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A Robust Variable Structure Controller for the Mixed Tracking Control of Robot Manipulators

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Abstract – In this paper, a robust variable structure tracking controller is designed for the mixed tracking control of highly nonlinear rigid robot manipulators for the first time. The mixed control problem under consideration is extended from the basic tracking problem, with the different initial condition of both the planned trajectory and link of robots. This control problem in robotics is not addressed to until now. The tracking accuracy to the sliding trajectory after reaching is analyzed. The stability of the closed loop system is investigated in detail in Theorem 2. The results of Theorem 2 provide the stable condition for control gains. Combing the results of Theorem 1 and Theorem 2 gives rise to possibility of designing the improved variable structure tracking controller to guarantee the tracking error from the determined sliding trajectory within the prescribed accuracy after reaching. The usefulness of the algorithm has been demonstrated through simulation studies on the mixed tracking control of a two link robot under parameter uncertainties and payload variations.

Key Words : Rrobot control, Variable structure system, Tracking control, Disturbance observer

1. Introduction

In servo control, three fundamental problems are the point-to-point control(regulation) problem, tracking problem(trajectory following), and mixed problem. The point-to-point problem is concerned with moving control objects from a point to another[1]. While the controllers for the point-to-point problem are required to provide a small positioning error and superior tracking. In the tracking control, control objects must be moved along the desired trajectory with the same initial position as that of plants[2]. Particularly, the mixed problem is the extended tracking problem with the severely different initial position of plants from that of planned trajectory in which the features of both regulation and tracking problems exist[3]. The regulation, tracking, and mixed problems are very important in many mechanical systems such as robot manipulators, machining systems, tracking antennas etc. These three control problems may be combined in practical fields. Among them, the mixed tracking control problem of robot manipulators is the theme of this paper.

A great deal of the researches on the control of highly nonlinear rigid robot manipulators has been reported in order to improve the performance of controllers and to extend the application fields of robot manipulators. There are several approaches to attempt to obtain the desired performances such as decentralized linear PID[4], optimal control, state feedback control(linear techniques until now), computed torque method[5][6], adaptive control[7][8], sliding mode control[1][9]-[16], and others[17]-[27](nonlinear techniques). Each method has its merits and shortcomings. In the model based methods[15] among them, specially, all of highly nonlinear dynamics models are taken into account to calculate the control input which is a hard task in view of the computation time of the process for controllers, which needs the robustness property for the controllers against all the modeling errors. In order to obtain the robustness against modeling uncertainties and parameter variations, the variable structure system(VSS) with the sliding mode control(SMC) for robot manipulators has been studied by many researchers[1][9]-[16]. The first application of SMC to robot manipulator seems to be in the work of Young[1] dealing with a set point tracking problem. A modification of the Young's controller was presented by Morgan[10]. Other SMCs of robot manipulators may be found[11]-[16]. However, the existing SMCs for robot manipulators unfortunately are not applied to the mixed tracking controls of robot manipulators with the different initial conditions of both the planned trajectory and link of robots.

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In this paper, a robust improved variable structure tracking controller with the prescribed accuracy after reaching is designed for the mixed tracking control of highly nonlinear rigid robot manipulators. After reaching, the relationship between the value of the sliding surface and the error to the sliding trajectory is analyzed in Theorem 1. The continuous sliding mode input can derive robot manipulators to follow the sliding trajectory within the prescribed accuracy after reaching. The stability of the closed loop system is investigated in detail in Theorem 2. The results of Theorem 2 provide the stable condition for control gains. Combing the results of Theorem 1 and Theorem 2 gives rise to possibility of designing the improved variable structure tracking controller to guarantee the tracking error from the pre-determined sliding trajectory within the prescribed accuracy after reaching. The usefulness of the algorithm has been demonstrated through the simulations of the mixed tracking control of a two-link robot under parameter uncertainties and payload variations.

2. A New Variable Structure Mixed Tracking Controller

2.1 State Equation of Robot Manipulators

The motion equations of an n degree-of-freedom manipulator can be derived using the Lagrange-Euler formulation as[2]

$$J(q(t),\phi)\cdot\ddot{q}(t)+D(q(t),\dot{q}(t),\phi)=\tau(t) \tag{1}$$

where $J(q(t),\phi)\in R^{n\times n}$ is a symmetric positive definite inertia matrix, $D(q(t),\dot{q}(t),\phi)\in R^{n}$ is called a smooth generalized disturbance vector as follows:

$$\begin{aligned}D(q(t),\dot{q}(t),\phi)&=H(q(t),\dot{q}(t),\phi)\\&\quad+F(q(t),\dot{q}(t),\phi)+G(q(t),\phi)\end{aligned} \tag{2}$$

including the centrifugal and Coriolis terms $H(q(t),\dot{q}(t),\phi)\in R^{n}$, Coulomb and viscous or any other frictions $F(q(t),\dot{q}(t),\phi)\in R^{n}$, gravity terms $G(q(t),\phi)\in R^{n}$, unknown payload and etc. where τ is an input vector, and $q(t)$, $\dot{q}(t)$, and $\ddot{q}(t)\in R^{n}$ are the generalized position, velocity, and acceleration vector, respectively. The ϕ is the vector composed of the parameters of robot manipulators (i.e. the masses, lengths, offset angles, and inertia of links). An exact modeling of physical robot dynamics is difficult because of the existence of parameter uncertainties, unknown frictions, and payload variations. In this study for the mixed tracking problem, a desired trajectory $q_d(t)\in R^{n}$ is given as

$$q_d(t)=\left\{q_i+\frac{(q_f-q_i)}{T}-\frac{(q_f-q_i\sin(\pi t/T)}{\pi}\right\}\cdot\frac{180}{\pi}[\text{degree}] \tag{3}$$

from an initial state $q_i\in R^{n}$ to a final state $q_f\in R^{n}$ and $\dot{q}(t)=\ddot{q}(t)=0$ is satisfied at $t=0$ and $t=T$ where T is the execution time from q_i to q_f[2]. In this mixed tracking problem, the initial position of the desired trajectory may differ from an initial position of the links, i.e. $q_i\neq q(0)$[3]. Let us define the state vector $X(t)\in R^{2n}$ in the error coordinate system for the integral variable structure mixed tracking controller as

$$X(t)=\left[X_1(t)^T \quad X_2(t)^T\right] \tag{4}$$

where $X_1(t)$ and $X_2(t)$ are the trajectory errors and its derivative as

$$X_1(t)\equiv e(t)=q_d(t)-q(t) \tag{5}$$

$$X_2(t)\equiv\dot{e}(t)=\dot{q}_d(t)-\dot{q}(t) \tag{6}$$

Then the state equation of robot system for the tracking control becomes

$$\begin{aligned}\dot{X}(t)&=\begin{bmatrix}0 & I\\0 & 0\end{bmatrix}\cdot X(t)-\begin{bmatrix}0\\J(q(t),\phi)^{-1}\end{bmatrix}\cdot\tau(t)\\&\quad+\begin{bmatrix}0\\J(q(t),\phi)^{-1}\cdot D(q(t),\dot{q}(t),\phi)\end{bmatrix},\quad X(0)\end{aligned} \tag{7}$$

where $X(0)=\left[q_i^T-q(0)^T \quad -\dot{q}(0)^T\right]^T$ is a given initial condition. For (7), a new improved variable structure tracking controller will be designed through the two steps, i.e. design the sliding surface and choice of continuous control input. And some analysis about the relationship between the error to the sliding trajectory and the value of the sliding surface and the closed loop stability will be given in each step.

2.2 A Sliding Surface, Its Sliding Trajectory, and Error Analysis

First of all, let's define a sliding surface vector $s(t)$ be

$$s(t)\equiv X_2(t)+K_v\cdot X_1(t)\quad(=0) \tag{8}$$

where K_v is diagonal coefficient matrix. This sliding surface determines the ideal sliding mode dynamics to have an ideal first order dynamics. The sliding dynamics from a given initial to origin defined by equation (8) is obtained from $\dot{s}(t)=0$ as follows:

$$\dot{X}_2{}^*(t)+K_v\cdot X_2{}^*(t)=\dot{s}(t)=0 \tag{9}$$

Then rewrite equation (9) into state equation form with the part equation of (7)

$$\dot{X}_1{}^*(t)=X_2{}^*(t)\qquad X_1{}^*(t_s) \tag{10}$$

$$\dot{X}_2{}^*(t)=-K_v\cdot X_2{}^*(t)\qquad X_2{}^*(t_s) \tag{11}$$

where $X_1{}^*(t)=\left[q_d(t)^T-q_s{}^*(t)^T\right]^T\in R^{n}$ and $X_2{}^*(t)=\left[\dot{q}_d(t)^T-\dot{q}_s(t)^T\right]^T$, t_s is the time of the first touching to the sliding surface. The solution of the state equation of the sliding dynamics (10) $q_s{}^*(t)$ and $\dot{q}_s{}^*(t)\in R^{n}$ theoretically determines the sliding trajectory defined by (8) or (9). Since $K_v\in R^{n\times n}$ can be chosen as the negative real parts, which guarantees the exponential stability of the system (10), then there exists positive scalar constants κ such that

$$\|e^{-K_v t}\| \leqq e^{-\kappa t} \tag{12}$$

where $\|\cdot\|$ is the induced Euclidean norm.

Now, define $\overline{X_1}(t)$ is the error to the sliding trajectory as

$$\overline{X_1}(t) = [q_s^*(t) - q(t)] \tag{13}$$

If the sliding surface is zero for all time after reaching, naturally this defined error is also zero. The sliding surface may be not exactly zero if the input of the improved variable structure tracking controller is continuous. Hence the effect of the non-zero value of the sliding surface to the error to the sliding trajectory is analyzed in the following Theorem 1 as a prerequisite to the main theorem.

Theorem 1: If the sliding surface defined by equation (7) satisfies $\|s(t)\| \leqq \gamma$ for any $t \geqq t_s$ and $\|\hat{X}(t_0)\| \leqq \gamma/\kappa$ is satisfied at the initial time, then

$$\|\overline{X_1}(t)\| \leqq \epsilon_1 \tag{14}$$

$$\|\overline{X_2}(t)\| \leqq \epsilon_2 \tag{15}$$

is satisfied for all $t \geqq t_0$ *where* ϵ_1 *and* ϵ_2 *are positive constants defined as follows:*

$$\epsilon_1 = \frac{1}{\kappa} \cdot \gamma, \quad \epsilon_2 = \gamma \cdot \left[1 + Z \cdot \frac{1}{\kappa}\right], \quad Z = \|[K_v]\| \tag{16}$$

Proof: Let us define new error vector as

$$\widehat{X^T} \equiv \left[\int_0^t q_s^*(\tau) - q(\tau) d\tau \quad q_s^*(t) - q(t)\right]. \tag{17}$$

Refer the proof of Theorem 1 in [3] with a re-written sliding surface as

$$s(t) = X_2(t) + K_v \cdot X_1(t) - \{X_2^*(t) + K_v \cdot X_1^*(t)\} \tag{18}$$

The above Theorem 1 implies that the error to the ideal sliding trajectory $q_s^*(t)$ and its derivative are uniformly bounded provided the sliding surface is bounded for all time $t \geqq t_s$. Using this result of Theorem 1, we can give the specifications on the error to the ideal sliding trajectory being dependent upon the sliding surface, (8). In the next section, we will designed a variable structure tracking controller which can guarantee the boundedness of s(t), i.e., $\|s(t)\| \leqq \gamma$ for a given γ, then the error to the ideal sliding trajectory is bounded as ϵ_1 in virtue of Theorem 1.

2.3 Continuous Control Input and Its Stability Analysis

Robot manipulators activated by several servo motor amplifiers are subject to a variety of disturbances. The robust control of highly nonlinear robot manipulators is essential for developing robotics. It is often noted that the generalized nonlinear disturbances, $D(q(t), \dot{q}(t), \phi)$, must be compensated for improving the performance. As an ideal control input in the sliding mode control, the equivalent control of the augmented sliding surface (8) for the robot system (6) is obtained from equation (9)

$$\tau_{eq}(t) = D(q(t), \dot{q}(t), \phi) + J(q(t), \phi) \cdot (\ddot{q}_d(t) + K_v X_2(t)) \tag{19}$$

The smooth generalized disturbance $D(q(t), \dot{q}(t), \phi)$ is included in an equivalent control, $\tau_{eq}(t)$. Since generally this smooth generalized disturbance is very complex, a direct calculation of the smooth generalized disturbance from the model results in a long sampling time, limitations of the control performance, and difficulties of controller design.

In this paper, we consider the following continuous control input, $\tau(t)$

$$\tau(t) = \tau_{eqm}(t) + \tau_s(t) \tag{20}$$

where $\tau_{eqm}(t)$ is the modified equivalent control for the dynamics of equation (1), and is so designed that the error dynamics of the controlled system has the sliding surface dynamics defined by equation (10), which is defined as

$$\tau_{eqm}(t) = J_N \cdot (\ddot{q}_d(t) + K_v \cdot X_2(t)) \tag{21}$$

where J_N is the nominal matrix of the original inertial matrix. The $\tau_s(t)$ is the continuous feedback term of the sliding surface as follows:

$$\tau_s(t) = J_N \cdot \{\kappa_{x^1} \cdot s(t) + \kappa_{x^2} \cdot \sigma(t)\}, \ \sigma(t) = \frac{s(t)}{\|s(t)\| + \delta}\} \tag{22}$$

where κ_{x^1}, κ_{x^2} and δ are the suitable positive constant as the design parameters for the control input. If we apply the input control torque given by equation (20)-(22) to the robot system (6), the following equation is obtained

$$\begin{aligned}\dot{X}_2(t) = & J^{-1}(q(t), \phi) \cdot D(q(t), \dot{q}(t), \phi) + \ddot{q}_d(t) \\ & - J^{-1}(q(t), \phi) J_N [\ddot{q}_d(t) + K_v X_2 + \kappa_{x^1} s(t) + \kappa_{x^2} \sigma(t)]\end{aligned} \tag{23}$$

and the dynamics of $s(t)$ is expressed in the following simple form

$$\dot{s}(t) = n_1(t) - [\kappa_{x^1} \cdot s(t) + \kappa_{x^2} \cdot \sigma(t)] \tag{24}$$

where $n_1 \in R^n$ is the resultant disturbance vector given by

$$\begin{aligned}n_1(t) = & (I - J(q(t), \phi) \cdot J_N^{-1})(\ddot{q}_d(t) + K_v X_2) \\ & + J(q(t), \phi)^{-1} \cdot D(q(t), \dot{q}(t), \phi)\end{aligned} \tag{25}$$

From the equation (25), the $2n$-th order original mixed tracking control problem is converted to the 2n-th stabilization problems with three degree of freedoms κ_{x^1}, κ_{x^2}, and δ against the resultant disturbance n_1 by means the proposed algorithm which implies the robustness problems in the design of controllers. For some positive constants ϵ_1 and ϵ_2 defined in (15), let the constant N be defined as follows:

$$N \equiv \max\left\{\|n_1(t)\| : q(t) \in B(\epsilon_1; q_s{}^*(t)) \quad \text{and} \quad \dot{q}(t) \in B(\epsilon_2; \dot{q}_s{}^*(t))\right\} \tag{26}$$

where the matrix norm is defined as the induced Euclidean norm, and for a positive number $\sigma > 0$ and a vector $\lambda \in R^n$ the boundary set defined by as

$$B(\sigma;\lambda) = \left\{w \in R^n ; \|w - \lambda\| \leq \sigma\right\} \tag{27}$$

The stability property or the system (6) with control laws (20)-(22) will be stated in the next theorem:

Theorem 2: Consider the robot system with controls given by equation (20)-(22). Assume that for some positive γ, $\|s(t_0)\| \leq \gamma$ and $\|\hat{X}(t_0)\| \leq \gamma/\kappa$ are satisfied at the initial time $t = t_0$, and if the gain κ_{x^2} satisfies

$$\kappa_{x^2} \geqq N - \kappa_{x^1} \cdot \delta \tag{28}$$

for given κ_{x^1} and δ, then the closed loop control system is uniformly bounded (i.e. the solution $\hat{X}$ is uniformly bounded at origin in error coordinate state space) for all $t \geqq t_0$ until $\|s(t)\| \leq \eta$ where η is defined by

$$\eta = \sqrt{\alpha^2 + \beta^2} - \alpha, \quad \alpha = \frac{1}{2}\delta - \frac{\kappa_{x^2} - N}{2\kappa_{x^1}}, \quad \beta = \frac{\delta \cdot N}{\kappa_{x^1}} \tag{29}$$

Proof: The proof is straightforward, first take Lyapunov candidate function as

$$V(t) = \frac{1}{2} s^T(t) \cdot s(t) \tag{30}$$

and differentiate with respect to time, it leads to

$$\dot{V}(t) = s^T(t)\dot{s}(t) = s^T(t) n_1(t) - s^T(t)\left[\kappa_{x^1} s(t) + \kappa_{x^2}\sigma(t)\right] \tag{31}$$

By matrix inequality, (31) becomes

$$\dot{V}(t) \leq \|s^T(t)\| \cdot \|n_1(t)\| - \|s(t)\|\left[\kappa_{x^1}\|s(t)\| + \kappa_{x^2}\sigma(t)\right] \tag{32}$$

$$\leq \|s^T(t)\| \cdot N - \left[\kappa_{x^1} \cdot \|s(t)\| + \kappa_{x^2} \cdot \sigma(t)\right] \tag{33}$$

$$= -\frac{\kappa_{x^1}\|s(t)\|}{\|s(t)\| + \delta}\left\{\|s(t)\|^2 + 2\alpha\|s(t)\| - \beta\right\} \tag{34}$$

If the control gains κ_{x^1} and κ_{x^2} satisfy the inequality (29)

$$\dot{V}(t) < 0 \tag{35}$$

at all $t = t_0$ as long as $\|s(t)\| < \eta$, which completes the proof f Theorem 2.

Theorem 2 guarantees the uniform bounded stability of the proposed continuous improved integral variable structure tracking controller for robot manipulators. The smaller δ in control algorithm (24), the lower bound of η. The η can be decreased by an increase of κ_{x^1} for a given δ and N so that η is sufficiently smaller than γ the bound of the sliding surface in Theorem 1($\eta < \gamma$). If the initial value of the sliding surface is small($\|s(t)\| < \gamma$) which is reasonable in case of the known initial state of robot manipulators, the feedback control (20)-(22) designed by Theorem 1 and Theorem 2 maintains the bounded stability of the system with the prescribed performance:

$$q(t) \in B(\epsilon_1; q_s{}^*(t)) \quad \text{and} \quad \dot{q}(t) \in B(\epsilon_2; \dot{q}_s{}^*(t)) \quad \text{for} \quad t \geqq t_0 \tag{36}$$

which implies guaranteeing the tracking error ϵ_1 to the ideal sliding trajectory $q_s{}^*(t)$ determined by the sliding surface after reaching. Therefore, a new SMC can be realized effectively. And robot manipulators can be controlled to follow the predetermined sliding trajectory.

3. Numerical Simulation Studies

3.1 Description of a Two Link Manipulator

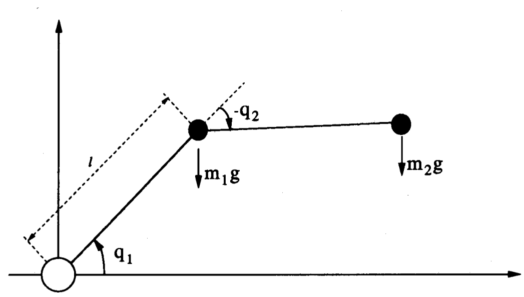

Fig. 1 A SCARA-type two degree of freedom manipulator.

Numerical simulations are performed to show the accurate and robust control property of the proposed algorithm. The dynamic model of a SCARA-type two degree-of-freedom manipulator shown in Fig. 1 used in this simulation is as follows:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = l \cdot \begin{bmatrix}\frac{1}{3}m_1 + \frac{4}{3}m_2 + m_2C_2 & \frac{1}{3}m_2 + \frac{1}{2}m_2C_2 \\ \frac{1}{3}m_2 + \frac{1}{3}m_2C_2 & \frac{1}{3}m_2\end{bmatrix} \cdot \begin{bmatrix}q_1\\ q_2\end{bmatrix}$$
$$+ l^2 \cdot \begin{bmatrix} -\frac{1}{2}m_2S_2\dot{q}_1^2 - m_2S_2\dot{q}_1\dot{q}_2 \\ \frac{1}{3}m_2S_2\dot{q}_1^2\end{bmatrix} + l \cdot \begin{bmatrix}\frac{1}{2}m_1gC_1 + \frac{1}{2}m_2gC_{12} + m_2gC_1 \\ \frac{1}{2}m_2gC_{12}\end{bmatrix} \tag{37}$$

where C_i, S_i and C_{ij} imply $\cos(q_i)$, $\sin(q_i)$ and $\cos(q_i + q_j)$, respectively. The parameters are $m_1 = m_2 = 0.782[kg]$, $l = 0.23[m]$ and $g = 9.8[m/\sec^2]$.

3.2 Design Example of a New Variable Structure Tracking Controller

The initial and final positions of the desired trajectory are given as $q_i = [30^\circ \quad -20^\circ]$ and $q_f = [90^\circ \quad -60^\circ]$ for the two links as an example. The planned trajectories are shown in Fig. 2 for the link1 and Fig. 3 for the link2.

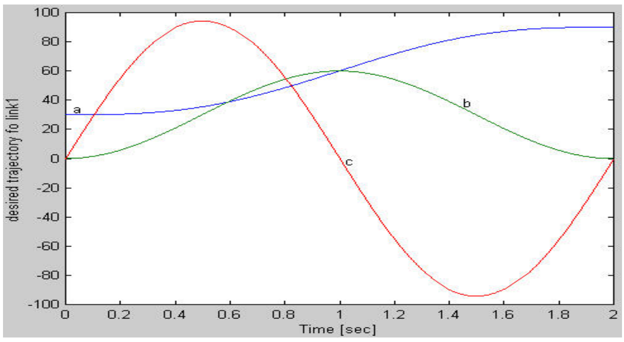

Fig. 2 The desired trajectory(a), speed(b), and acceleration (c) of link 1.

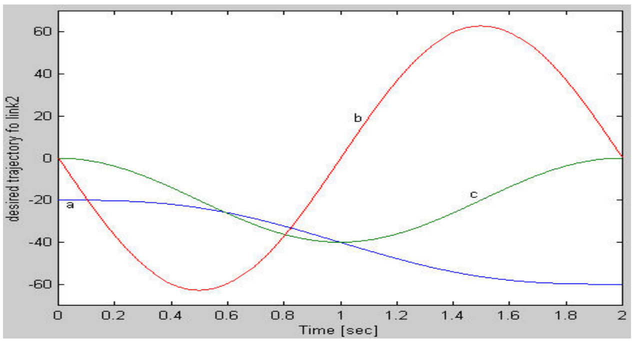

Fig. 3 The desired trajectory(a), speed(b), and acceleration (c) of link 2.

Following the design procedure, the coefficients of an sliding surface is designed as $K_v = 20$ in (7) for locating simple poles at -20 into the ideal sliding dynamics (10). The corresponding constants in (12) κ become 20. By the results of Theorem 1, the error to the sliding trajectory and its derivative, $\overline{X_1}$ and $\overline{X_2}$, are bounded as $\epsilon_1 = 1.653\gamma$ and $\epsilon_2 = 981\gamma$ for a given γ of the bound of the sliding surface. For a $\epsilon_1 = 0.1^\circ$ maximum error, γ is selected as 0.064. Now, the controller gains, κ_{x^1} and κ_{x^2}, are selected to be 800 and 4 for $\delta = 0.02$, and $N = 20$ by Theorem 2 which satisfy the condition (29) in order to guarantee the prescribed error $\epsilon_1 = 0.1^\circ$ to the sliding trajectory previously determined by the sliding surface 1.

3.3 Simulation Studies

The simulations are carried out under the conditions of 10 [%] modeling error and 1[kg] unknown payload. The sampling time is selected as 0.2 [msec]. The desired planned trajectories, speeds, and accelerations of link1 and link2 are depicted in Fig. 2 and Fig. 3, respectively. Fig. 4 shows the output time trajectories of two links by proposed algorithm under the condition of 10 [%] modeling error and 1[kg] unknown payload. Fig. 5 shows the sliding surface of the two links. The control inputs of the two links is depicted in Fig. 6.

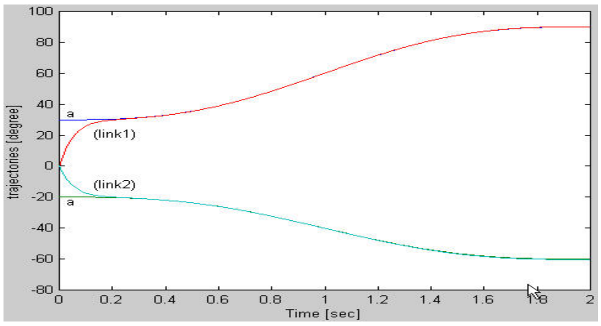

Fig. 4 Output trajectories of two links by proposed algorithm $10[\%]$ modeling error and $1[kg]$ unknown payload.

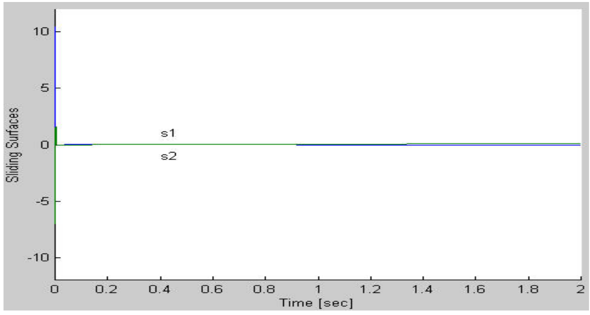

Fig. 5 Sliding surfaces.

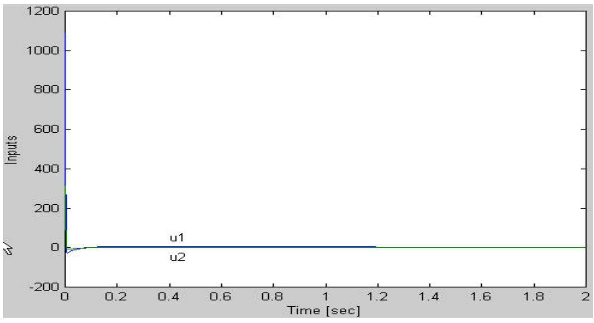

Fig. 6 Continuous control input.

4. Conclusions

In this paper, a robust improved variable structure tracking controller is suggested for the mixed tracking control of highly nonlinear rigid robot manipulators fro the first time. The sliding dynamics of the switching surface is analytically obtained as the differential equation. The relationship between the maximum bound of the tracking error to the sliding trajectory and non-zero value of the sliding surface after reaching is derived in Theorem 1. The continuous sliding mode input can derive robot manipulators to follow the sliding trajectory within the prescribed accuracy after reaching. The uniform bounded stability of the suggested algorithm is investigated in Theorem 2. Hence robot manipulators can be controlled to the sliding trajectory within the prescribed accuracy after reaching for all modeling errors and unknown payload variations. The usefulness of the algorithm has been demonstrate by the simulations about the mixed tracking control of a two link robot under parameter uncertainties and payload variations with example design.

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