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Model free sliding mode control for serial robot manipulator: rigid and elastic joint robot

***Abstract**. The control of robotic manipulators with flexible joints is still a challenging problem for researchers. In this paper, a comprehensive investigation into the dynamic modeling and control of a two-degree-of-freedom (2-DOF) robot, both with and without flexible joints, is presented. Firstly, the mathematical modeling of the considered robot is presented to understand its dynamical behavior. Then, two types of controllers, namely the intelligent Proportional-Derivative (iPD) and the intelligent Proportional-Derivative Sliding Mode (iPDSM), are applied to the considered robot and purposefully compared in terms of robustness, setting time, and overshoot while tracking various trajectories. Two cases are considered in the simulation tests: In the first case, trajectory tracking is performed with no elasticity at the joints. However, in the second case, elasticity and damping are added. To verify the effectiveness of the proposed controllers, simulation analyses through MATLAB are carried out. Based on the obtained results, iPDSM provides satisfying results compared to iPD. Namely, iPDSM accurately generates the angular motion of the robot's flexible joints, allowing the robot to properly track the prescribed trajectory independently of any information derived from the mathematical model, even in the presence of Stribeck friction and elasticity.*

Streszczenie.** Sterowanie robotami manipulacyjnymi wyposażonymi w elastyczne przeguby nadal stanowi wyzwanie dla badaczy. W artykule przedstawiono kompleksowe badanie dynamicznego modelowania i sterowania robotem o dwóch stopniach swobody (2-DOF), zarówno z elastycznymi przegubami, jak i bez nich. W pierwszej kolejności zaprezentowano model matematyczny rozpatrywanego robota, pozwalający zrozumieć jego zachowanie dynamiczne. Następnie do rozpatrywanego robota stosowane są dwa typy sterowników, a mianowicie inteligentny tryb proporcjonalno-różniczkujący (iPD) i inteligentny tryb proporcjonalno-różniczkujący (iPDSM), które są stosowane do rozpatrywanego robota i celowo porównywane pod względem wytrzymałości, czasu ustawiania i przeregulowania podczas śledzenia różnych trajektorie. W badaniach symulacyjnych uwzględniane są dwa przypadki: W pierwszym przypadku śledzenie trajektorii odbywa się bez elastyczności w stawach. Jednak w drugim przypadku dodaje się elastyczność i tłumienie. W celu sprawdzenia efektywności proponowanych sterowników przeprowadzane są analizy symulacyjne w programie MATLAB. Na podstawie uzyskanych wyników iPDSM zapewnia satysfakcjonujące wyniki w porównaniu do iPD. Mianowicie iPDSM dokładnie generuje ruch kątowy elastycznych przegubów robota, umożliwiając robotowi prawidłowe śledzenie zadanej trajektorii niezależnie od jakichkolwiek informacji pochodzących z modelu matematycznego, nawet w obecności tarcia i elastyczności Stribecka.* (Sterowanie trybem swobodnego przesuwania dla manipulatora robota szeregowego: robo ze sztywnym i elastycznym przegubem***)

Keywords: Elastic joint manipulator, under actuated, Model Free, Sliding Mode, tracking control
Słowa kluczowe: Manipulator elastycznego złącza, niedostatecznie uruchomiony, bez modelu, tryb ślizgowy, kontrola śledzenia

Introduction

The study of flexible joint robots regarding their modeling and control has been amajor topic for several decades. Flexibility can be considered in the links and joints of robot manipulators. Robot manipulators with flexible joints are very complex mechanical systems that, due to the flexibility of the joints, have a greater number of degrees of freedom (DOF) than the control input, making them difficult to control [8] [5]. Contrary to the rigid case, the dynamic model of robot manipulators with elastic joints requires twice as many generalized coordinates to exhaustively characterize the configuration of all rigid bodies (motors and links) composing the manipulator [22]. One of the main challenges in this regard is to design a controller that can manage both oscillatory behavior, caused by mechanical flexibility, and motor constraints like torque or speed limits. Therefore, several research efforts have been investigated in this topic, such as electrically driven flexible-joint manipulators using the voltage control strategy in [12] and [8] with an adaptive control, a stable neural network-based observer, and an observer-based setpoint controller in [1] and [4]. Moreover, singular perturbation is widely applied because of its ability to describe the elastic joint model in [22], [27], [16], and [23]. In [18] and [10], the state-dependent Riccati equation was implemented. In [20], backstepping control is used. MPC was applied in [33] using neural networks, learning model predictive control, and time-varying dynamics in [21], with a flexible link in [11], and with a singular perturbation approach in [13].

Among these robust algorithms, we use the Model Free Control (MFC); a recently introduced approach proposed by Fliess et al. has gained significant attention for its practical application in various processes. This algorithm demonstrates promising results by utilizing an online updated ultra-local model of the system, which relies solely on input and output measurements. Typically, MFC incorporates proportional (P), proportional-integral (PI), proportional-derivative (PD), or proportional integral-derivative (PID) controllers along with compensated terms to account for estimation errors. The MFC controller gains can be adjusted based on uncertainty estimations, resulting in improved performance compared to classical controllers. This control method operates independently of any specific model for determining the control law. Ultra-local model-free control is a control approach that emphasizes utilizing a local understanding of the system's behavior instead of relying on a global mathematical model. It focuses on controlling the system based on direct observations and data collected within a specific local region. Model-free control has already demonstrated a remarkable range of successful applications in various fields such as quadrotor attitude control [30], two-wheeled inverted pendulum [32], flapping-wing flying robot [7], robotic exoskeleton [31], experimental green- houses [19], glycemia regulation in type-1 diabetes [25], ther- mal processes [6], wheeled autonomous vehicles [9], twin- rotor aerodynamic systems [26], and many more. Hassane Abouaïssa et al. reported application of the MFC to the con- trol of multi/input multi/output (MIMO) robot manipulators [2]. Tolgay KARA and Ali Hussien MARY present a tracking con- trol of a nonlinear robotic manipulator using an adaptive PD- SMC [15]. Many of these references provide practical implementations, and some are even associated with patents. Regarding the Flexible Joint Robots, many researchers have used the MFC. Min Jun Kim et al. used the Model-free Friction Observers with Torque Measurements [17]. John T Agee et al.introduce a computationally efficient and model-free intelligent proportional-integral (iPI) controller [3].Jorge Villagra et al.investigated the Data-driven fractional PID control [29]. Maolin Jin et al. propose a model-free robust adaptive controller with a time delay estimation [14]. In this paper, a novel model-free proportional-derivative controller based on the sliding mode approach is examined for an elastic joint robot. The study highlights two main features: Firstly, the proposed scheme is entirely model-free, meaning it solely relies on input and output measurements to enhance the system's performance, without relying on any information from the mathematical model. The remainder of this paper, after a brief review on the elastic joint robots, is organized as follow. Section describes the modeling of the dynamic model of 2- DOF serial manipulator with joint elasticity including the stribeck friction model. Section is dedicated to the proposed MFPDSMC controller with the stability analysis. Section 0.1 presents simulation results of the proposed controller. Finally, some conclusions are presented in the closing section.

Dynamic Modeling Of Two Degree Of Freedom Robot Manipulator

A. Rigid joint Robot:

Consider the general form of dynamic equation of a n axis rigid robot can be presented as:

(1) $$\Gamma + \Gamma_f = M(q)\ddot{q} + N(q,\dot{q})\dot{q} + P(q)q$$

In which $M(q)$ is the inertia matrix, $N(q, q^{\cdot})$ is the vector consists of terms due to the centrifugal and Coriolis forces as well as viscous joint friction, $P(q)$ is the gravity forces and Γ the input torques or force. .$\Gamma_f = \left[\Gamma_{f1}\Gamma_{f2}\right]^T$ is the vector of dry friction torque.

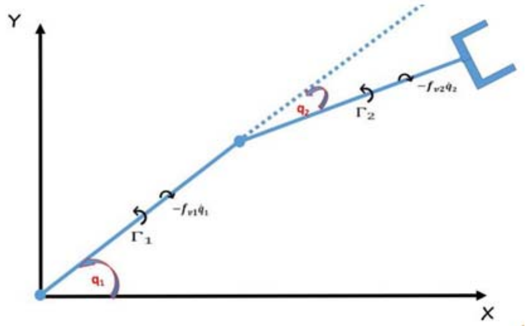

Fig. 1. Schematic representation of two links manipulator

In fact, the flexibility in the joints is always present and the assumption of the rigidity of joints is only a simplistic as-sumption.

B. Elastic joint Robot:

It is a well-known fact that joints in any mechanism exhibit some degree of clearance, flexibility, and friction. To simplify the model, these factors are often neglected during the modeling process. However, for a more accurate repre- sentation, it is beneficial to consider the flexibility of the joints in a robot or mechanism.

The flexibility of a joint can be represented by introducing additional components such as a mass and a spring and sometimes by adding a damper, which are connected to the joint.

The purpose of the elastic joint model is to represent the elasticity concentrated in the mechanical transmission chain between the motors and the rigid segments driven by the joint torques. From the modelling viewpoint, the above deformation can be characterized as being concentrated at the joints of the manipulator, and thus we often refer to this situation by the term elastic joints in lieu of flexible joints.

Consider the dynamic behavior of a two-link arm with elastic joints, as depicted in Fig. 2. This system also takes into account the presence of dry friction. The equations of motion governing the system as [24] are as follows:

(1) $\Gamma = M_a\ddot{q}_a + N_a\dot{q}_a + K_t(q_{a-}q_b) + B_t(\dot{q}_a - \dot{q}_b) - \Gamma_f$

(2)

$$0 = M_b(q_b)\ddot{q}_b + N_b(q_b,\dot{q}_b)\dot{q}_b \quad + P_b(q_b)q_b + K_t(q_b - q_a) + B_t(\dot{q}_b - \dot{q}_a)$$

where $q_a = [q_{a1}q_{a2}]^T, \Gamma = [\Gamma_1\Gamma_2]^T$ are the vector of angular positions and torques of the actuators, $M_a = diag(I_{a1}, I_{a2})$ and $N_a = diag(f_{v1}, f_{v2})$ are the matrices of motor inertia and viscous friction coefficients, $K_t = diag(k_{t1}, k_{t2})$ and $B_t = diag(b_{t1}, b_{t2})$ are the matrices of stiffness and damping constants of the joints,$\Gamma_f = \left[\Gamma_{f1}\Gamma_{f2}\right]^T$ is the vector of dry friction torque. . The matrices of arm inertia M_b, Coriolis/centripetal terms N_b and gravitational terms P_b can be written in the form:

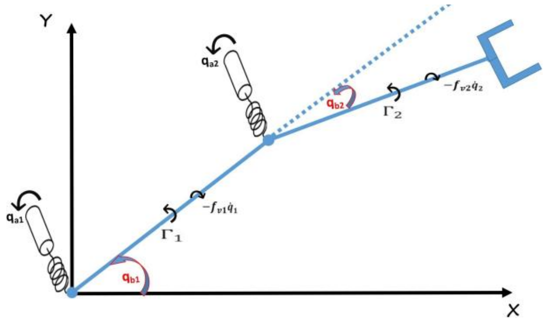

Fig. 2. Schematic representation of two links elastic joint manipulator

(4) $$M_b = \begin{bmatrix} c_1 + 2c_2\cos(q_{b2}) & c_3 + c_2\cos(q_{b2}) \\ c_3 + c_2\cos(q_{b2}) & c_3 \end{bmatrix}$$

(5) $$P_b = \begin{bmatrix} -c_4\frac{\sin(q_{b1})}{q_{b1}} - c_5\frac{\sin(q_{b2})}{q_{b2}} & -c_5\frac{\sin(q_{b12})}{q_{b12}} \\ -c_5\frac{\sin(q_{b12})}{q_{b12}} & -c_5\frac{\sin(q_{b12})}{q_{b12}} \end{bmatrix}$$

(6) $$N_b = \begin{bmatrix} 2c_2\dot{q}_{b2}\sin(q_{b2}) & c_2\dot{q}_{b2}\sin(q_{b2}) \\ -c_2\dot{q}_{b1}\sin(q_{b2}) & 0 \end{bmatrix}$$

with

$q_{b12} = q_b1 + q_b2$, $c_1 = m_1r_1^2 + I_1 + m_2L_1^2 + m_2r_2^2 + I_2$, $c_2 = m_2L_1r_2$, $c_3 = m_2r_2^2 + I_2$, $c_4 = m_1gr_1 + m_2gL_1$, $c_5 = m_2gr_2$.

The Stribeck friction model describes the dry friction torques as follows:

(7) $$\Gamma_{fi} = \begin{cases} \Lambda_{ai} & \text{if } \quad |\dot{q}_{ai}| > 0\text{(slip)}, \\ \Lambda_{ai} & \text{if } \quad \dot{q}_{ai} = 0\text{(stick)}, \end{cases}$$

where

(8) $$\Lambda_{ai} = \left[\Gamma_{fci} + (\Gamma_{fsi} - \Gamma_{fci})e^{-\left(\frac{\dot{q}_{ai}}{vs}\right)^2}\right]sign(\dot{q}_{ai}),$$

$$\Lambda_{bi} = \min(|\Gamma_i - \Gamma_{ti}|, \Gamma_{fsi})sign(\Gamma_i - \Gamma_{ti}).$$

Controller design

In this section, we will first control the rigid robot and then proceed to control the elastic joint robot using the proposed controllers.

A. Model-Free Control:

is a nonlinear control approach in which the mathematical model of a system is substituted with an ultra-local model equation comprising a small number of parameters. These parameters are updated solely based on the input-output information of the system. The expression for ultra-local modeling is provided by

(9) $$y^{(n)} = F + \alpha\tau$$

Where y is the output of the plant; n is the order of time derivation of t F is the unknown part of all exogenous perturbations and unmodeled dynamics such as nonlinearities and uncertainties.he output (generally is chosen equal to 1 or 2); τ is the control torque; α is an arbitrary constant parameter chosen such that $y^{(n)}$ and $\alpha\tau$ have the same size

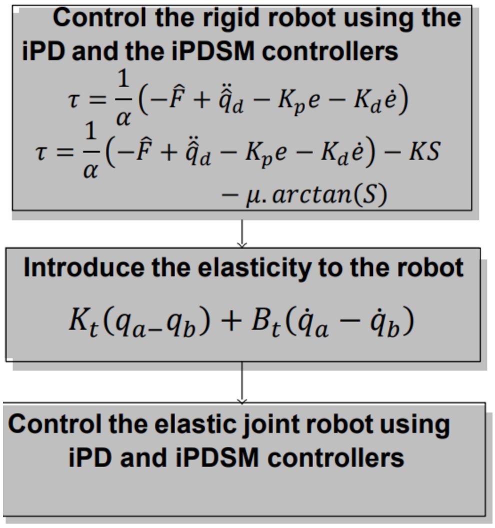

Fig. 3. The flowchart of the protocol of the control

By taking $n = 2$, The estimate of F is defined as follows

(10) $$\hat{F} = \hat{y}^{(2)} - \alpha\tau$$

where $\hat{y}$ is the estimate of y.

To estimate y, diverse strategies relying on algebraic methods have been employed, as discussed in [15]. To circumvent potential algebraic loop problems, we utilize a combination of a first-order derivative and a low-pass filter to produce the variable $\hat{y}$:

(11) $$H = \left(\frac{K_1 s}{T_1 s+1}\right)^2$$

B. The proposed controller:

a) The intelligent Proportional Derivative (i-PD) control law can be defined as follows:

(12) $$\tau = \frac{1}{\alpha}(-\hat{F} + \ddot{q}_d - K_p e - K_d \dot{e})$$

where K_p and K_d are the proportional and derivative gains. and

(13) $$e = q(t) - q_d(t)$$

The intelligent PD Sliding Mode Control (i-PDSM). A typical classical form of sliding mode control is:

(14) $$\tau = \tau_{eq} + \tau_{dis}$$

In the given context, the value of τ_{eq} relies on the mathematical model of the system, while τ_{dis} represents a discontinuous control input. This study aims to propose an i-PD sliding mode control approach:

(15) $$\tau_{eq} = \frac{1}{\alpha}(-\hat{F} + \ddot{q}_d - K_p e - K_d \dot{e})$$

The discontinuous control τ_{dis} is considered as follows:

(16) $$\tau_{dis} = -KS - \mu.arctan(S)$$

in which S is the sliding surface to avoid the problem of chattering, we have chosen atan as the function:

(17) $$S = \dot{e} + \lambda e$$

and

$$\arctan(S,\lambda) = \begin{cases} -1, & if\ S < -\gamma \\ S\gamma & if\ |S| \le \gamma \\ 1, & if\ \ S > \gamma \end{cases}$$

The i-PDSMC has the following form:

(18) $$\tau = \frac{1}{\alpha}(-\hat{F} + \ddot{q}_d - K_p e - K_d \dot{e}) - KS - \mu.arctan(S)$$

Using equation (9), the system model can be rewritten as

(19) $$\ddot{q}(t) = F + \alpha\tau$$

By making a good estimate of F , i.e., $\hat{F}_i \Rightarrow F_i$. Combining equations (18) and (13) yields

(20) $$\ddot{e} + K_p e + K_d \dot{e} + KS + \mu.arctan(S) = 0$$

Observe that we arrive at a linear differential equation with constant coefficients. The estimated component of F, which handles the unknown aspects of external disturbances and unmodeled dynamics, simplifies the tuning of K_p and K_d to achieve desirable performance. This presents a significant advantage compared to the conventional PD controller.

0.1 Stability Analysis

The main feature of this work is that the derivation of the control laws does not require any knowledge of the system model.

Define the Lyapunov function V as

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

The time derivative of V is

(22) $$\dot{V} = S\dot{S}$$

Introducing a state variable error such as

(23) $$x_1 = e$$

(24) $$x_2 = \dot{e}$$

The sliding surfaces are rewritten using the new state variables

(25) $$\dot{S} = \dot{x}_2 + \lambda x_2$$

The time derivative of S is

(26) $$\dot{S} = \dot{x}_2 + \lambda x_2$$

Since the same procedure is used to estimate F_i, $\ddot{q}_i$ and , we can define the estimation error e_{est} as

(27) $$e_{est} = F - \hat{F} = \ddot{q} - \ddot{\hat{q}} = \ddot{q}d - \ddot{\hat{q}}_d$$

Introducing (13) in (20), we get

(28) $$\ddot{q} = F - \hat{F} + \ddot{q}_d - K_p e - K_d \dot{e} - \alpha(KS - \mu.arctan(S))$$

We have the time derivative of x_2 :

(29) $$\dot{x}_2 = \ddot{q}(t) - \ddot{q}_d$$

Replacing by (29) in (28) , we get

(30) $$\dot{x}_2 = F - \hat{F} + (\ddot{q}_d - \ddot{\hat{q}}_d - K_p e - K_d \dot{e} - \alpha(KS - \mu.arctan(S))$$

From the statements (24), (25), (28), (27) , the expression (30) follows :

(31) $$\dot{x}_2 = -K_p x_1 - K_d x_2 - \alpha\big(KS + \mu.arctan(S)\big)$$

Considering (31) , (26) can be rewritten as

(32) $\dot{S} = -K_p x_1 - K_d x_2 - \alpha\big(KS + \mu.\arctan(S)\big) + \lambda x_2$

Using (32), $\dot{V}$ can be expressed at this stage:

$$\dot{V} = S\big[-K_p x_1 - K_d x_2 - \alpha\big(KS + \mu.\arctan(S)\big) + \lambda x_2\big]$$

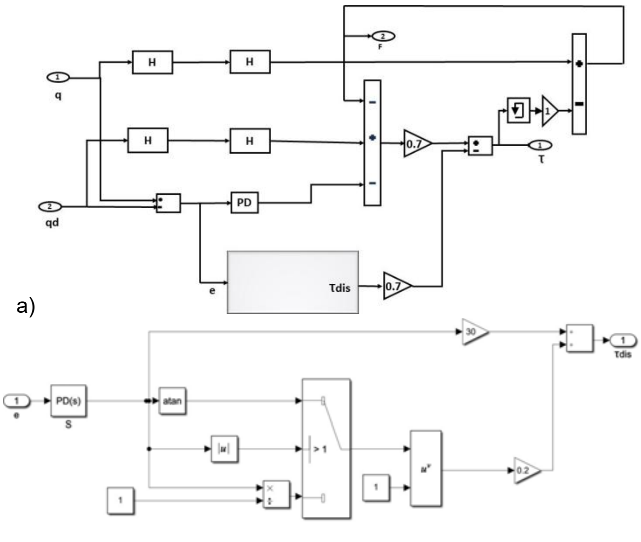

Fig. 4. (a) Block diagram of the i-PDSM control structure. (b) Block diagram of the i-PDSM discontinuous term

Two cases are considered at this stage:

case 1: if $|S| \le \gamma$

With $\gamma > 0$ is the boundary layer thickness of $arctan(S)$ then:

(33) $\dot{V} \le S\big[-K_p x_1 - K_d x_2 - \alpha(KS + S\gamma) + \lambda x_2\big]$

Yet

(34) $\dot{V} \le -\alpha[\left(K + \frac{\mu}{\gamma}\right) S^2$

With

(35) $-K_p x_1 - (K_d - \lambda) x_2 = 0$

Equation (35) is verified if

(36) $x_1 = e^{-\left(\frac{Kp}{\lambda - K_d}\right)t}$

To guarantee $x_1 \Rightarrow 0$, we must have

(37) $\frac{K_p}{\lambda - K_d} > 0$

Consequently

(38) $K_p > 0 \ and\ \lambda > Kp$

For the first part of $\dot{V}$, $V < 0$ if and only if

(39) $\alpha \neq 0 \ and\ K > -\frac{\mu}{\gamma}$

case 2: if $|S| > \gamma$

(40) $\dot{V} \le S\big[-K_p x_1 - K_d x_2 - \alpha K S_{+} \mu\alpha + \lambda x_2\big]$

Additionally

(41) $\dot{V} \le -\alpha K S^2$

With

(42) $-K_p x_1 - K_d x_2 - \mu\alpha + \lambda x_2 = 0$

o check equations (42), x_2 must be equal to

(43) $x_2 = \frac{K_p x_1 + \mu\alpha}{\lambda - K_d}$

Then

$$K_p \neq \lambda;\ \forall \mu, \alpha > 0;\ x_2 = \frac{K_p x_1 + \mu\alpha}{\lambda - K_d}$$

Simulation results

This section presents the performance evaluation of the proposed iPD and iPDSM controllers by means of simulation (Matlab/ Simulink) using Simulation Data Inspector instruction. The reference trajectory is a Motion generation (straight trajectory with angular point) and sine wave. The physical parameters of the flexible manipulator are taken from [28] and are given in table 1.

Table 1. System Nomenclature [28]

Symbol	Description	Value
L_1, L_2	Lengths of robot arms (m)	$0.5, 0.5$
m_1, m_2	Masses of robot arms (kg)	$15, 9$
I_1, I_2	Inertia of robot arms relative to the centre of mass (kgm^2)	$0.313, 0.1878$
r_1, r_2	Distances between joints and mass centers (m)	$0.25, 0.25$
f_{v1}, f_{v2}	Coefficients of viscous friction (Nms/rd)	$1/7, 1/7$
g	Gravitational acceleration (m/s^2)	9.81
I_{a1}, I_{a2}	Inertia of actuator rotors (kgm^2)	$2.71, 0.50$
k_{t1}, k_{t2}	Stiffness constant (Nm/rd)	$6.4, 1.2$
b_{t1}, b_{t2}	Damping constant (Nms/rd)	$20.4, 3.8$
$\Gamma_{fs1}, \Gamma_{fs2}$	Static friction Torque (Nm)	$6, 3$
$\Gamma_{fc1}, \Gamma_{fc2}$	Coulomb friction torque (Nm)	$4, 2$
vs	Sliding speed coefficient (m/s)	0.1

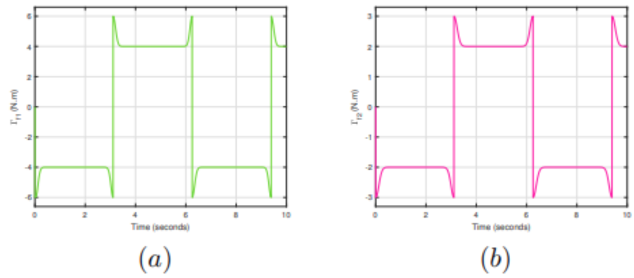

Fig. 5. Curves of the Stribeck frictions

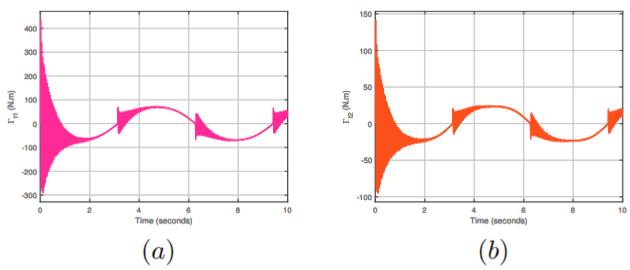

Fig. 6. Curves of the transmition torque (Elasticity & Damping)

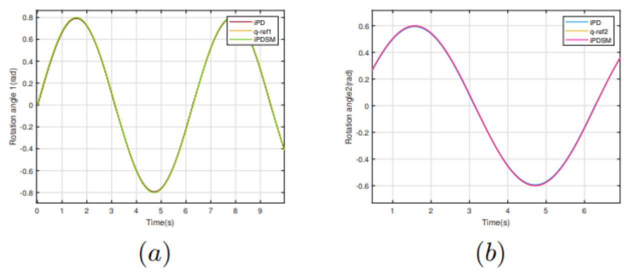

Fig. 7. The angular position of the first and the second link

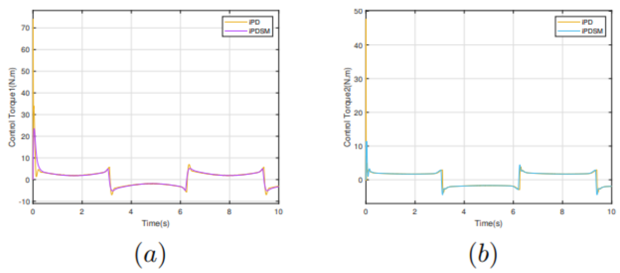

Fig. 8. The control input of first and the second link

the controller parameters applied for the rigid robot are:
i-PD:

$$K_p = \begin{bmatrix} 45 & 0 \\ 0 & 45 \end{bmatrix}, K_d = \begin{bmatrix} 45 & 0 \\ 0 & 45 \end{bmatrix}, \& = \begin{bmatrix} 90 \\ 100 \end{bmatrix}$$

i-PDSM:

$$K_p = \begin{bmatrix} 45 & 0 \\ 0 & 45 \end{bmatrix}, K_d = \begin{bmatrix} 45 & 0 \\ 0 & 45 \end{bmatrix}, \& = \begin{bmatrix} 90 \\ 100 \end{bmatrix},$$
$$\mu = \begin{bmatrix} 0.02 \\ 0.02 \end{bmatrix}, \lambda = \begin{bmatrix} 4 \\ 4 \end{bmatrix}, K = \begin{bmatrix} 40 \\ 4 \end{bmatrix}$$

Rigid joint Robot:
The figures Fig. 7, Fig. 8, Fig. 9 display the simulation outcomes for the rigid joint robot when controlled by the iPD and iPDSM controllers. The tracking of angular articulation exhibits excellent performance. Control torque is confined within the range of]-10;10 [(N.m), although there is a noticeable overshoot in the initial phase for the iPD torque. The simulation error does not surpass the threshold of 0.03 (N.m).

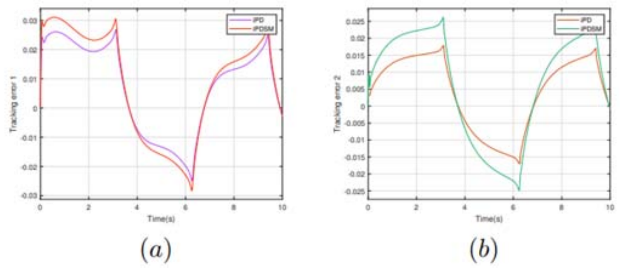

Fig. 9. Curves of the joint position error

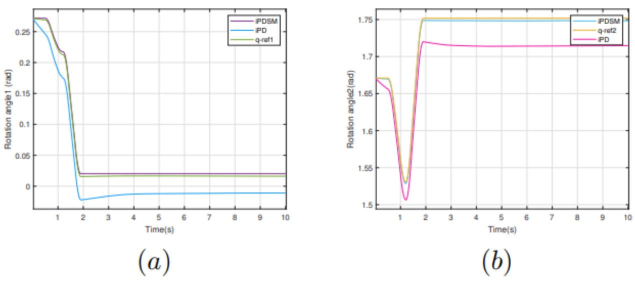

Fig. 10. The angular position of the first and the second link

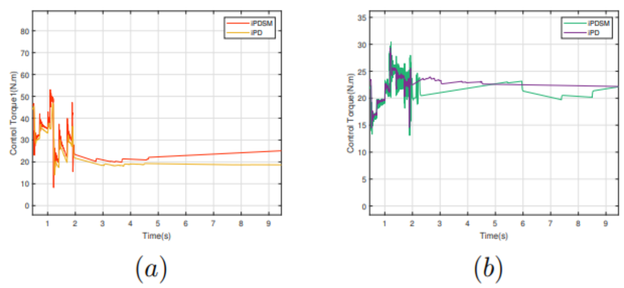

Fig. 11. The control input of first and the second link

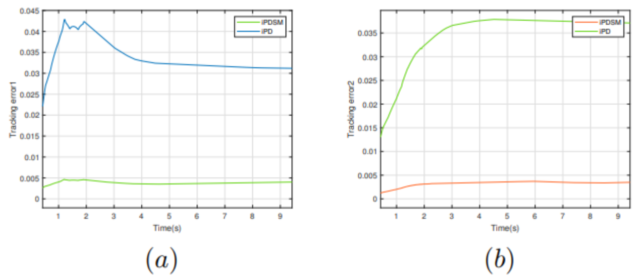

Fig. 12. Curves of the joint position error

Robot with joint elasticity:
The figures Fig. 10, Fig. 8 Fig. 11, Fig. 12 depict the simulation outcomes for the robot with joint elasticity. In terms of rotation angle, iPDSM exhibits favorable results, while iPD tracking deviates significantly from the reference trajectory. The control torque remains within the range of] 8 : 55 [(N.m). Furthermore, the tracking error for iPDSM is notably smaller compared to that of the iPD controller.

Conclusion

In this paper, the trajectory tracking analysis is done for a 2-DOF robotic manipulator with and without elastic joints using the intelligent PD and the intelligent PDSM controllers. The systems dynamics of 2-DOF system is discussed. The central aim of the model-free controller is to function according to the ultra-local model, prioritizing control actions independent of the need for a pre-established mathematical system model. The examination of i-PDSM's stability is conducted, and a condition ensuring robustness in tracking trajectories is identified. In the case of rigid robot, both of the two controllers gave good results regarding the control signal, the tracking error, and the rotation angles. However when introducing the elasticity, the iPD controller is unable to fend off the elasticity in the joints, simulation results show a remark- able tracking error whereas the iPDSM controller gives good results thanks to the sliding mode capability to reject the vibration caused by the elasticity and proved its efficiency to control under-actuated and complicated systems.

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