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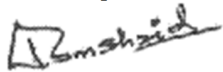
Reference: Article # 4786

Good morning Prof. Butala,

Following your letter regarding the manuscript “*Nonlinear Control of Flexible Joint Robotic Manipulator with Experimental Validation*” submitted to SV-JME for publication, we thank you for arranging peer review of the article. We found the reviewer’s comments very helpful and constructive. In the light of these comments, the manuscript has been revised.

We are confident that the new version of the manuscript has a more fluent scientific discourse. Please find attached the detailed response to reviewer’s comments highlighting the changes performed on the manuscript.

Best regards,



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Response to the Reviewer's Comments

Nonlinear Control of Flexible Joint Robotic Manipulator with Experimental Validation

The authors are grateful to the reviewer for the encouraging words about our research and giving us expert suggestions to further improve the manuscript. Here are the point-wise details of the revisions performed in accordance with the reviewer's comments.

Reviewer #1:

The paper shows a Nonlinear Control of a flexible joint robotic manipulator. Both the model of the actuator and of the controller are well exposed. Convergence and stability of the full system are studied and ensured.

The model of the joint and of the controller are tested in Matlab/Simulink. The controller is test in a real platform using LabView connected with external hardware using MyRio daq. Two quadrature encoders provide feedbacks of the angular positions corresponding to the motor and the link.

I think model of the joint and the controller are well exposed and the study of convergence and stability are well explained. Experimental results must be clarified. Some questions related to the test are listed below.

-
- 1. I assume the Control input is the output of the controller, the control signal.**

Response:

Yes. For clarification, following sentence has been added on **[Page 2]**"

"The control input i.e. output of the controller is fed to the plant i.e. the DC motor and the flexible joint."

- 2. It is not clear to me which angular position are you shown in figures: the motor position, the link position? The key of the controller is to control a flexible joint. How do you have the measurement of the flexibility of the joint in the real platform?**

Response:

Following text has been added in the revised version for the sake of clarity:

[Page 6]

"The angular position shown in the figure is basically position of the flexible joint."

and

"The rotary encoder is attached to the flexible joint so as to provide the joint position independent of the motor's position."

3. **The actuator is a 24V DC motor and output controller signal is upper this value. (i.e, Fig. 5, Fig. 7, Fig. 11). Is the input signal to the actuator? How do you explain it?**

Response:

Thanks for making this valid point. Figs. 5, 7 and 11 are corrected in the revised version. The control input shown in these figures is the output of the controller and input to the plant i.e. the motor. The motor is controlled using motor drive module L298 which require PWM signal as an input. Therefore, the actual voltage applied to the motor may vary from 0 to 24VDC, depending on the value of PWM signal. However, the PWM signal will change from 0 to 100%. Thus, the maximum voltage applied to the motor is not more than 9VDC ($35 \times 24 / 100$) in this case. This is evident from modified Figs. 5, 7 and 11.

4. **May be the grey frame of the figures from Matlab/Labview can be remove to white color, but it is no too much important.**

Response:

The figures are modified as per suggestions. Please see the revised version of the manuscript.

Nonlinear Control of Flexible Joint Robotic Manipulator with Experimental Validation

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This article addresses the design and implementation of robust nonlinear control approaches in order to obtain the desired trajectory tracking of flexible joint manipulator driven with DC geared motor. The nonlinear control schemes have been designed and implemented such that it locally stabilizes the closed loop system considering all the states as bounded. The system model has been derived using Euler-Lagrange approach. Two different approaches based on Sliding Mode Control (SMC) i.e. the traditional SMC and Integral SMC have been considered in the present study. To experimentally validate the proposed control laws, an electrically-driven single-link flexible manipulator has been designed and indigenously fabricated. The designed control algorithms have been developed and experimentally validated on the custom-developed platform. The results obtained both from MATLAB/Simulink and experimental platform verifies the performance of the proposed control algorithms.

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Keywords: flexible joint manipulator; modern control system; sliding mode control; integral sliding mode control

0 INTRODUCTION

The domain of robotics has recently drawn significant attention in scientific community [1]. In industrial applications, trajectory tracking control [2] of flexible joint manipulators has received considerable attention in the last two decades. Accurate end effector's position through reliable control approaches is critical for high-performance robotic applications accomplishing dangerous and tedious jobs [3]. Thus, a robotic manipulator is designed in a way to increase stiffness, in order to reduce undesirable oscillations of the end effector to track desired position. The stiffness can be achieved by using heavy materials, which may increase power consumption and decrease speed of operation [4]. The basic approach to maximize operational speed and minimize power consumption is to use lightweight flexible joint manipulator, however, subject to improving performance in endpoint tracking.

In [5], it has been emphasized, that joint flexibility and actuator dynamics should be considered while modeling as well as designing appropriate control law so as to achieve high performance. The literature focused on the design

of controllers for flexible joint manipulators is extensive. However, incorporating actuator dynamics in the modern control of end effector's position of a flexible joint manipulator is still a motivating problem in robotics community [6]. Some methodologies are reported to control the manipulator without taking into account the dynamics of the actuator. Examples include feedback linearization method [7], the singular perturbation approach [8], the integral manifold control [9], the passivity approach [10], the Proportional Derivative (PD) control approach [7] and the adaptive sliding mode technique [11]. The major limitation, which exists in the above mentioned research works is that, these schemes assumed torque as an input to the rigid link. However, it is highlighted in [4], that in electro-mechanical system, the actuator dynamics are of great importance, especially in a case in which a system has to deal with varying loads. Ailon and Lozano proposed an iterative control law to regulate the set-point of a flexible robotic system which is driven electrically and is subjected to model uncertainty [12]. Another research reported in [13] presents a controller based on adaptation law for a flexible joint robot to improve the

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trajectory tracking in the presence of time varying uncertainty in the system's parameters. Traditional backstepping approach has been applied successfully to solve the control problem of robots with flexible joints [14-16]. However, in these schemes, the torque is assumed to be directly applied to the links of the robot. In [16], a robust control law based on backstepping technique for tracking trajectory of manipulators has been proposed, where only armature current and link position are measured for feedback purpose. Despite these efforts [14-16], most of the reported backstepping techniques suffer from two limitations; The first one is that the systems under consideration did not have time varying parametric uncertainties. The second limitation is related with the level of complexity resulting by iterative differentiations of nonlinear virtual functions and thus leading to a complex and computationally expensive algorithm.

In the present article, the problem of robust control law design for accurate trajectory tracking of flexible joint manipulator is addressed by considering actuator dynamics, joint flexibility and viscous friction into account. Owing to computational simplicity and ease in implementation, the nonlinear law has been realized on custom developed hardware. The control input i.e. output of the controller is fed to the plant i.e. the DC motor and the flexible joint.

1 MATHEMATICAL MODELLING

To derive the mathematical model of the system, the considered parameters and their values are listed in Table 1.

Table 1. Description of System parameters

S#	Parameter	Symbol	Value	Unit
1	Link mass	m	1	Kg
2	Gears ratio	N	1	-
3	Armature resistance	R	1.6	Ω
4	Joint stiffness	k	14	N.m/rad
5	Motor torque constant	k_t	0.2	N.m/A
6	Back emf constant	B	0.001	N.m.s/rad
7	Link length	d	0.5	M
8	Gravitational acceleration	g	10	m/sec ²

9	Link moment of inertia	J_1	1	kg.m ²
10	Motor shaft inertia	J_2	0.3	kg.m ²
11	Armature inductance	L	0.01	H

The flexibility in joint is modeled as a linear torsional spring [16]. Using Euler Lagrange equation, the equations of motion for an electro-mechanical system can be derived. The total Kinetic Energy (K.E) and total Potential Energy (P.E) can be written as in (1) and (2):

$$K.E = \frac{1}{2}J_1\dot{q}_1^2 + \frac{1}{2}J_2\dot{q}_2^2 \quad (1)$$

$$P.E = mgd(1 - \cos q_1) + \frac{1}{2}k(q_1 - q_2)^2 \quad (2)$$

where q_1 and q_2 are angular positions of the link and the motor shaft respectively, while J_1 and J_2 are coefficients corresponding to link and motor inertia respectively. The Lagrange equation is,

$$L = K.E - P.E \quad (3)$$

Using (1) and (2), (3) can be written as,

$$L = \frac{1}{2}J_1\dot{q}_1^2 + \frac{1}{2}J_2\dot{q}_2^2 - mgd(1 - \cos q_1) + \frac{1}{2}k(q_1 - q_2)^2 \quad (4)$$

Lagrangian equations of motion w.r.t. motor and link angular position can be written as,

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_2} - \frac{\partial L}{\partial q_2} = 0 \quad (5)$$

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_1} - \frac{\partial L}{\partial q_1} = \tau - B\dot{q}_2 \quad (6)$$

while the torque produced is;

$$\tau = k_t I \quad (7)$$

where I is the armature current. Now taking derivatives of (5) and (6),

$$\begin{aligned} \frac{\partial L}{\partial \dot{q}_1} &= J_1 \dot{q}_1 \\ \frac{\partial L}{\partial \dot{q}_2} &= J_2 \dot{q}_2 \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_1} &= J_1 \ddot{q}_1 \\ \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_2} &= J_2 \ddot{q}_2 \end{aligned} \quad (9)$$

$$\frac{\partial L}{\partial q_1} = -Mgd(1 - \sin(q_1)) - k(q_1 - q_2) \quad (10)$$

$$\frac{\partial L}{\partial q_1} = k(q_1 - q_2)$$

Equations of motion for the mechanical subsystem are given as;

$$J_1 \ddot{q}_1 + mgd \sin(q_1) + k(q_1 - q_2) \quad (11)$$

$$J_2 \ddot{q}_2 - k(q_1 - q_2) = \tau - B\dot{q}_2 \quad (12)$$

The flexible joint manipulator consists of DC gear motor whose equation is derived by applying Kirchhoff's Voltage Law (KVL),

$$V = V_R + V_L + e \quad (13)$$

where V_R is the voltage across resistor, V_L is the voltage across inductor and e is back Electro Motive Force (emf) given by,

$$e = K_b \dot{q}_2 \quad (14)$$

where K_b is back emf constant. In this system, the input voltage to DC motor is the excitation input given as,

$$v = u = RI + L \frac{di}{dt} + K_b \dot{q}_2 \quad (15)$$

where u is motor input voltage. The nonlinear dynamics of the system can be formulated as,

$$J_1 \ddot{q}_1 + mgd \sin(q_1) + k(q_1 - q_2) \quad (16)$$

$$J_2 \ddot{q}_2 - k(q_1 - q_2) + B\dot{q}_2 = k_t I \quad (17)$$

Assumption 1: The parameters mentioned in (17) can be expressed as $R(\cdot) = R_0 + \Delta R(t)$, $L(\cdot) = L_0 + \Delta L(t)$, $K_b(\cdot) = K_{b0} + \Delta K_b(t)$.

Assumption 2: The parameters mentioned in (16) can be expressed as $J_2(\cdot) = J_{20} + \Delta J_2(t)$, $B(\cdot) = B_0 + \Delta B(t)$, $K_t(\cdot) = K_{t0} + \Delta K_t(t)$,

Remarks: In these realistic assumptions, the system parameters are split into a known nominal value and the unknown part which is considered as uncertainty. In practical control systems, parameters may not be unknown completely, their nominal values are exactly known to us, which is under consideration in this research.

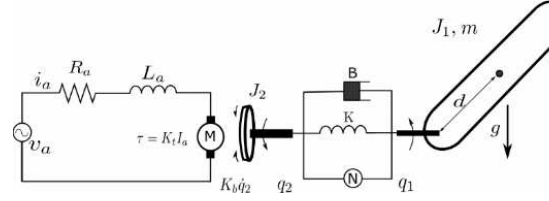


Fig. 1. Schematic diagram of flexible joint manipulator

The equations of motion of electrically driven flexible joint manipulator in state space form are represented below. The state vector contains angular position and angular velocity of the link side, angular position and angular velocity on the motor side and the motor armature current, i.e. $[x_1, x_2, x_3, x_4, x_5] = [q_1, \dot{q}_1, q_2, \dot{q}_2, I]$

$$\dot{x} = f(x) + g(x)u \quad x \in \mathbb{R}^5 \quad (18)$$

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -a \sin(x_1) - b(x_1 - x_3)$$

$$\dot{x}_3 = x_4 \quad (19)$$

$$\dot{x}_4 = O(x_1 - x_3) - \frac{B}{J_2} x_4 + dx_5$$

$$\dot{x}_5 = -\frac{R}{L} x_5 - \frac{k_b}{L} x_4 + \frac{1}{L} u$$

where $O = (k/J_2)$, $b = (k/J_1)$, $a = (mgd/J_1)$ and $d = (k_t/J_2)$. Here, angular position of the link is considered as an output. The system equations are complex and exhibit highly nonlinear dynamics thereby highlighting the challenge involved in the controller design.

2 CONTROLLER DESIGN

The control objective is to accurately control the position of flexible joint in finite time by control laws. The proposed control laws are based on two robust nonlinear control techniques i.e. Sliding Mode Control (SMC) and Integral SMC.

2.1. Sliding Mode Control Technique

SMC is a robust nonlinear control scheme, having powerful capability to reject disturbances and plant uncertainties. This control scheme works on the principle of altering continuously the configuration of the controller in order to keep the state variables on the sliding manifold. Due to this

phenomenon, undesirable chattering occurs. In mechanical parts, it produces high wear, while in electric parts, it may cause high heat losses [17]. In SMC, the controller comprises of two phases [18]; One is used to force the system trajectory to achieve sliding manifold, while second one is used to drive the states on sliding manifold toward desired equilibrium point. Consider a linear system given in (20).

$$\dot{\xi} = A\xi + Bu \quad (20)$$

where A and B represent coefficients of the system and ξ is the state vector. The sliding manifold for this system can be selected as:

$$S = c^T \xi \quad (21)$$

where c is the sliding mode control design parameters matrix. Differentiating (21), we get

$$\dot{S} = c^T \dot{\xi} = c^T (A\xi + Bu) \quad (22)$$

Since, $\dot{S} = 0$ during sliding mode, therefore

$$\dot{S} = c^T (A\xi + Bu) = 0 \quad (23)$$

In SMC, the control law u is a combination of two types of control given by,

$$u = u_{eq} + u_{dis} \quad (24)$$

where u_{eq} is the equivalent controller used to control the system states during sliding phase. Eq. (22) is solved to obtain the equivalent control given by,

$$u_{eq} = (c^T B)^{-1} (c^T A\xi) \quad (25)$$

while u_{dis} represents the switching controller that ensures the system stability.

$$u_{dis} = -k_1 \text{sign } S - k_2 S \quad (26)$$

where $k_1 > 0$ and $k_2 > 0$ are the design parameters and

$$\text{Sign}(S) = \begin{cases} 1 & \text{for } S > 0 \\ -1 & \text{for } S < 0 \end{cases}$$

Substituting (25) and (26) in (24),

$$u = (-k_1 \text{sign } S - k_2 S - (c^T A\xi))(c^T B)^{-1} \quad (27)$$

This is the control law u which is required for driving system's initial states to equilibrium point in a finite time. The proposed control method is now applied to a flexible joint manipulator. The sliding surface selected for the system is:

$$S = \left(\frac{d}{dt} + c\right)^{n-1} e \quad (28)$$

where $e = x_1 - x_d$ is the error between the actual and desired outputs. n is the relative degree of the system, c is a constant known as design parameter, i.e. $c > 0$.

$$S = \left(\frac{d}{dt} + c\right)^2 \left(\frac{d}{dt} + c\right)^2 e \quad (29)$$

After expanding (29),

$$S = \ddot{e} + 4\dot{e}c + 6\ddot{e}c^2 + 4\dot{e}c^3 + \dot{e}c^4 \quad (30)$$

Taking derivative of error variables, we get

$$e = x_1 - x_d$$

$$\dot{e} = \dot{x}_1 - \dot{x}_d$$

$$\ddot{e} = \ddot{x}_1 - \ddot{x}_d$$

$$\ddot{e} = -a \cos(x_1) \dot{x}_2 + a(x_2)^2 \sin(x_1) - b\ddot{x}_2 + b(O(x_1 - x_3) - \left(\frac{B}{J_2}\right)x_4 + dx_5) + b\ddot{f}_1 + \ddot{x}_d$$

For the sake of brevity, a symbol W is defined as

$$W = c^4 x_2 + 4c^3 \dot{x}_2 + 6c^2 \ddot{x}_2 + 4c(-a \cos(x_1) \dot{x}_2 + a x_2^2 \sin(x_1) + ab \sin(x_1) + b^2(x_1 - x_3) + bO(x_1 - x_3) - \frac{bB}{J_2} x_4 + bdx_5) - a \cos(x_1) \ddot{x}_2 + ax_2 \ddot{x}_2 \sin(x_1) + 2ax_2 \dot{x}_2 \sin(x_1) + ax_2^2 \cos(x_1) + abx_2 \cos(x_1) + b^2(x_2 - x_4) + bO(x_2 - x_4) - \left(\frac{BB}{J_2}\right)(O(x_1 - x_3)) - x_4 \frac{B}{J_2} + dx_5) + bd\left(\left(\frac{-R}{L}\right)x_5 - \frac{k_b}{L}x_4\right) - c^4 \ddot{x}_d - 4c^3 \ddot{x}_d + 6c^2 \ddot{x}_d - 4c \ddot{x}_d - \ddot{x}_d$$

Substituting and taking derivative of S ,

$$\dot{S} = W + bd \frac{1}{L} u \quad (31)$$

The control Law u thus obtained is,

$$u = \left(\frac{L}{bd}\right) (-W - k_1 \text{Sign}(S) - k_2 S) \quad (32)$$

The designed control law, when subjected to system for tracking purpose, resulted in undesirable chattering in the control input. For stability analysis, Lapanov function is defined as in (33) with its time derivative given in (34).

$$V = \frac{1}{2} S^2 \quad (33)$$

$$\dot{V} = S\dot{S} \quad (34)$$

Substituting (31) in (34), we get,

$$\dot{V} = S\{W + bd(1/L)u\} \quad (35)$$

Putting values in (35),

$$\dot{V} = -k_1|S| - k_2|S|^2 \quad (36)$$

Eq. (36) indicates that the derivative of Lapanov function is definite, which means that the system is asymptotically stable as long as both k_1 and $k_2 > 0$. Steady state error can be calculated by taking Laplace transform of (30).

$$E(s) = \frac{s^3 + 4cs^2 + 6c^2s + 4c^3}{s^4 + 4cs^3 + 6c^2s^2 + 4sc^3 + c^4}$$

where the inverse Laplace transform is

$$e(t) = e(0)\{e^{ct} + \frac{c^2t^2e^{-ct}}{2} + \frac{c^3t^3e^{-ct}}{6} + cte^{-ct}\} \quad (37)$$

The designed control input drives the steady state error $e(t)$ to the sliding surface $S = 0$ asymptotically i.e. $\lim_{t \rightarrow \infty} e(t) = 0$ with convergence rate given by (37) and remains there subject to positive gains of the controller [19].

2.2. Integral Sliding Mode Control Technique

To overcome the major drawbacks encountered in conventional SMC approach, the Integral term can be included in SMC. The main idea behind ISMC is high frequency switching gain, which is designed to force the state to achieve the integral sliding surface. Then, the integral action in the sliding manifold drives the states to the desired equilibrium point. It is an efficient control technique used to overcome several problems encountered in SMC approach such as high frequency chattering effect and its insensitivity property. It mitigates chattering and improves robustness and accuracy of the control system while guaranteeing the nominal control performance. The dynamics of flexible joint manipulator is explained in (19). The sliding manifold selected for the system is

$$s = \int e \left(c + \frac{d}{dt} \right)^n \quad (38)$$

where $e = x_1 - x_d$ is the error between the actual and desired outputs. n is the relative degree of the system, c is a constant known as design parameter, i.e. $c > 0$. After expanding, we take,

$$s = \int ec^5 + 5c^4e + 10c^3\dot{e} \quad (39)$$

Taking derivative of error variables,

$$e = x_1 - x_d$$

$$\dot{e} = \dot{x}_1 - \dot{x}_d$$

$$\ddot{e} = \ddot{x}_1 - \ddot{x}_d$$

$$\ddot{e} = -a \cos(x_1)\dot{x}_1 - b\dot{x}_1 + b\dot{x}_3 - \ddot{x}_d$$

$$\ddot{e} = -a \cos(x_1)\dot{x}_2 + ax_2^2 \sin(x_1) - b\dot{x}_2 +$$

$$b \left(O(x_1 - x_3) - \frac{B}{J_2}x_4 + dx_5 \right) + bf_1 - \ddot{x}_d$$

For the sake of brevity, defining a symbol Q i.e.

$$Q = c^5e + 5c^4\dot{e} + 10c^3(\dot{x}_2 - \ddot{x}_d) + 10c^2(-a \cos(x_1)x_2 - b\dot{x}_2 + b\dot{x}_4 - \ddot{x}_d) + 5c(-a \cos(x_1)\dot{x}_2 + ax_2^2 \sin(x_1) - b\dot{x}_2 + b\dot{x}_4 - \ddot{x}_d) - a \cos(x_1)\dot{x}_2 + ax_2\dot{x}_2 \sin(x_1) + 2ax_2\dot{x}_2 \sin(x_1) + ax_2^3 \cos(x_1) - b\ddot{x}_2 + bO(x_2 - x_4) - \frac{bB}{J_2} \left(O(x_1 - x_3) - \frac{B}{J_2}x_4 + dx_5 \right) + bd \left(\frac{-R}{L}x_5 - \frac{k_b}{L}x_4 \right) - \ddot{x}_d \pi r^2$$

Putting the values and taking derivative of sliding surface, we obtain

$$\dot{s} = Q + \frac{bd}{L}u \quad (40)$$

The control law u thus obtained is,

$$u = \frac{L}{bd}(-Q - k_1 \text{Sign}(s) - k_2s) \quad (41)$$

For stability analysis, the Lapanov function is given by

$$V = \frac{1}{2}s^2 \quad (42)$$

Taking time derivative of (42)

$$\dot{V} = s \dot{s} \quad (43)$$

Substituting (40),

$$\dot{V} = s \left\{ Q + \frac{bd}{L}u \right\} \quad (44)$$

After putting values,

$$\dot{V} = -k_1|s| - k_2s^2 \quad (45)$$

ISMC ensures asymptotic stability in finite time. The steady state error between the desired and the actual trajectory is calculated by considering integral sliding manifold as

$$S = \int c^5 e + 5c^4 e + \ddot{e} + 5c\ddot{e} + 10c^2\ddot{e} + 10c^3\dot{e}$$

Assuming the condition $S = 0$ and by taking the Laplace transform,

$$E(s) = \left\{ \frac{10c^3s + 10c^2s^2 + 5cs^3 + s^4}{c^5 + 5c^4s + 10c^3s^2 + 10c^2s^3 + 5cs^4 + s^5} \right\}$$

Now taking inverse Laplace transform,

$$e(t) = e(0)e^{-ct} \left\{ 1 + \frac{c^2t^2}{2} + \frac{c^3t^3}{6} - \frac{c^4t^4}{6} + ct \right\} \pi r^2 \quad (46)$$

Equation (46) indicates the steady state error with its convergence rate, which means that it approaches to zero in finite time i.e. $\lim_{t \rightarrow \infty} e(t) = 0$

3 SIMULATION AND EXPERIMENTAL RESULTS

The performance and effectiveness of the designed controllers for desired tracking performance of flexible joint manipulators are verified through results gathered from simulation carried out in MATLAB/Simulink and custom developed platform. The setup is a single-link flexible joint manipulator shown in Fig. 2.

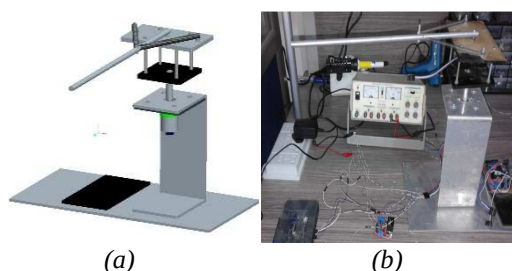


Fig. 2. Custom developed experimental setup:
(a) CAD model (b) Fabricated prototype

The joint consists of aluminum sheet tilted in such pattern that link is connected to a motor shaft through the sheet by two torsional springs. The actuator is a 24V DC gear motor, actuated with Pulse Width Modulated (PWM) signal, which converts the control effort into amplified voltage using H-Bridge L298 and MyRio-1900 controller kit. DC gear motor drives the aluminum plate directly. Two quadrature encoders provide feedbacks of the angular positions corresponding to the motor and the link. The rotary encoder is attached to the flexible joint so as to provide the

joint position independent of the motor's position.

Real-time control implementation is carried out in LabVIEW connected with external hardware using MyRio-1900 data acquisition device. Two types of trajectories are tested for tracking purpose; step and sinusoidal. Simulation and experimental results corresponding to both types of input are presented and discussed below:

3.1. Step Tracking Using SMC and ISMC Laws

In this case, the desired trajectory is a constant value function. It has been observed that SMC produces undesirable chattering phenomena in control input, which can make the system unstable at any time. The designed control law, when subjected to system for tracking purpose, practically affects system's mechanical and electric parts. This adverse phenomenon can be eliminated using ISMC.

Fig. 3 presents simulation results where the designed control law is tracking a unit step function of 60° amplitude. The angular position shown in the figure is basically position of the flexible joint. As evident from the results that response of ISMC is better than SMC in terms of steady state error. However, the transient response of SMC shows good compliance with reference to the input.

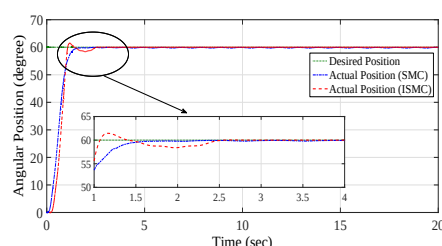


Fig. 3. Responses of step tracking in simulation by control laws based on SMC and ISMC

Fig. 4 shows the control input applied to the system in simulation. As clear from the results that control input has undesirable chattering phenomenon in case of SMC, which can be harmful for electrical and mechanical parts of the system.

Fig. 5 presents results obtained from experimental platform for tracking performance of the flexible joint manipulator using SMC approach. The control input used for tracking purpose is also shown in the form of percentage of PWM signal applied to the motor. The results

clearly show that with SMC approach, flexible joint manipulator can reasonably track the desired trajectory, however, at the expense of undesirable chattering in the control input.

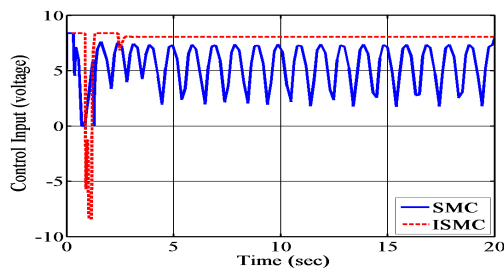


Fig. 4. Simulation results for the control input applied to SMC and ISMC (Step references)

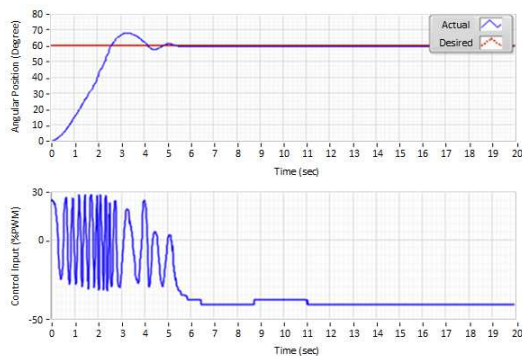


Fig. 5. Experimental results of trajectory tracking and the control effort using SMC

Fig. 6 shows tracking error between actual trajectory and desired trajectory in case of SMC. The control law drives the steady state error to zero within 5 sec.



Fig. 6. Experimental results of steady state error using SMC

Fig. 7 shows experimental results of ISMC based law where the tracking performance of flexible joint manipulator and the control input are presented. The results clearly show that using ISMC approach, the manipulator tracked the desired trajectory with reasonable transient as well as steady state performance.

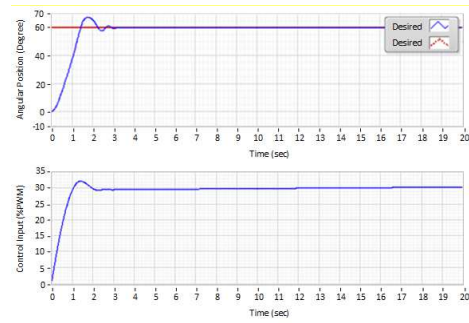


Fig. 7. Experimental results of the trajectory tracking and the control effort using ISMC

Fig. 8 shows trajectory tracking error between the actual and the desired positions, which is very small when compared to SMC (see Fig. 6).

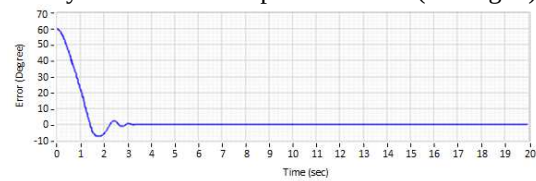


Fig. 8. Experimental results of Steady state error using ISMC

3.2. Sinusoidal Input Tracking using SMC and ISMC

In this case, the desired trajectory is time-dependent sinusoidal function. The amplitude of the desired trajectory is taken as 60° with a frequency set to as low as 0.0048Hz for smooth tracking. In case of ISMC, results collected both from simulation and experimental platform reflect that chattering is reduced due to the continuous control action while preserving robustness and accuracy of the controller to high degree. This observation is in consistent with the theoretical advantage of ISMC over the traditional SMC approach.

Fig. 9 presents simulation results where sinusoidal signal representing the angular position of the flexible joint manipulator serves as the reference for trajectory tracking. Results demonstrate that both the control laws exhibit good settling time and zero steady state error.

Fig. 10 shows simulated control input used to drive flexible joint manipulator in order to track the desired trajectory. As is clearly evident from the figure that, in case of SMC, the control input has undesirable chattering phenomena, which is an inherent property of SMC.

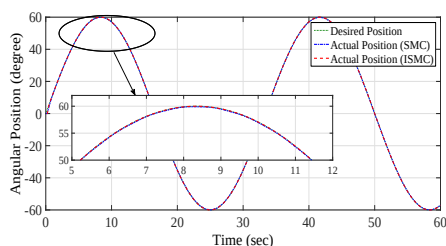


Fig. 9. Simulation results of sinusoidal input tracking for SMC and ISMC

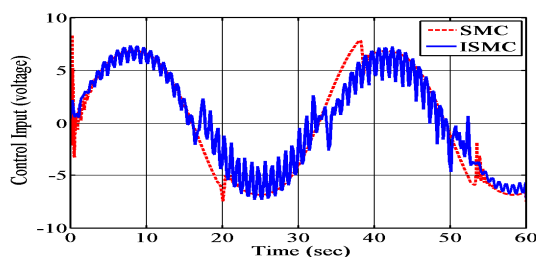


Fig. 10. Simulation results for the control input applied to SMC and ISMC (Sine reference)

Fig. 11 illustrates desired trajectory tracking of flexible joint manipulator obtained through experimental platform using SMC. This figure shows tracking performance of the manipulator in real time along with control input, which was used for the said purpose. These results confirm adequate tracking performance at the expense of undesirable chattering in the control input as observed in simulation (see Fig. 10).

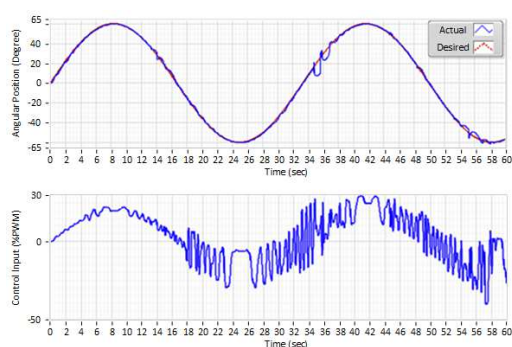


Fig. 11. Experimental results of trajectory tracking and control effort using SMC

Fig. 12 shows error in tracking between the actual trajectory and the desired trajectory when the manipulator is subjected to SMC approach in real time.

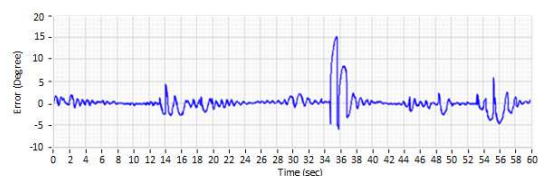


Fig. 12. Experimental result of steady state error using SMC

Fig. 13 presents experimental results of desired trajectory tracking of the manipulator based on ISMC law. The control input used by system for tracking purpose is also shown. Over performance of ISMC over SMC in terms of tracking performance is obvious while comparing Fig. 11 and Fig. 13. Also, ISMC offers negligible steady state error between the actual trajectory and the reference trajectory as depicted in Fig. 14.

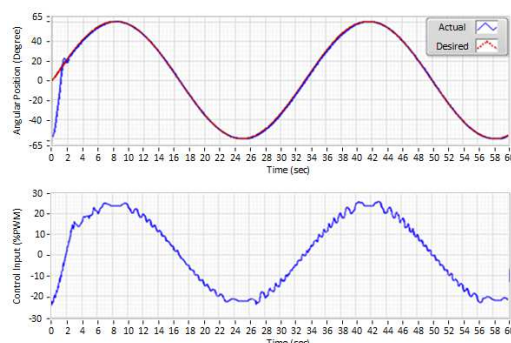


Fig. 13. Experimental results of trajectory tracking and control effort using ISMC

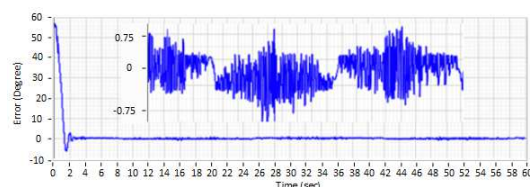


Fig. 14. Experimental results of steady state error using ISMC

4 CONCLUSION

This research addresses the behavior of flexible joint manipulator including actuator dynamic for nonlinear control approaches. The model of the manipulator has been derived using Euler-Lagrange method, which is then used to study the effectiveness of the nonlinear control techniques for tracking performance. The nonlinear approaches under study include MSC

and ISMC. Simulation has been conducted in MATLAB/Simulink while experimental validation of the designed control law has been carried out on a custom developed platform consisting of single link flexible joint manipulator. SMC approach resulted in chattering phenomena both in simulation and experimental results. This problem was eliminated by devising a control law based on ISMC, which also reduces steady state error. Experimental results obtained in the present research can find enormous potential in application domains involving flexible robotic manipulators including but not limited to; medical, space and industrial automation.

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