International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

Application of PID Controller and Nonlinear Sliding Mode Control on Two Link Robotic Manipulator

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***Abstract*:- Robotic manipulators plays an important role in industrial autonomous manufacturing. Non linearity as well as parameter variations or uncertainties caused by inaccurate system modeling, insufficient parameter identification, external disturbances and environmental conditions are the most challenging issues in robot engineering. The dynamic model of the two link robotic manipulator is done using the Euler-Lagrange equation. A conventional PID controller and a robust nonlinear sliding mode control is introduced to control the motion of the end effector at specific position for pick and place tasks. Comparative study is done and the results shows that Sliding mode control surpass PID control with minimum tracking error. Simulation results validate that the chattering of control input can be mitigated effectively using SMC**

Keywords:- Dynamic model ; robot manipulator; PID control; Sliding Mode Control

I. INTRODUCTION

Contemporary industrial robots are programmable machines which can perform distinct operations by simply improving stored data, a trait that has emerged from the application of numerical control. Remote manipulators are the origin of today's industrial robots. It's a device that performs a task at a distance. Robotic manipulators are capable of performing repetitive tasks at speeds and accuracies that far exceed those of human operators. They are widely used in several fields such as painting and welding in manufacturing processes, free floating space manipulators in astronautics, underwater robot manipulators for subsea interventions for ocean developments, limb rehabilitation manipulators in medical field, ammunition auto loading manipulator in artillery or tank weapons. The major problem faced by industrial manipulators are the vibration of arm during high speed movement. Positions and velocities of end effector are to be controlled digitally to perform the desired tasks accurately and reliably. Each motion or degree of freedom (D.O.F.) of the manipulator is positioned using a separate position control system. All the motions are coordinated by a supervisory computer to achieve the desired speed and positioning of the end-effector.

Pawan Singh Yadav and Narinder Singh et.al [1] developed H-infinity controller and μ-synthesis controllers for two link rigid manipulator (TLRM). The dynamics of TLRM is derived using Lagrange-Euler method. The results validate that both controllers are capable of stabilizing the manipulator very effectively. The transient response of $H\infty$ controller is having a slight longer settling time which is improved by using μ-synthesis controller, but this comes on the cost of disturbance rejection which is slightly poor in μ-synthesis controller. A combination of a feedback linearization control and an MPC control approach for a two-link robot arm were proposed by El-Hadi Guechi and Samir Bouzoualegh et.al [2]. The study shows that the proposed MPC control approach gives a better performance than the LQ optimal control approach. Moreover both proposed approaches (MPC control and LQ control) give a better system performance than conventional PID controller. In recent years, nonlinear and adaptive back stepping control design schemes have been widely developed and applied in various nonlinear systems, including manipulators. Fang-Shiung Chen and Jung-Shan Lin et.al [3] developed a nonlinear back stepping control design scheme with a velocity observer for the trajectory tracking control of a robot manipulator which has exact model knowledge. The exponential stability of the resulting closed loop system is demonstrated via Lyapunov stability theory with a useful lemma in [11]. The proposed nonlinear back stepping control design not only stabilized the robot system, but also all the tracking errors are forced to converge to zero exponentially. Lafmejani and Zarabadipour et.al [4] modeled, simulated and controlled 3-DOF articulated robot manipulator by extracting the kinematic and dynamic equations using Lagrange method. The model is further linearized with feedback and a PID controller is implemented to track a desired trajectory. It was concluded in the research work that robot manipulator is difficult to control as result of complexity and nonlinearity associated with the dynamic model.

Motivated by an endeavor to solve the trajectory tracking control problem of two link manipulator, a sliding mode control approach and a conventional PID controller is presented in this paper. The effectiveness of the proposed control schemes for the pick and place activities of two link manipulator was illustrated by simulations in MATLAB SIMULINK.

II. DYNAMIC MODELING OF TWO LINK MANIPULATOR

A large number of control problems for mechanical systems are based on controlling the position or location of a mass using a force or a torque as the input variable. Dynamics of a robot arm is explicitly derived based on the Euler-Lagrange formulation. Figure 1 shows the dynamic model of a two link manipulator.

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ISSN: 2278-0181
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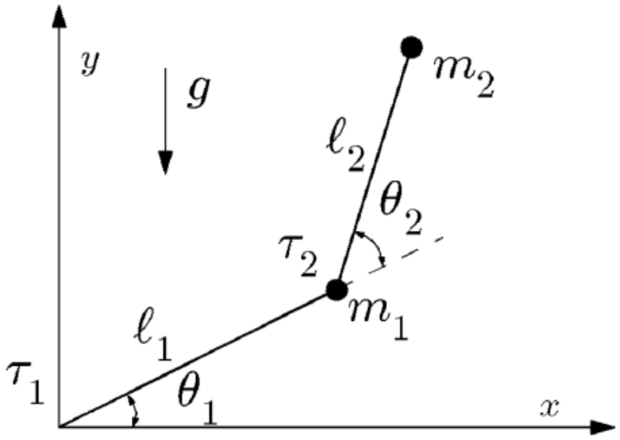

Fig.1. Schematic diagram of two link manipulator

Positions of mass m_1 and m_2 are,

$$x_1 = l_1 \cos\theta_1 \quad (1)$$

$$y_1 = l_1 \sin\theta_1 \quad (2)$$

$$x_2 = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \quad (3)$$

$$y_2 = l_1 \sin\theta_2 + l_2 \sin(\theta_1 + \theta_2) \quad (4)$$

Velocities of mass m_1 and m_2 are,

$$\dot{x}_1 = -l_1 \sin\theta_1 . \dot{\theta}_1 \quad (5)$$

$$\dot{y}_1 = l_1 \cos\theta_1 . \dot{\theta}_1 \quad (6)$$

$$\dot{x}_2 = (-l_1 \sin\theta_1 - l_2 \sin(\theta_1 + \theta_2))\dot{\theta}_1 - l_2 \sin(\theta_1 + \theta_2)\dot{\theta}_2 \quad (7)$$

$$\dot{y}_2 = (l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2))\dot{\theta}_2 + l_2 \cos(\theta_1 + \theta_2)\dot{\theta}_2 \quad (8)$$

Kinetic energy of individual links in an n-link arm is

$$K_i = \frac{1}{2} m_i v_{ci}^T v_{ci} \quad (9)$$

Potential energy of individual link is given by

$$P_i = m_i l_{ci} g \sin(\theta_i) \quad (10)$$

Lagrangian L is defined as the difference between kinetic and potential energy:

$$L(\theta, \dot{\theta}) = K - P \quad (11)$$

With Lagrangian L, equations of motions can be computed, can be defined as

$$\tau = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} \quad (12)$$

The dynamic model of a robotic arm with two degrees of freedom (DOF) can be written as

$$F = M(q)\ddot{q} + C(q, \dot{q}) + g(q) \quad (13)$$

Where $q, \dot{q}$ and $\ddot{q}$ denotes the link position, velocity and acceleration respectively.

M (q) is the symmetric nonsingular inertia matrix, given by

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

Where

$$M_{11} = m_2(l_1^2 + 2l_1 l_{c2} \cos\theta_2 + l_2^2) + m_1 l_1^2$$
$$M_{12} = m_2 l_1 l_2 \cos\theta_2 + m_2 l_2^2$$
$$M_{21} = M_{12}$$
$$M_{22} = m_2 l_2^2$$

C (q) is the Coriolis and centrifugal force matrix,

$$C = \begin{bmatrix} C_{11} \\ C_{21} \end{bmatrix}$$

Where

$$C_{11} = m_2 l_1 l_2 \sin\theta_2 (2\dot{\theta}_1 + \dot{\theta}_2)\dot{\theta}_2$$
$$C_{21} = m_2 l_1 l_2 \dot{\theta}_1^2 \sin\theta_2$$

g (q) is the gravitational torques vectors given by,

$$g = \begin{bmatrix} g_{11} \\ g_{21} \end{bmatrix}$$

Where

$$g_{11} = -(m_1 + m_2) g l_1 \sin\theta_1 - m_2 g l_2 \sin(\theta_1 + \theta_2)$$
$$g_{21} = -m_2 g l_2 \sin(\theta_1 + \theta_2)$$

and

$$F = \begin{bmatrix} F_{\theta_1} \\ F_{\theta_2} \end{bmatrix}$$

is the control torque applied to the joints.

III. CONTROLLER DESIGN

The control of robotic manipulator to follow a desired trajectory is extremely a challenging problem. The dynamics of a two link robotic arm is highly nonlinear. Controller formulation along with the integration of system dynamics is provided in this section. A PID and a variable structure Sliding Mode Controller is designed for trajectory tracking problem.

A. PID CONTROLLER

PID controllers are widely used in industrial manipulators due to their simple structure compared to other control algorithms. In industrial operations each joint of the robotic arm are independently controlled by PID algorithms.

General structure of PID controller for any input would be

$$f = K_p e + K_D \dot{e} + K_I \int e \; dt \quad (14)$$

PID controller for the two links of the manipulator is given by

$$f_1 = K_{p1}(\theta_{1f} - \theta_1) - K_{D1}\dot{\theta}_1 + K_{I1}\int e(\theta_1)\,dt \quad (15)$$

$$f_2 = K_{p2}(\theta_{2f} - \theta_2) - K_{D2}\dot{\theta}_2 + K_{I2}\int e(\theta_2)\,dt \quad (16)$$

The complete system equations with control would be

$$\ddot{q} = M(q)^{-1}[-C(\dot{q}, q) - g(q)] + \hat{F} \quad (17)$$

Therefore

$$\hat{F} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} K_{p1}(\theta_{1f} - \theta_1) - K_{D1}\dot{\theta}_1 + K_{I1}\int e(\theta_1)\,dt \\ K_{p2}(\theta_{2f} - \theta_2) - K_{D2}\dot{\theta}_2 + K_{I2}\int e(\theta_2)\,dt \end{bmatrix} \quad (18)$$

Complete system equations are

$$\dot{x}_1 = \theta_{1f} - \theta_1 \quad (19)$$

$$\dot{x}_2 = \theta_{2f} - \theta_2 \quad (20)$$

$$\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} = M(q)^{-1}[-C(\dot{q}, q) - g(q)] + \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \quad (21)$$

By using ode45 command in MATLAB the system of ordinary differential equations can be solved.

B. SLIDING MODE CONTROL

The Sliding Mode Controller approach is a discontinuous nonlinear controller, also called the variable structure control, is a typical robust control scheme. SMC can be implemented to any dynamic system having equal number of outputs and

International Journal of Engineering Research & Technology (IJERT)
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inputs. Precise modeling of the system is not possible due to unmodeled external forces, frictions which affect the stability. Sliding mode control is a robust and adaptive control which can deal with modeling inaccuracies suitable for nonlinear systems. The design procedure of SMC contains two steps:

(1) Selection of sliding surface so as to achieve desired system characteristics when the system reaches the sliding surface

(2) Selection of a control law such that the existence of sliding mode can be guaranteed.

A system with dynamics f and control input u,

$$x^{n}(t) = f(x,t) + u(t) \tag{22}$$

Considering our 2nd order system:

$$\ddot{x} = f + u \tag{23}$$

For position and velocity control, we define sliding surface s as

$$s = \left(\frac{d}{dt} + \lambda\right)\tilde{x} = \dot{\tilde{x}} + \lambda\,\tilde{x} \tag{24}$$

Where $\tilde{x} = x - x_d$

Setting $\dot{s}$=0 and substituting (23) ,

$$\ddot{x} - \ddot{x}_d + \lambda\,\dot{\tilde{x}} = 0 \tag{25}$$

$$f + u - \ddot{x}_d + \lambda\,\dot{\tilde{x}} = 0 \tag{26}$$

$$u = -f + \ddot{x}_d + \lambda\,\dot{\tilde{x}}$$

Approximated control law that would achieve

$$\hat{u} = -\hat{f} + \ddot{x}_d + \lambda\,\dot{\tilde{x}} \tag{27}$$

Introducing the switching action will maintain system work in sliding surface

$$u_{sw} = -K\,sign(s) \tag{28}$$

where

$$sign(s)\begin{cases} -1, s < 0 \\ 0, s = 0 \\ 1, s > 0 \end{cases}$$

Overall control law can be expressed as

$$u = \hat{u} + u_{sw} = -\hat{f} + \ddot{x}_d + \lambda\,\dot{\tilde{x}} - K\,sign(s) \tag{29}$$

Where K is a diagonal controller discontinuity gain matrix. The elements of gain matrix must be decided suitably. The "sgn" function returns a vector with the sign of the elements of s. However, this "sgn" function results in a serious issue in SMC called chattering. The surface parameter s_i will never goes to zero rather they change from a small negative to small positive value. Significant fluctuations in the control command occurs due to magnifying term K in the control law. To overcome the effect of chattering, the discontinuity of the SMC caused by sign function must be replaced with a saturation function given by

$$u_{sw} = -K\,sat(s) \tag{30}$$

The saturation function must be operated inside a boundary whose thickness is $\emptyset$

$$sat(s)\begin{cases} -1, \frac{s}{\emptyset} < 0 \\ 0, \left|\frac{s}{\emptyset}\right| < 1 \\ 1, \frac{s}{\emptyset} < -1 \end{cases}$$

TABLE 1 SIMULATION PARAMETERS

Simulation parameters		
Parameter	***Description***	***Value(Unit)***
m_1	Mass of link 1	0.5 kg
m_2	Mass of link 2	0.5kg
l_1	Length of the link1	1m
l_2	Length of the link2	0.8m
g	Acceleration due to gravity	9.8

IV. SIMULATION RESULTS AND DISCUSSIONS

The proposed controllers are implemented and simulated, and the results showed that the tracking error is considerably reduced.

The regulation curve of an uncompensated system without an initial condition of is shown in figure 2

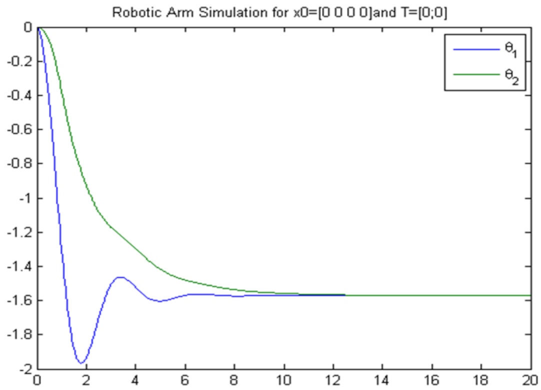

Fig.2.Regulation curve of uncompensated system

Its clearly understood from the figure that the system doesnot regulates without a controller.

A. *PID Controller Results:*

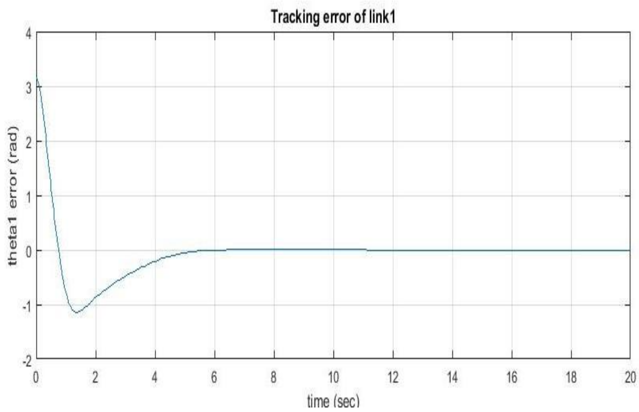

Fig.3.Tracking error curve of link1 with PID controller

The tracking error response for link 1 using the PID controller is depicted in Fig.3, it is clear that the PID controller take at least 5 seconds to bring the arm at the desired position.

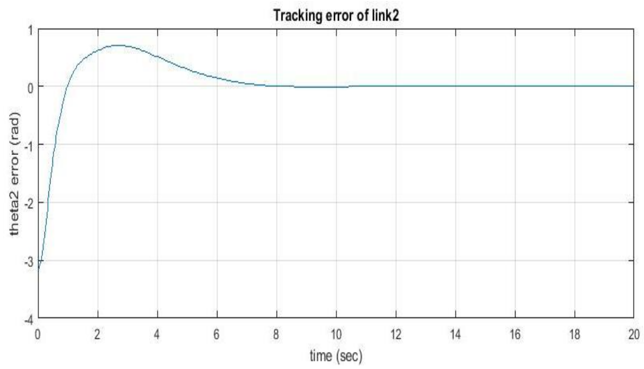

Fig.4. Tracking error curve of link2 with PID controller

Figure 4 shows the trajectory tracking error curve of link 2 with controller. The error between the trajectories settles down within 6.5 sec.

B. SLIDING MODE CONTROLLER RESULTS:

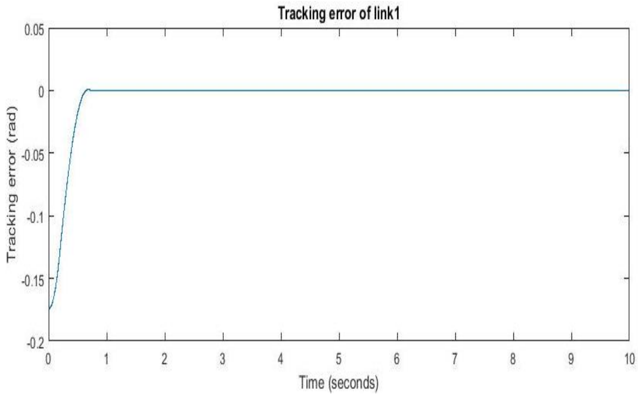

Fig.5.Tracking error curve of link1 with SMC controller

Figure 5 shows the trajectory tracking error curve of link 1 with SMC controller. The settling time of error curve is about 0.54 sec

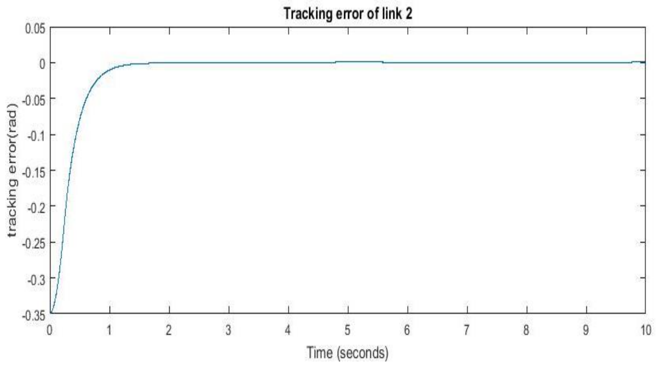

Fig.6. Tracking error curve of link2 with SMC controller

The trajectory tracking error curve of link 2 with SMC controller is shown in figure 6. The error settles down within a duration of 0.71 sec.

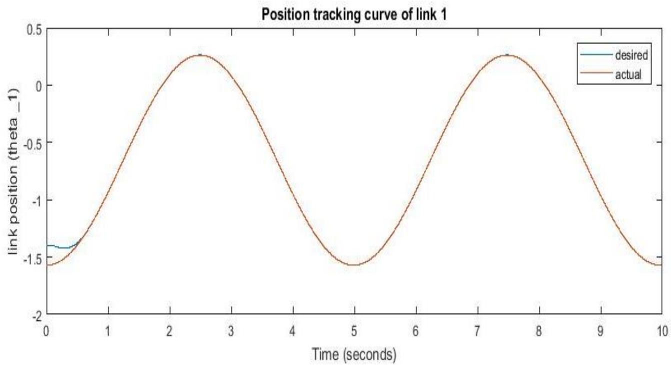

Fig. 7. Sinusoidal Tracking curve of link 1

Sinusoidal trajectory tracking curve for link 1 is shown in figure 7. The result shows that within a fraction of second proper tracking is obtained with SMC controller.

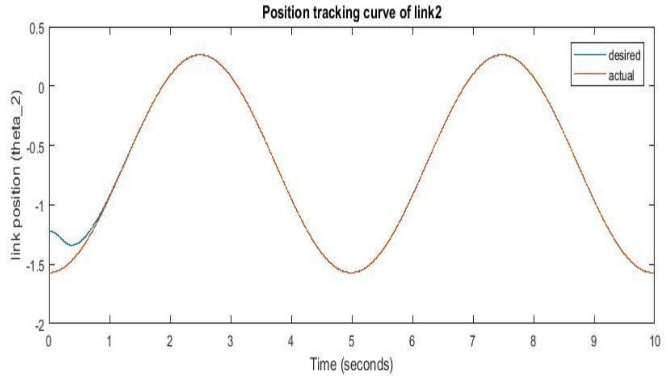

Fig. 8. Sinusoidal Tracking curve of link 2

Figure 8 depicts that Link 2 follows the desired trajectory within a short duration of time than the time taken by the PID controller.

TABLE 2 STEP RESPONSE CHARACTERISTICS

Properties	PID		SMC	
Settling time(sec)	θ_1	θ_2	θ_1	θ_2
	5	7	0.58	0.69
Overshoot (%)	71	44	0	0

V. CONCLUSIONS

Control of robotic manipulator is a benchmark problem in control system. Dynamics of two link manipulator is complex and it’s highly nonlinear. In this paper, mathematical model of two link manipulator has been developed using Euler-Lagrangian method. Different control strategies such as conventional PID control and variable structure Sliding Mode control have been implemented for controlling the position of end effector. The variable structure control method is a robust method that appears to be well suited for robotic manipulators than PID controller for pick and place activities. Simulation results showed smooth control activity and excellent tracking performance with SMC controller.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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