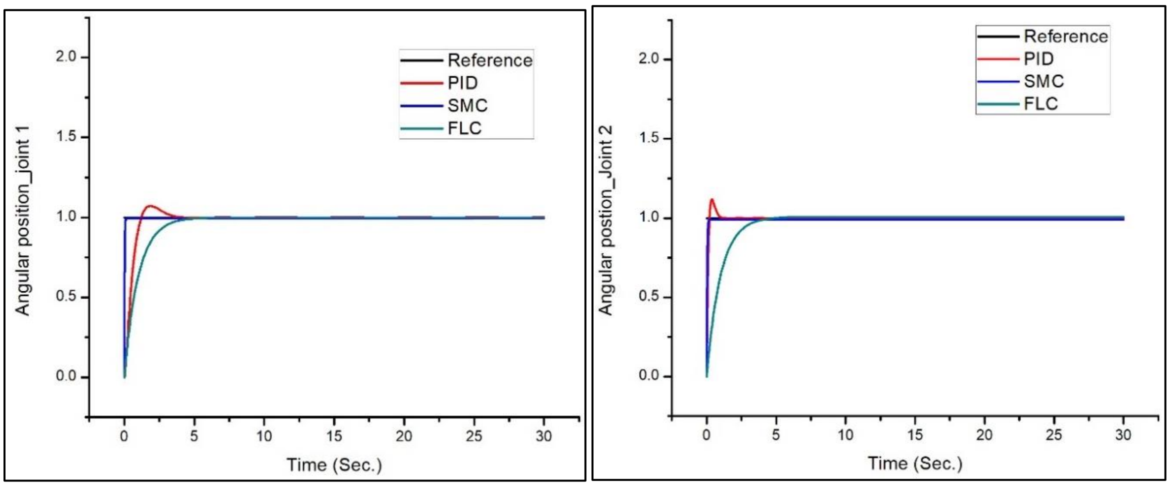


Figure 4. Block diagram of FLC.

4. Result and Discussions

The present research mainly aims to design a SMC for a 2-DOF planar manipulator. Later on, the developed SMC is verified with the PID and fuzzy logic controllers in terms of angular positional error and torque. Once the controllers are designed, the designed SMC, PID and FLC controllers are tested in MATLAB simulations. It has been observed that the simulation results achieve the reference trajectory using any control technique. In SMC, the switching surface boundary μ is picked as 1 for both the surfaces. The angular positional error 2-DOF robotic manipulator at joint 1 and joint 2 are shown in Figure 5(a) and (b). It has been identified that the angular positional error is high for PID and fuzzy logic controller when compared to sliding mode controller. Moreover, the time required to stabilize the error is 5 seconds for PID and fuzzy logic controller and 0 seconds for the sliding mode controller. The result indicates that the performance of SMC is greater than the PID and fuzzy logic controller (Mandava and Vundavilli, 2020; Mandava and Vundavilli, 2021; Kodali et al., 2022).



(a) (b)

Figure 5. Angular positional error at (a) Joint 1 and (b) Joint 2.

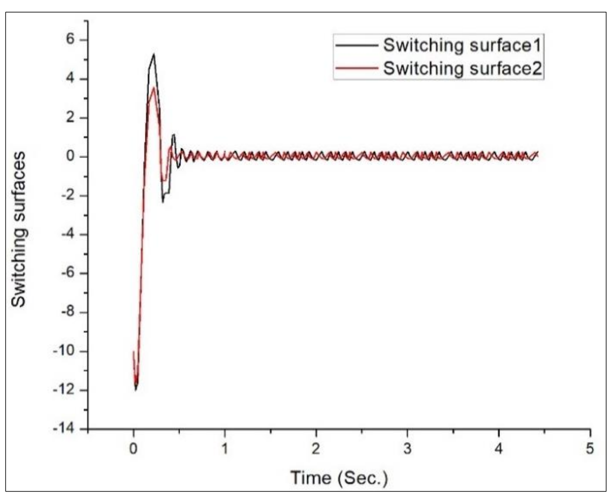
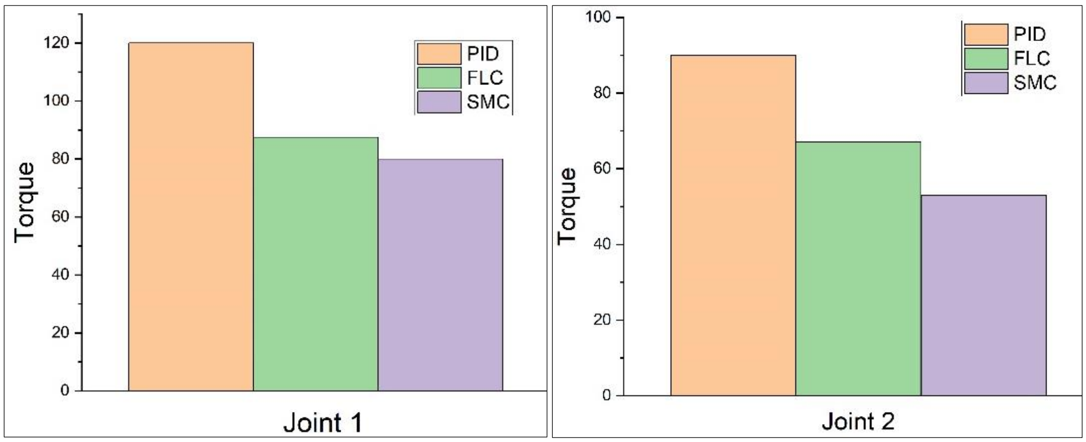


Figure 6. Switching surfaces of the SMC.

Figure 6 shows the switching surfaces of the SMC. It has been observed that the switching surface converges to zero, which displays the sliding mode is related with jabbering. Figure 7, indicates the average torque required for obtaining the desired position of each and every joint of the manipulator using PID, FLC and sliding mode controllers. From the results, it has been observed that the torque essential at joint 1 is more when compared with joint 2. Because, in all controllers, the joint carries the other two links and another joint of the manipulator. Moreover, it has also been found that the torque essential at several joints of the PID controller is high when compared with the fuzzy and sliding mode controllers. Because the gains of the PID controllers are with the help of trail and error process. Further, the torque essential at two joints of the SMC is low when compared to the other two controllers.



(a) (b)

Figure 7. Average torque required (a) Joint 1 and (b) Joint 2.

5. Conclusions

In this research paper, various controllers such as, PID, FLC and SMC are designed for the 2-DOF planar manipulator. The forward and inverse kinematics approach is solved to obtain the position and orientation of the 2-DOF manipulator. To estimate the torque required for every joint of the manipulator, the dynamics of the said manipulator have been obtained using the Lagrangian-Euler formulation. Further, the SMC is verified with the PID and fuzzy logic controllers in terms of angular positional error and torque. It has also been observed that the SMC performs well in uncertain dynamics to achieve high accuracy trajectory tracking in a real-time environment. Finally, it concludes that the performance of the SMC is superior than traditional PID and Fuzzy logic controllers in terms of path tracking. The developed controllers will test on real 2-DOF and 4-DOF industrial manipulators to complete the specific task considered as a future scope.

Conflict of Interest

The authors of this article endorse that there is no conflict of interest to declare for this publication.

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