IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 11, Issue 3 Ver. II (May- Jun. 2014), PP 46-56
www.iosrjournals.org

Control of Trajectory Kinematics for Flexible Manipulators Applying Integral Variable Structure Strategy

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Abstract: *Tracking control of manipulators with joint flexibility is considered to achieve a higher control technique performance. An integral variable structure control **(IVSC)** approach for robot manipulators is presented for accurate servo-tracking in the presence of load variation, parameter uncertainty and nonlinear dynamic interactions. A procedure is proposed for choosing the control function so that it guarantees the existence of the sliding mode and for determining the coefficients of the switching plane and integral control gain. Furthermore, a modified proper continuous function is introduced to overcome the chattering problem. The proposed **(IVSC)** approach has been simulated for a two-degree of freedom flexible joint robot, each joint modeled by two-equations of second order. Stability is insured by the use of Liapunov's direct method. The simulation results demonstrate the potential of the proposed scheme.*
Keywords: *Flexible joint robot, Integral variable structure system, Sliding mode, Switching plane, Servo-tracking, Stability criterion, Dynamic uncertainty, Chatter.*

I. Introduction

Most industrial robots are composed of multi links. Such a case is a highly nonlinear system with complicated coupled dynamics and uncertainty (various load, inertia, and gravitational forces etc.). With regard to such a complicated system, various controllers have been developed [1], such as adaptive controllers [2-4], robust controllers [5-7] and controllers based on the theory of variable structure [8-11]. However, the applicability of these controllers to practical robot is limited because the assumption of perfect rigidity is never satisfied exactly.

Sweet and Good [12-13] have identified several problems that limit the performance of a typical robot manipulators. One of the main issues is the un modeled dynamics, especially the flexibility of the mechanical arm. Rivin [14] determined many sources of flexibility such as harmonic drives, the presence of elastic drive belts and the compressibility of hydraulic fluid in hydraulic manipulators. The use of "rigid" control laws in such systems has been shown to result in poor tracking performance with a low controller bandwidth and instability at higher bandwidth [15].

Several control strategies [16-17] have been proposed for the control of manipulators with joint flexibility based on reduced-order system models derived in separate time-scales using singular perturbation techniques. However, the problems associated with parameter variations have not been addressed in these works. Therefore, consideration of the joint flexibility in the course of modelling and control can contribute significantly to a better performance for most industrial robots.

Robust tracking controller for **(FJR)** is developed using voltage control strategy [18], achieving pre-set performance on link position error [19] both are free of manipulator dynamics and nonlinearities. A novel observer-based robust dynamic feedback without velocity measurements was developed [20] resulting tracking error as small as possible, In case of the set-point regulation problem it can be simplified to a linear time invariant controller. A variable structure control method with a mathematical tool is applied [21] to control errors in a controller that is robust to the model uncertainties. The proposed scheme is applicable to industrial robot for robust position control.

The integral variable structure control **(IVSC)** approach previously proposed in [22] considered the single-input single-output **(SISO)** system and has been successfully applied to electrohydraulic servo control systems. The **(IVSC)** approach comprises an integral controller for achieving a zero steady-state error under step input and variable structure controller [23-25] for enhancing the robustness. With this special scheme, two control loops are obtained, and it yields improved performance when compared to conventional **(VSC)** and linear approaches [22].

This paper extends previous results to the multi-input multi-output **(MIMO)** case, with an application to robot manipulators. The position control of a two-degree of freedom flexible joint robot **(FJR)** manipulators using **(IVSC)** algorithm has been simulated for illustrating the design procedure and demonstrating the robustness property.

II. Description Of (IVSC) Methodology

The **(IVSC)** approach presented here is derived for the class of second-order dynamic equations with a positive-definite symmetric inertia matrix. Since the dynamics of most mechanical system can be modelled in this form, this approach will have wide application. Consider the dynamic equation [10].

$$M\ddot{\theta} + B\dot{\theta} + D\theta = W + U \tag{1a}$$

Where $\theta, \dot{\theta}, \ddot{\theta}$ are n x 1 position, velocity and acceleration vectors, respectively; M = M $(\theta, \dot{\theta})$ is an n x n symmetric positive-definite inertia matrix; B = B $(\theta, \dot{\theta})$ is an n x n matrix; D = D$(\theta, \dot{\theta})$ is an n x n matrix; W = $W(\theta, \dot{\theta})$ is an nx1 vector representing the gravity term; and U is an n x 1 control vector.

The corresponding state-space model can be written as

$$\begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -M^{-1}D & -M^{-1}B \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} U + \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} W \tag{1b}$$

The proposed configuration of the **(IVSC)** is shown in Fig. 1. It combines an integral controller, a **VSC** and the plant (Eqn. 1), and is described as follows:

$$\begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 \\ -M^{-1}D & -M^{-1}B & 0 \\ -I & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ Z \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1} \\ 0 \end{bmatrix} U + \begin{bmatrix} 0 \\ M^{-1} \\ 0 \end{bmatrix} W + \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} \theta^d \tag{2}$$

Where $\theta^d = [\theta_1^d \quad \theta_2^d \ldots\ldots \quad \theta_n^d]^T$ represent the desired position; $Z = [z_1 z_2 \ldots . z_n]^T$ is an n x 1 vector; I is the n x n identity matrix; K_I = diag$[k_1 k_2 \ldots k_n]$ is the gain matrix of the integral controller; and the control function U = $[U_1 U_2 \ldots U_n]^T$ is piecewise linear of the form

$$U_i = \begin{cases} U_i^+(x,t) & if \ \equiv \sigma_i > 0 \\ U_i^-(x,t) & if = \sigma_i < 0 \end{cases} \quad i = 1, \ldots, n \tag{3}$$

Where σ_i is the component of the n-dimensional switching plane σ = 0 and is chosen as

$$\sigma_i = c_i(\theta_i - k_i z_i) + \dot{\theta}_i \qquad i = 1, \ldots, n \tag{4a}$$

Or, in matrix form,

$$\sigma = C\,(\theta - K_I Z) + \dot{\theta} \tag{4b}$$

Where $\sigma = [\sigma_1 \sigma_2 \ldots\ldots \sigma_n]^T \qquad and \qquad C = diag\,[c_1 c_2 \ \ldots\ldots \ \ c_n] c_i > \ \ 0$

Design of such a system involves

1. The choice the functions U^+ and U^- to guarantee the existence of a sliding mode.
2. The determination of the switching function σ and the integral control gain K_i, such that the system has the desired eigenvalues.
3. The elimination of chattering of the control input.

CONTROL FUNCTION

From eqns. (2 and 4), one has

$$\dot{\sigma} = -M^{-1}\,D\,\theta - M^{-1}\,B\,\dot{\theta} + C\dot{\theta} - C\,K_i(\theta^d - \ \theta\,) + M^{-1}W + M^{-1}\,U \tag{5}$$

Let

- $M = M^0 + \Delta M$
- $B = B^0 + \Delta B$
- $D = D^0 + \Delta D$
- $W = W^0 + \Delta W$

Where M^0, B^0, D^0, and W^0 are nominal values of M, B, D and W, and ΔM, ΔB, ΔD and ΔW are the deviations.

Let the control function U be decomposed as

$$U = U_{eq} + \Delta U \tag{6a}$$

Where U_{eq} , called equivalent control, is defined as the solution of the problem $\dot{\sigma}$ = 0 under $M = M^0$, $B = B^0$, $D = D^0$ and $W = W^0$. That is,

$$U_{eq} = D^0\theta + B^0\dot{\theta} - M^0 C\dot{\theta} + M^0\,C\,K_i(\theta^d - \theta) - W^0 \tag{6b}$$

The function ΔU is used to eliminate the influence due to the plant parameter variations in ΔM, ΔB, ΔD and ΔW so as to guarantee the existence of a sliding mode. It is constructed as follows:

$$\Delta U = M^0 \ \Delta\tau \tag{6c}$$

Where

$$\Delta\tau = \Psi(\,\theta - K_I Z) + \Phi\dot{\theta} + \varphi \tag{6d}$$

$$\Psi = \text{diag}\,[\,\Psi_1 \ \Psi_2 \ \ldots\ldots \Psi_n\,]$$

$$\Phi = \text{diag}\,[\,\Phi_1 \ \Phi_2 \ldots\ldots \Phi_n\,]$$

$$\varphi = [\varphi_1 \varphi_2 \ldots \ldots . . \varphi_n]^T$$

$$\Psi_i = \begin{cases} \Psi_i^+ & if\ (\theta_i - k_i)\sigma_i > 0 \\ \Psi_i^- & if\ (\theta_i - k_i)\sigma_i < 0 \end{cases} \quad i = 1, \ldots., n$$

$$\Phi_i = \begin{cases} \Phi_i^+ & if\ \dot{\theta}\sigma_i > 0 \\ \Phi_i^- & if\ \dot{\theta}_i\ \sigma_i < 0 \end{cases} \quad i = 1, \dots, n$$

$$\varphi_i = \begin{cases} \varphi_i^+ & if\ \sigma_i > 0 \\ \varphi_i^- & if\ \sigma_i < 0 \end{cases} \quad i = 1, \dots, n$$

For a mechanical system such as a robot arm, each diagonal component of $M^{-1} M^0$ is larger than the absolute value of the sum of other components in the same row [10]. Thus the following equation is obtained:

$$M^{-1} M^0 = I + \Delta I \qquad (7)$$

Where $\Delta I = [\ \Delta i_{ij}]$ ($i = 1,\dots,n,\ j = 1,\dots, n$) and each entry $\Delta i_{ij} \ll 1$.

The condition for the existence of a sliding motion on the ith switch plane is [23-25]

$$\lim_{\sigma_i \to 0} \dot{\sigma_i}\sigma_i < 0 \qquad (8)$$

Substituting eqn. 6 into eqn.5 gives

$$\dot{\sigma_i} = -M^{-1}\Delta D\ \theta - M^{-1}\Delta B\ \dot{\theta} - \Delta IC\theta + \Delta ICK(\theta^d - \theta) + M^{-1}\Delta W + \Delta I\ \Delta\tau$$

Let

$\Delta W = [\ \Delta W_1, \dots, \Delta W_n]^T$

$M^{-1} = [\ m_{ij}^{-1}]$ $(i = 1, \dots, n, j = 1, \dots, n)$

$M^{-1}\ \Delta D = [\Delta d_{ij}\ ](i = 1, \dots, n, j = 1, \dots, n)$

$M^{-1}\ \Delta B = [\Delta b_{ij}\ ](i = 1, \dots, n, j = 1, \dots, n)$

Each component of $\dot{\sigma}$ is represented as

$$\dot{\sigma_i} = (\Delta d_{ii} - \Delta i_{ii}c_i - \Delta i_{ii}c_ik_i + \Psi_i)(\theta_i - k_iz_i) + (-b_{ii} + \Phi_i)\dot{\theta} + (g_i + \varphi_i) \qquad (9)$$

Then

$$\lim_{\sigma_i \to 0} \dot{\sigma_i}\sigma_i = (\Delta d_{ii} - \Delta i_{ii}c_i - \Delta i_{ii}c_ik_i + \Psi_i)(\theta_i - k_iz_i)\sigma_i + (-b_{ii} + \Phi_i)\dot{\theta}\sigma_i + (g_i + \varphi_i)\sigma_i \qquad (10)$$

And the conditions for satisfying the inequality eqn. 8 are

$$\Psi_i = \begin{cases} \Psi_i^+ < \inf(\Delta d_{ii} - \Delta i_{ii}c_i - \Delta i_{ii}c_ik_i) & if(\theta_i - k_iz_i)\sigma_i > 0 \\ \Psi_i^- > sup(\Delta d_{ii} - \Delta i_{ii}c_i - \Delta i_{ii}c_ik_i) & if(\theta_i - k_iz_i)\sigma_i < 0 \end{cases} \quad i = 1, \dots, n \qquad (11a)$$

$$\Phi_i = \begin{cases} \Phi_i^+ < \inf(\Delta b_{ii})\ if\ \dot{\theta}_i\sigma_i > 0 \\ \Phi_i^- > \sup(\Delta b_{ii})\ if\ \dot{\theta}_i\sigma_i < 0 \end{cases} \quad i = 1, \dots, n \qquad (11b)$$

$$\varphi_i = \begin{cases} \varphi_i^+ < inf|g_i|\ if\ \sigma_i > 0 \\ \varphi_i^- > sup|g_i|\ if\ \sigma_i < 0 \end{cases} \quad i = 1, \dots, n \qquad (11c)$$

Note that g_i in eqn. 9 is dependent not only on parameter variations, load variation and coupling effects but also on the control parameters C_i, K_i, $\Delta\tau_i$ ($i=1,\dots,n$). Since the plant parameter variations $\Delta d_{ij}, \Delta b_{ij}, \Delta w_j$ are bounded and the term $\Delta i_{ij} \ll 1$ as described in eqn. 7, one can guarantee the existence of the gain φ_i such that the inequality eqn. 11c is held.

DESIGN OF SWITCHING PLANE AND INTEGRAL CONTROL GAIN

While in the sliding motion, the system described by Eqn. 2 can be reduced to the following linear equations [23-25]:

$$\dot{\theta} = -C\ (\theta - K_i\ Z) \qquad (12a)$$

$$\dot{Z} = \theta^d - \theta \qquad (12b)$$

Since C and K_I are diagonal matrices, the **(MIMO)** system can be decomposed into n sets of **(SISO)** systems, as follows:

$$\begin{bmatrix} \dot{\theta}_i \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} -c_i & c_ik_i \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \theta_i \\ z_i \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \theta_i^d \quad i = 1, \dots, n \qquad (13)$$

The closed-loop transfer function of the system described by eqn. 13 is

$$H_i(S) = \frac{\theta_i(S)}{\theta_i^d} = \frac{c_ik_i}{S^2 + c_iS + c_ik_i} \quad i = 1, \dots, n \qquad (14)$$

Where θ_i (S) and θ_i^d(S) are the Laplace transforms of $\theta_i\ and\ \theta_i^d$, respectively. The characteristic equations of the systems are

$$S^2 + c_i\ S + c_ik_i = 0 \quad i = 1, \dots, n \qquad (15)$$

Since these characteristic equations are independent of the plant parameters, the **(IVSC)** approach is robust to the plant parameter variations. It can achieve a zero steady-state error, and its eigenvalues can be set arbitrarily. Let the desired eigenvalues of the systems be $\lambda_{1i}, \lambda_{2i}(i = 1, \dots, n)$, or the equivalent desired characteristic equations

$$S^2 + \alpha_{1i}S + \alpha_{2i} = 0 \quad i = 1, \dots, n \qquad (16)$$

Then the switching plane coefficients c_i and the integral control gains k_i can be chosen as follows:

$$c_i = \alpha_{1i} \qquad and \qquad k_i = {}^{\alpha_{2i}}/_{\alpha_{1i}}$$

CHATTERING CONSIDERATION

For the control law given by eqn. 6d, if $\Psi_i, \Phi_i, and\ \varphi_i\ (i = 1, \dots, n)$ are chosen as

$$\Psi_i = \Psi_i^+ = -\Psi_i^-$$
$$\Phi_i = \Phi_i^+ = -\Phi_i^-$$
$$\varphi_i = \varphi_i^+ = -\varphi_i^-$$

Then the control function $\Delta\tau$ can be represented as

$$\Delta\tau_i = \left(\Psi_i|\theta_i - k_i z_i| + \Phi_i|\dot{\theta}| + \varphi_i\right) sign\ (\sigma_i) \tag{17}$$

Since the control $\Delta\tau_i$ contains the sign function sign (σ_i), direct application of such control signals to the plant may give rise to chattering. To obtain continuous control signals, the sign function sign (σ_i), in eqn. 17 can be replaced by a modified proper continuous function as Eqn. (18)

$$P_i(\sigma_i) = \frac{\sigma_i}{|\sigma_i| + \delta_i} \tag{18}$$

Where δ_i is chosen as a function of $|\theta_i - \theta_i^d|$ as

$$\delta_i = \delta_{1i} + \delta_{2i}|\theta_i - \theta_i^d| \qquad i = 1, \dots\dots, n \tag{19}$$

Where $\delta_{1i}\ and\ \delta_{2i}$ are positive constants.

DYNAMIC MODEL FOR (FJR)

The dynamic mathematical model for flexible joint robot developed by [26] is adopted. It is derived for the experimental two-degree of freedom articulated robot using Euler-Lagrange equation [27], and it is given by the following equations:

$$M(\theta)\ddot{\theta} + W(\theta, \dot{\theta}) + B\dot{\theta} - D(\theta_m - \theta) = -J^T F \tag{20a}$$
$$I_m\ddot{\theta}_m + B_m\dot{\theta}_m + D(\theta_m - \theta) = U \tag{20b}$$

Where θ is the 2 x 1 link angular position vector, θ_m is the 2 x 1 motor angular position vector, M (θ) is the 2x2 manipulator inertia matrix, W $(\theta, \dot{\theta})$ is the 2x1 coriolos and centrifugal forces vector, D is 2x2 diagonal matrix with entries equal to the joint stiffness, J^T is the 2x2 transpose of the manipulator Jacobian, F is 2x1 forces vector at the end effector expressed in the reference frame, I_m is the 2x2 diagonal matrix with entries equal to the rotors inertia, B_m is the 2x2 diagonal matrix with entries equal to the coefficient of viscous damping at the motors, and U is 2x1 applied motor torque vector. The inertia matrix and the coriolos and centrifugal forces vector are given by:

$$M(\theta) = \begin{bmatrix} d_1 + 2d_2\cos(\theta_2) & d_3 + d_2\cos(\theta_2) \\ d_3 + d_2\cos(\theta_2) & d_3 \end{bmatrix}$$

$$W(\theta, \dot{\theta}) = \begin{bmatrix} -\dot{\theta}_2(2\dot{\theta}_1 + \dot{\theta}_2)\sin(\theta_2) \\ \dot{\theta}_2^2 d_2 \sin(\theta_2) \end{bmatrix}$$

Where

$$d_1 = I_1 + I_2 + a_1^2 m_1 + l_1^2 m_{r2} + m_2(l_1^2 + a_2^2)$$
$$d_2 = 2\, m_2 l_1 a_2$$
$$d_3 = l_2 + a_2^2 m_2$$

Where I_1, I_2, m_1, m_2, a_1, a_2, l_1, l_2, and m_{r2} are the moment of inertia about an axis parallel to the axis of rotation passing through the center of mass, the mass, the distance from the center of rotation to the center of mass, length of the first and second link, respectively, and the mass of the second rotor. The system undamped natural frequencies are given by the following characteristic equation:

$$\left\| \begin{bmatrix} D & -D \\ -D & D \end{bmatrix} - \omega^2 \begin{bmatrix} M(\theta) & 0 \\ 0 & I_m \end{bmatrix} \right\| = 0$$

The system has four natural frequencies. The first two correspond to the rigid body modes which are the free rotation of the two rotors. The remaining two natural frequencies are due to joint flexibility and are used in the design of the flexible joints.

PROBLEM FORMULATION

The process of controlling the dynamic model given by equations (20) is difficult because the system is multi-input multi-output (MIMO) nonlinear. However, considering each link and its driving motor only reduces the system to two single input multi-output linear subsystems, which simplifies the identification and control process. [28] Has implemented this identification technique on a two-link flexible joint experimental robot. The first subsystem is the first joint (the first motor and the first link) and the second subsystem is the second joint (the second motor and the second link). The following procedures are performed to control these two subsystems.

a) First, constrain the first subsystem by clamping the first link to the fixed table, and thus the second subsystem characteristic can be isolated, identified, and control.
b) To identify and control the first subsystem, the brake of the second motor is applied. Hence, the second subsystem is considered as extra mass add to the end of the first link.

STEPS OF THE PROPOSED CONTROL (IVSC)

1. Based on the block diagram shown in Fig. 1, by combining eqn. 20 and the (IVSC), one obtains a set of state equations of the integral-variable structure-controlled two-link manipulator control system as in eqn. 2.
2. Compute the control signal (U) following the design procedure using eqn. 6 (using the modified form for [Δτ] eqn. (17-19).
3. The control gains $[\Psi, \Phi, \varphi]$ are chosen according to eqn. 11, also the proper function (P_i) is calculated using the [σ] function obtained from eqn. 4.
4. In the sliding motion, the controlled system eqn. 2 can be reduced to simple linear form (the MIMO system can be decomposed into two SISO systems) as shown eqn. 12-15, second order characteristic equations.
5. The dynamic performance can now be determined by simply choosing the coefficients [C_I and K_I], let $\lambda_{1i}, \lambda_{2i}$ are the desired eigenvalues of the characteristic equation. Then C_i & K_I as follows.

$$C_i = -(\lambda_{1i} + \lambda_{2i}) \qquad and \qquad K_i = \frac{-\lambda_{1i}\lambda_{2i}}{(\lambda_{1i} + \lambda_{2i})}$$

SIMULATION STUDY

To evaluate the robustness of the proposed **(IVSC)** approach against large variations of plant parameters and load disturbances, a simulation studies was carried out for demonstration. The nominal values of the system parameters used in simulation {the two-degree of freedom flexible joint robot [FJR]} are given in Table 1, [28].

Table 1. Robot parameter from design and Sin Sweep Identification

	J_{l1} (Kg.m^2)	J_{l2} (Kg.m^2)	d_1 (Kg.m^2)	d_2 (Kg.m^2)	b_1 (N.m.s/rad)	b_2 (N.m.s/rad)
Sin Sweep			**2.087**	**0.216**	**2.041**	**0.242**
I - DEAS	**0.2269**	**0.0429**	**2.110**	**0.223**		

	b_{m1} (N.m.s/rad)	b_{m2} (N.m.s/rad)	k_1 (N.m/rad)	k_2 (N.m/rad)	J_{m1} (Kg.m^2)	J_{m2} (Kg.m^2)
Sin Sweep	**1.254**	**0.119**	**125.56**	**31.27**	**0.1224**	**0.0168**
I - DEAS			**198.49**	**51.11**	**0.1226**	**0.017**

Evaluation of the control methodology was carried out for:
Different external load disturbance

- Zero load
- Load case (A), [200% change in m_2, and 500% change in J_{12}]
- Load case (B), [random deviation of m_2 from 0 to 200%, and J_{12} from 0 to 500%]

Different control function

- Without P_i (σ_i), $\delta_i = 0$ [sign-function].
- With P_i (σ_i), $\delta_i = \delta_{1i} + \delta_{2i}\left|\theta_i - \theta_i^d\right|$

Choosing the eigenvalues of the system eqn. 13 as $\lambda_{1i} = -20 + j15 \qquad \lambda_{2i} = -20 - j15 \qquad i = 1,2$
The coefficients of the switching plane and the integral control gain given by eqn. 16
K = diag[15.625 15.625] and C = diag [40 40]
The control gains must be chosen to satisfy eqn. 11and, based on simulations, one possible set of the switching gains is chosen as follows:

Ψ= diag [-500 -500] Φ = diag [-10 -10] and φ = diag [-1 -1]

The control function [Δτ]calculated using eqn. 17-19, taking δ_{1i} = 0.1 and δ_{2i}= 10.

III. Results And Discussion

Series of simulation studies have been carried out to demonstrate the performance of the proposed **(IVSC)**. The simulation results of the dynamic responses are plotted for a comparison purpose.

Effect of the load variation on the output response

Fig. 2a and Fig. 2b show the output response of link-1 and link-2 respectively for zero load and load case (A). Obviously, the effect of load variation is eliminated and good tracking performance is obtained using the proposed method. Increasing the load effect as mentioned previously, i.e. the load case (B). The output tracking responses for this case are shown in Fig. 3a and Fig. 3b for link-1 and link-2 respectively. It is clear that the desired response can almost be maintained under sever variations of the load disturbance using the proposed scheme.

Effectiveness of the proposed control function (P_i) regarding chatter of the control input

Fig. 4 and Fig. 5 show the waveforms of the control signal of the two links respectively. Fig. 4a shows the control signal U without using the function P_i with zero load case. Smooth control signal without chattering is obtained when using the function P_i in spite of increasing the load to case (B). The same result was obtained for link-2 as seen in Fig. 5. So, it is clear that the chattering phenomena can be eliminated by using a modified proper continuous function P_i. Thus, the **(IVSC)** approach seems amenable for practical implementation.

IV. Conclusion

The problem of tracking control of a two-link direct drive with flexible joint robot (FJR) is presented. An **(IVSC)** design methodology for MIMO system is applied to improve the performance of the control system. It has been shown that the **(IVSC)** approach is robust to the plant parameter variations. It can achieve a zero steady-state error for step input and is possible for arbitrary eigenvalue assignment. The control of the robot arm is considered for demonstrating the design procedure and the potential of the **(IVSC)** approach. Simulations show that the proposed approach can give an almost accurate servo-tracking response in the face of large plant parameter variations, load variations and nonlinear dynamic interactions. It is a robust and practical control law for robot manipulators.

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Fig. 1 Block diagram of an integral variable structure control system for [FJR] manipulator

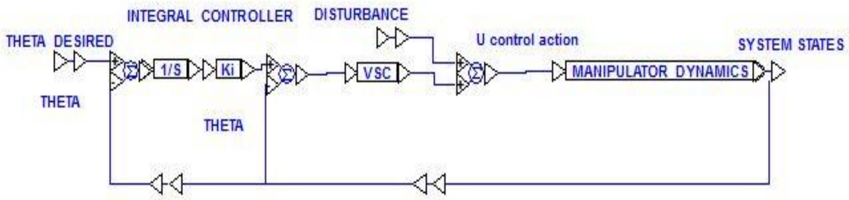


Fig. 2a Angular response of IVSC with function Pi
Theta desired = 1 (rad), Link-1

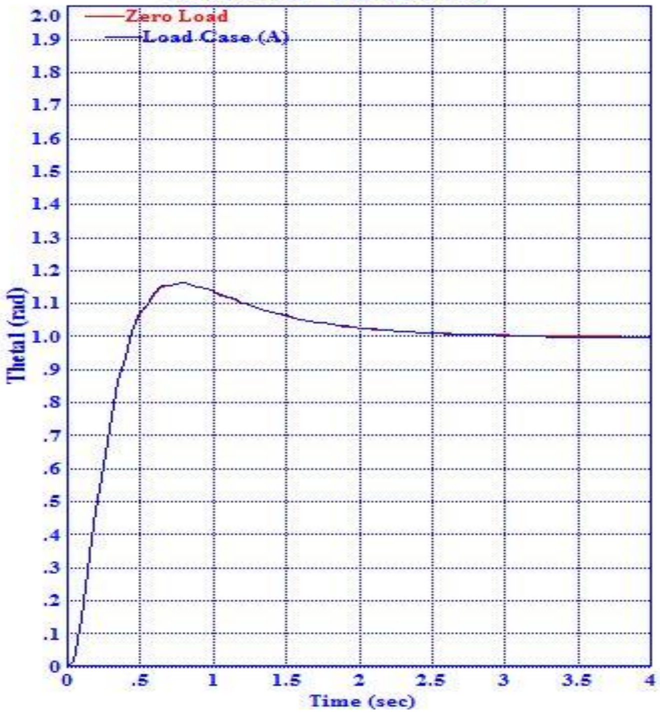


Fig. 2b Angular response of IVSC with function Pi
Theta desired = 1 (rad), Link-2

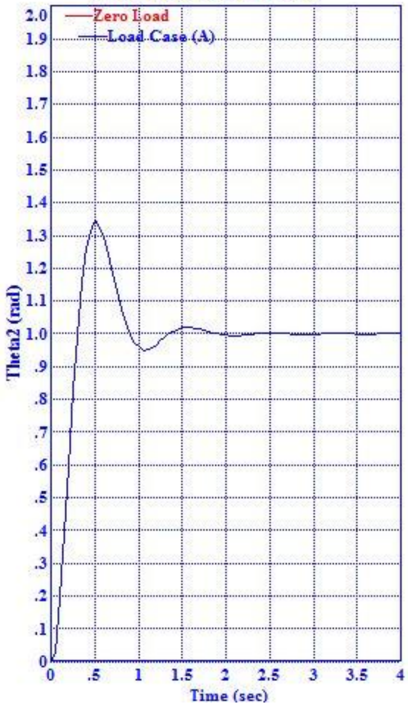


Fig. 3a Angular response of IVSC with function Pi
Theta desired = 1 (rad), Link-1

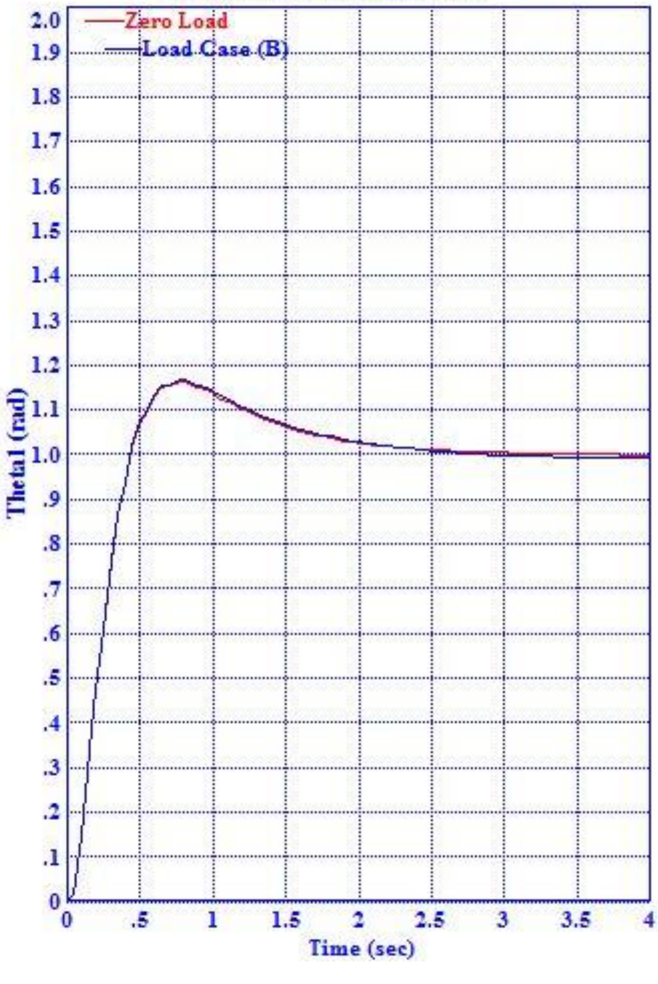


Fig. 3b Angular response of IVSC with function Pi
Theta desired = 1 (rad), Link-2

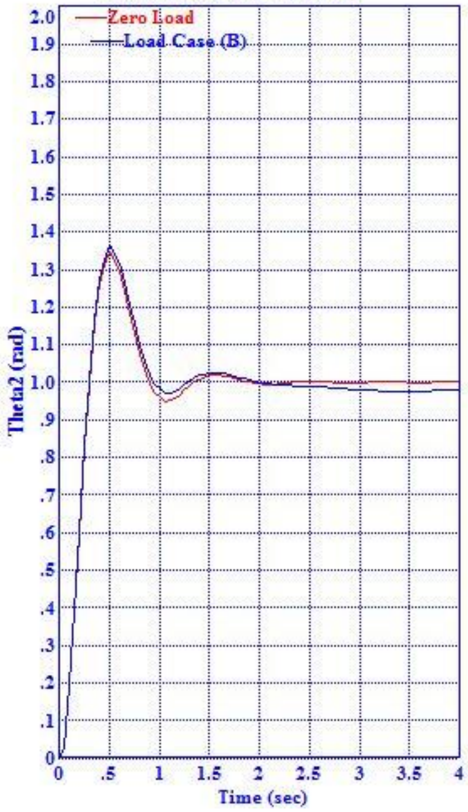


Fig. 4a Control signal of IVSC without function Pi
Theta desired = 1 (rad), Link-1

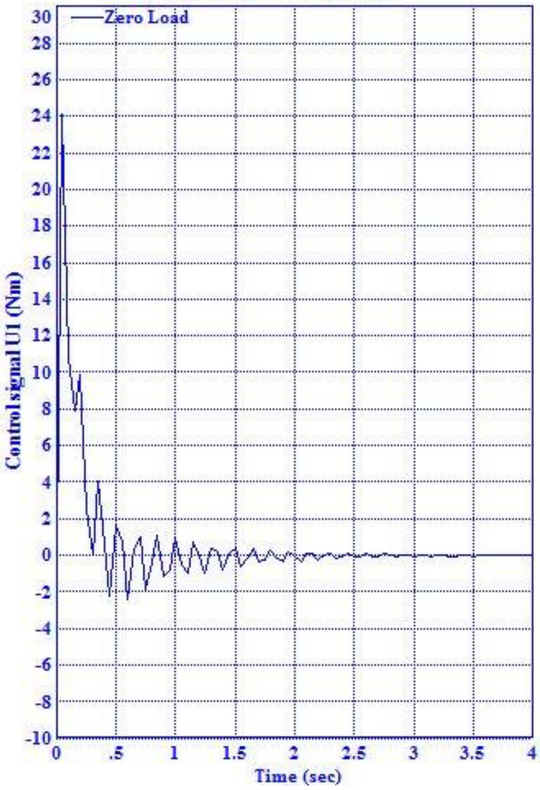


Fig. 4b Control signal of IVSC with function Pi
Theta desired = 1 (rad), Link-1

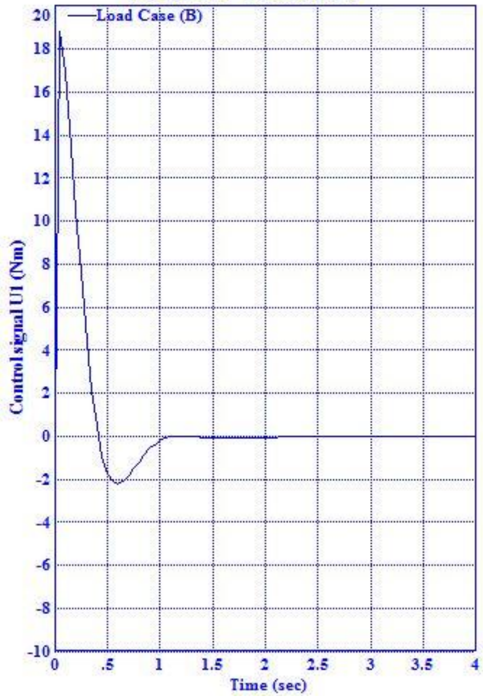
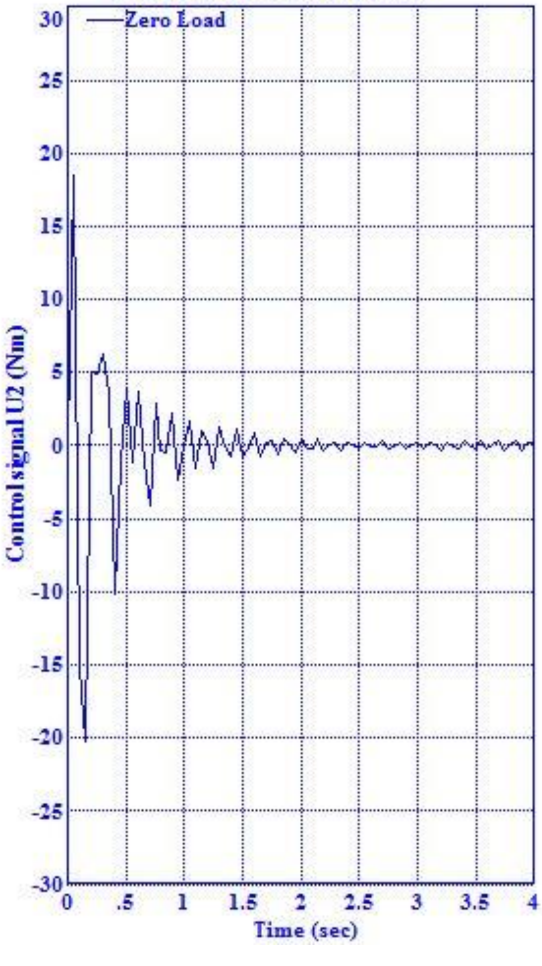


Fig. 5a Control signal of IVSC without function Pi
Theta desired = 1 (rad), Link-2



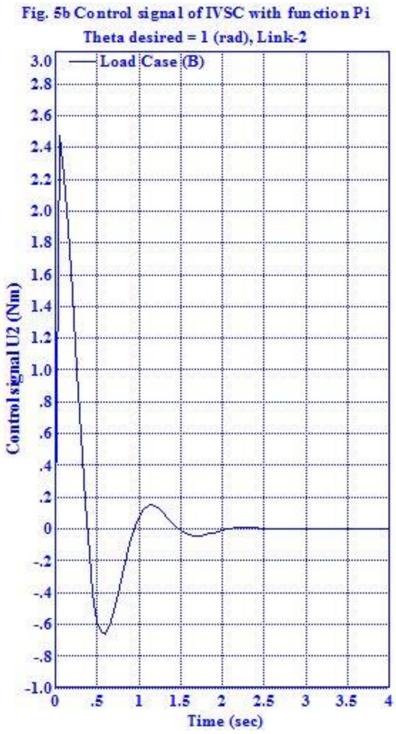


Fig. 5b Control signal of IVSC with function Pi
Theta desired = 1 (rad), Link-2
Load Case (B)
Control signal U2 (Nm)
Time (sec)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
0
.5
1
1.5
2
2.5
3
3.5
4