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Sliding Mode Control of SolidWorks Designed Robotic Manipulator Co-simulated in MATLAB

Paidi Ravi*[1], K. Rama Sudha[2]

Abstract

This study proposes a Sliding mode control (SMC) algorithm for controlling three degrees of freedom (3DOF) robotic arm. This concept was inspired by seeing the increasing of potential applications of robotic arm in automation industry, mainly in the applications like pick and place. The 3DOF robotic arm is designed in SolidWorks and then it is imported to MATLAB for simulation purposes. Initially, simulations are done by using the conventional PID controller but the permeance is not up to the mark, the end effector takes more time to track the reference trajectory. So, to improve the results, the proposed Sliding mode controller is designed and to increase the smoothness in the end effector moment, the sliding surface is constructed by using proportional and derivative constants. A detailed derivation of this proposed SMC controller is provided in this study. For each x, y and z axis, three different trajectory paths are generated. The obtained trajectory tracking error by using this SMC controller is compared with the PID controller. According to obtained results, conclusion is that this proposed controller gives good and accurate output. The complete simulations are done in MATLAB.

Keywords: Robotic arm, PID controller, MATLAB, SolidWorks, Sliding mode control

INTRODUCTION

Robotic arm technology is increasingly popular in industrial automation, as it is seen as a key component in the advancement of industrial progress. In industrial production, the process is becoming complicated day by day, so, humans are unable to complete the work within the time. So, robotic arm is the only solution to address it. Robotic arm technology can be used in various applications, such as car assemblies, to perform tough tasks such as welding of parts, during assembling of parts and parts' rotation. This technology can be used to perform tasks that may be risky for human beings. Furthermore, in the event of a fire or rescue operation, robotic arm technology can be utilized as a rescue tool. Compared to normal works, robots speed up the process, so, production time can be shortened [1].

***Author for Correspondence**
Paidi Ravi
E-mail: 32106626011@andhrauniversity.edu.in

[1]Student, Department of Electrical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India
[2]Professor, Department of Electrical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India

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So, we can conclude that robots can work more efficiently than human beings, so it is very important to control the robotic arm with good precision. So, we have prepared an accurate control system. For example, the controller of the robotic arm is designed in such a way that it moves point to point easily by using PID controller [2].

For packaging industries, objects are kept at different places in a line and sensors are attached to it. The sensors will give the information whether the end effector is accurately in contact with an object or not and measure the distance between them. If any error is there, then the PID controller will try to reduce the error and give accurate control such that it can move easily to all the points and pick up the objects easily [3]. A 3DOF robotic system is modelled by dividing it into subsystems based on their angular positions in coordinate space. This type of modelling is called switched system modelling [4]. For some advanced techniques like Sliding mode control, the Robotic arm responding very fastly. SMC based arm can easily pick the object from one point and place it at another point within a fixed time. For the conventional PID controllers, it is not possible to used an exoskeleton robotic arm. [5] The authors highlighted the model-based switching functions design.in advanced behavior of the system and transients were also analyzed. The control algorithm is designed such that the system is asymptotically stable under all conditions, and the torque control law is much simpler compared to previous studies [6].

For experimental purpose, design of a hardware robotic arm is costlier and more complex. For a student, it is too much of a cost to bear. If the hardware model failed, so much money is also wasted. So, experiments are becoming less in this research area. The only solution for this problem is to design a virtual model using 3-D model design software like SolidWorks.

SolidWorks is 3-D model designing software which is used for designing of various products like Robotic arm and some machine components like rotor and stator of motor etc. In this study, initially, a 3DOF robotic arm shown in Figure 1, is designed in SOLIDWORKS which has a circular base and three joints of the detailed design steps are discussed in this article.

The objective is to move the end effecter from the default position to a particular position within the workspace. The required trajectory path to move the arm from default position to end position was generated by trapezoidal trajectory block. Now the controller's aim is to produce enough torques at each joint such that the end effector will follow the Reference trajectory. By using conventions, PID-computed torque control response is not good as it takes more time to track the path. From the above study, the conclusion is that the SMC is giving good results in controlling the robotic arm. So, the aim is to design the SMC controller such that it follows the trajectory path with no error. In this work, the sliding surface is designed by using conventional PID controller gains. According to sliding mode controller, a system is said to be stable if the system trajectory is on the surface s=0. So, during the design of sliding mode controller, main aim is to move the system trajectory towards the surface s=0. Here $\dot{s}$ is change in sliding surface if s=0 then $\dot{s}$ is also zero.

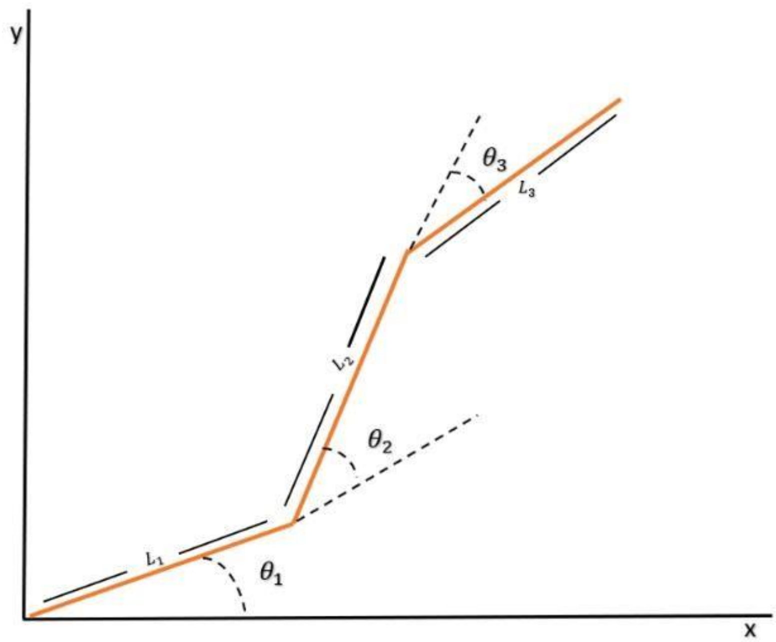

Figure 1. 3DOF robotic arm.

MODELING OF TORQUE

According to Lagrangian, the torque is defined as:

$$\tau_i = \frac{d}{dt}\frac{\partial L(\theta,\dot{\theta})}{\partial\dot{\theta}_i} - \frac{\partial L(\theta,\dot{\theta})}{\partial\dot{\theta}_i} \tag{1}$$

Where $L(\theta,\dot{\theta})$ is Lagrangian Matrix

$$L(\theta,\dot{\theta}) = \sum_{i=1}^{n}(K_i(\theta,\dot{\theta}) - P_i(\theta,\dot{\theta})) \tag{2}$$

Where i = 1, 2……n (n = DOF) in this problem n value is 3

General Formula of Kinetic Energy is.

$$K(\theta,\dot{\theta}) = \frac{1}{2}mv^2 \tag{3}$$

The Kinetic Energy at Joint 1 is.

$$K_i(\theta,\dot{\theta}) = \frac{1}{2}m_1(\dot{x}_1^2 + \dot{y}_1^2 + \dot{z}_1^2) \tag{4}$$

The kinetic energy at joint 2:

$$K_2(\theta,\theta) = \frac{1}{2}m_2(\dot{x}_2^{\,2} + \dot{y}_2^{\,2} + \dot{z}_2^{\,2}) \tag{5}$$

The kinetic energy at joint 3:

$$K_3(\theta,\theta) = \frac{1}{2}m_2(\dot{x}_3^{\,2} + \dot{y}_3^{\,2} + \dot{z}_3^{\,2}) \tag{6}$$

Potential energy at joint 1:

$$P_1(\theta,\dot{\theta}) = m_1 g l_1 \sin\theta_1 \tag{7}$$

Potential energy at joint 2:

$$P_2(\theta,\dot{\theta}) = m_2 g\,(l_1 \sin\theta_1 + l_2 \sin(\theta_1+\theta_2)) \tag{8}$$

Potential energy at joint 3:

$$P_3(\theta,\dot{\theta}) = m_3 g\,(l_1 \sin\theta_1 + l_2 \sin(\theta_1+\theta_2) + l_3 \sin(\theta_1+\theta_2+\theta_3)) \tag{9}$$

Substitute from Eq. (4) to (9) in Eq. (2) to get the Lagrangian Matrix.

Now substitute the Lagrangian Matrix in Eq. (1) than we get torque as:

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) \tag{10}$$

Where τ is an input torque vector $\tau \in R^{n\times 1}$

1. Where M(q) is a mass matrix M(q)$\in R^{n\times n}$
   Where $C(q,\dot{q})$ is a centrifugal force $C(q,\dot{q}) \in R^{n\times n}$
   Where $g(q)$ is a gravitational force vector $g(q) \in R^{n\times 1}$
2. Where q is position vector $q \in R^{n\times 1}$
   Where $\dot{q}$ is velocity vector $\dot{q} \in R^{n\times 1}$
   Where $\ddot{q}$ is acceleration vector $\ddot{q} \in R^{n\times 1}$

ROBOTIC ARM DESIGN IN SOLIDWORKS

Procedure for designing of this 3DOF robotic arm:

- *Step 1:* By using proper dimensions (50 mm), first draw a circle in top view for circular base and save with file name circular base.
- *Step 2:* For link 1 with same dimensions draw a circle in top view and now draw a rectangle with length 60 mm on the top of circle in front view and draw a small circle with 5 mm radius on the top of rectangle in front view for joint purpose. By using the circle joint will form a lattice.
- *Step 3:* For link 2 and link 3, draw a rectangle with length 120 mm in front view and draw the circle on top and bottom with radius for joint purpose.
- *Step 4:* Now for circular base, extrude circle with dimensions (50 mm) upward by using extrude out command.
- *Step 5:* For link 1 extrude the circle with (10 mm) in downwards by using extrude out command. For rectangle extrude (10 mm) by using extrude out command. Now by using the 5 mm small circle, make hole to the link 1 by using extrude in command with dimensions of (10 mm).
- *Step 6:* For link 2 and link 3, similar extrude (10 mm) radius by using extrude out command; and at bottom, extrude the small circle 10 mm upward by using extrude out command. On top by using the 5 mm small circle make hole to the link 1 by extrude in command with dimensions of 10 mm.
- *Step 7:* For assembling the parts, bring all the sketched files into assembly window now by using concentric and coincident mates join circular base, link 1, link 2 and link 3 with each other properly [7–10].

Then we get the final output as shown in Figure 2.

Length and mass values of the robotic arm are given in Table 1.
Moment of inertia at joint 1=0.09036 kg.m^2
Moment of inertia at joint 2=0.05664 kg.m^2
Moment of inertia at joint 3=0.03682 kg.m^2

Figures 3 and 4 show the position of robotic arm for different θ values.

Figure 2. Robotic arm designed in SolidWorks.

Table 1. Length and mass values.

	Base	Link 1	Link 2	Link 3
Mass (kg)	0.0589	0.02352	0.01376	0.02557
Length (m)	0.6	0.7	1.2	1.2

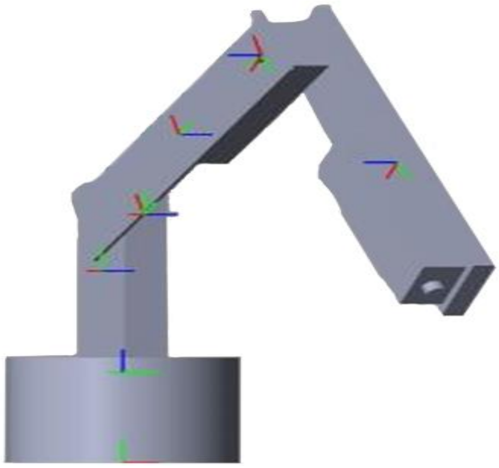

Figure 3. Robotic arm position for θ_1=45, θ_2=65, θ_3=72.

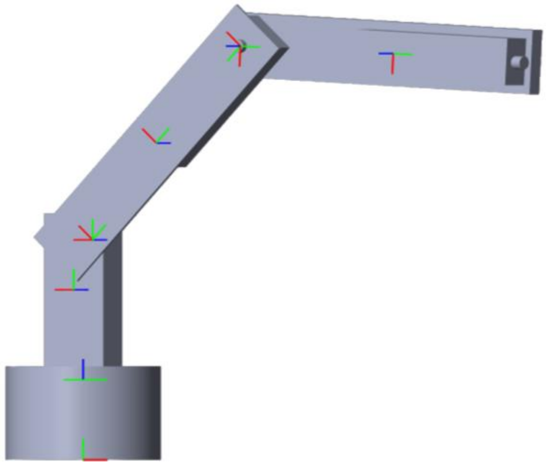

Figure 4. Robotic arm position for θ_1=30, θ_2=40, θ_3=50.

CONTROLLER DESIGN

The torque equation is given below; here τ_d is desired torque and τ is an input torque.

$$\tau+\tau_d=M(q)\ddot{q}+C\,(q,\,\dot{q})\,\dot{q}+g(q) \tag{11}$$

For a sliding mode controller, the primary thing is designing of a sliding surface. Let us take sliding surface as:

$$s=k_p e+k_d\dot{e} \tag{12}$$

Where k_d derivative gain, k_p proportional gain, e is error and $\dot{e}$ change in error.

The reachability condition of sliding mode control is:

$$s.\,\dot{s}<0 \tag{13}$$

where $\dot{s}$ is:

$$\dot{s}=k_p\dot{e}+k_d\ddot{e} \tag{14}$$

$$\dot{s}=k_p\dot{e}+k_d\,(\ddot{q}_d-\ddot{q}) \tag{15}$$

We can get $\ddot{q}$ from Eq. (11) as:

$$\ddot{q}=M(q)^{-1}(\tau-C\,(q,\,\dot{q})\,\dot{q}-g(q)+\tau_d) \tag{16}$$

Therefore, from Eqs. (16) and (15), $\dot{s}$ is.

$$\dot{s}=k_p\dot{e}+k_d\,(\ddot{q}_d-M(q)^{-1}(\tau-C\,(q,\,\dot{q})\,\dot{q}-g(q)+\tau_d)) \tag{17}$$

Now let us assume desired torque as shown below:

$$\tau_d=M(q)\,(k_1.s+(k_p/k_d)\,\dot{e}+\ddot{q}_d)+C\,(q,\,\dot{q})\,\dot{q}+g(q)-\tau \tag{18}$$

Substitute Eq. (18) in Eq. (17), now $\dot{s}$ is:

$$\dot{s}=-k_1k_d.\,s \tag{19}$$

Substitute Eq. (19) in Eq. (13), then,

$$-k_1k_ds^2<0 \tag{20}$$

Value is less than zero, so reachability condition is verified. So, the control law is:

$$\tau_d=M(q)\,(k_1.\,s+(k_p/k_d)\,\dot{e}+\ddot{q}_d)+C(q,\,\dot{q})\dot{q}+g(q)-\tau$$

RESULTS

The starting position of end effector is (3.5, 0.2, 3.7); the trajectory is designed such that in 5 sec, the end effector will move to its desired position (–0.5, 1, 0.4). As shown in Table 2, a trajectory path is generated from starting point to ending point.

The error between reference path and the actual path for PID controller is shown in Figure 5. The error between reference path and the actual path for sliding mode controller is shown in Figure 6. From Figures 5 and 6, it is clearly understood that by using the proposed controller, the performance of the system is increased than PID controller.

Table 2. Trajectory design table.

	Position 1	**Position 2**	**Position 3**	**Position 4**	**End**
x	3.5	1.5	1	0.6	–0.5
y	0.2	0.5	0.75	0.9	1
z	3.7	2	1.5	0.8	0.4

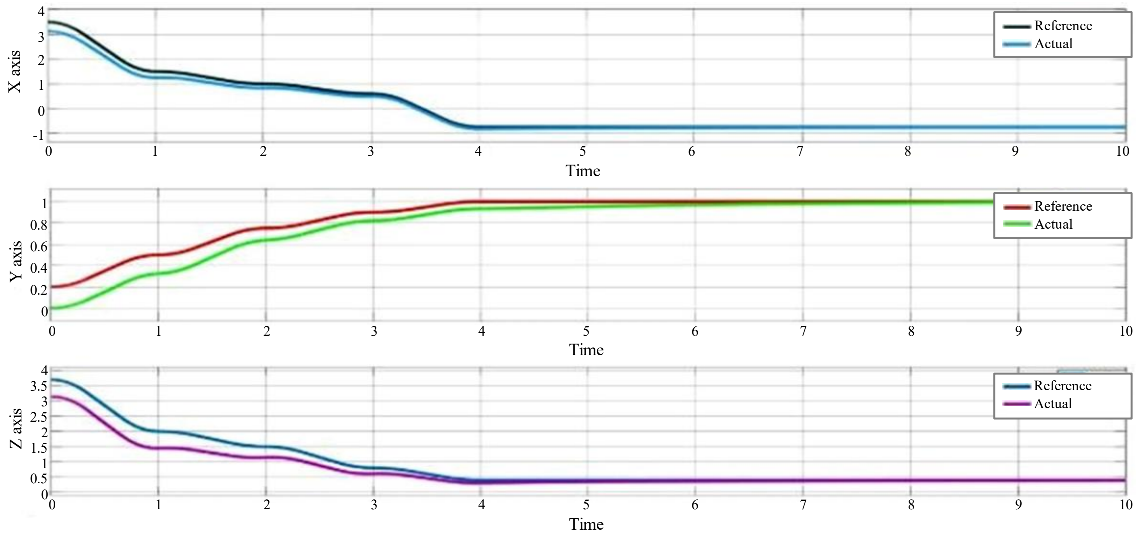

Figure 5. Error in X, Y, Z positions for PID controller.

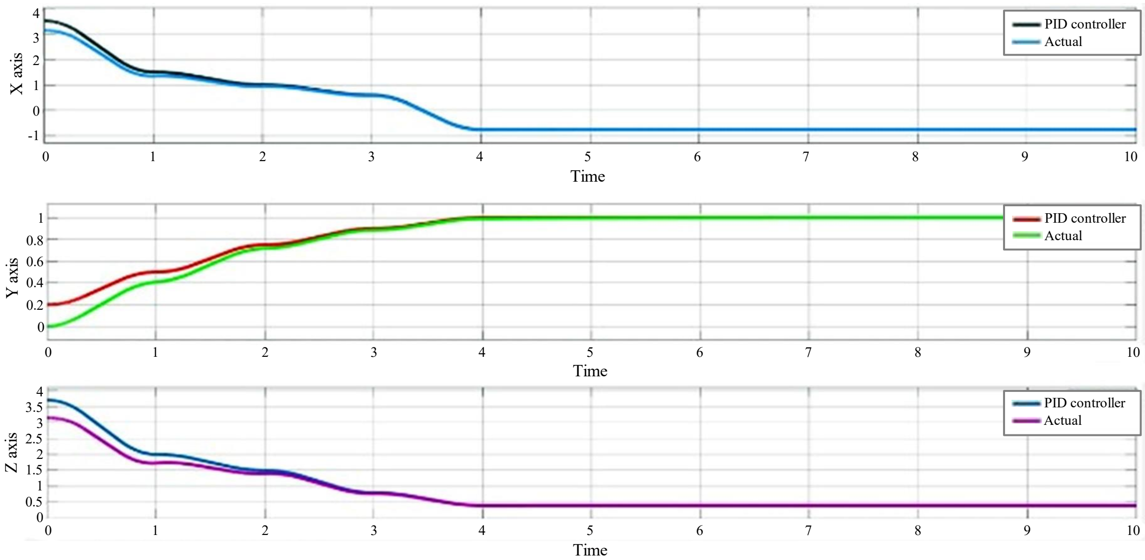

Figure 6. Error in X, Y, Z positions for sliding mode controller.

Table 3. Error analysis table.

Time (sec)	For PID controller			For SMC controller		
	Error in X-axis	*Error in Y-axis*	*Error in Z-axis*	*Error in X-axis*	*Error in Y-axis*	*Error in Z-axis*
0	0.58	0.2	0.37	0.58	0.2	0.37
1	0.42	0.15	0.2	0.53	0.17	0.25
2	0.23	0.1	0.1	0.37	0.15	0.16
3	0.1	0.08	0.06	0.2	0.12	0.11
4	0.05	0.04	0.03	0.1	0.09	0.08
5	0.01	0.01	0.01	0.07	0.085	0.05
6	0	0.005	0	0.06	0.07	0.04
7	0	0	0	0.04	0.06	0.01
8	0	0	0	0.02	0.045	0
9	0	0	0	0.01	0.02	0
10	0	0	0	0	0.02	0

From the above error analysis (Table 3), it is clearly understood that:

- For PID controller, the error in X-axis shows that, the end effector takes 10 sec to follow the reference path. In Y-axis, the end effector takes 10 sec to follow the reference path. In Z-axis, the end effector takes 8 sec to follow the reference path.
- For SMC controller, the error in X-axis shows that, the end effector takes 6 sec to follow the reference path. In Y-axis, the end effector takes 7 sec to follow the reference path. In Z-axis, the end effector takes 6 sec to follow the reference path.

CONCLUSION

The designed Robotic arm in SolidWorks is working properly and for experimental purposes, this type of SolidWorks based designed robotic arm is economical and simple. The proposed controller (SMC) is giving better results compared to the PID controller. From the results it is observed that PID controller takes a very long time to reduce the error, nearly 10 sec. But by using sliding mode controller, the error becomes zero at 6th sec only, which is half of the time compared to PID controller. The detailed derivation of control law provided will give complete information of the SMC design which will be useful for further works. To improve the results in future works, a terminal sliding mode controller is also included.

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