Conference Paper

Adaptive Terminal-Integral Sliding Mode Force Control of Elastic Joint Robot Manipulators in the Presence of Hysteresis

Part of the Advances in Intelligent Systems and Computing book series (AISC, volume 1058)

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CISTER-TR-200101

2019/10/26

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Abstract

In this paper, an adaptive terminal-integral sliding mode force control of elastic joint robot manipulators in the presence of hysteresis is proposed. One of the most important issues that is solved in this study is that the hysteresis phenomenon is considered something that provokes losses in the manipulator motion and controller errors. Force control is necessary because it can be implemented and very useful in the area of industrial robotics such as collaborative and cooperative robotics. Therefore, it can be implemented for precise control in which robot-operator or robot-robot interaction is needed. An adaptive terminal-integral sliding mode force control is proposed by considering the hysteresis and the effects between the end effector and a flexible environment. Force control has not been studied extensively nowadays and even less for elastic joint robot manipulators. Thus, to improve the system precision control, the adaptive sliding mode controller (ASMC) is designed by a Lyapunov approach obtaining the adaptive and controller laws, respectively. As an experimental case study, two links elastic joint robot manipulator is considered by obtaining the elastic joint model with hysteresis using a Bouc-Wen model.

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Key words: Hysteresis, Flexible Structures, Robotics, Force Control, Integral Sliding Mode Control, Terminal Sliding Mode Control

1 Introduction

Hysteresis and other non-linearities such as backlash sometimes are found in several kinds of actuators like linear and rotational, so for this reason, hysteresis in actuators has been studied since several years ago [5, 4, 3]. Hysteresis phenomenon must be avoided as it yields unwanted effects such as loss in precision and instability when classical and novel controller approaches are implemented resulting in negative and undesirable system performance. There are several hysteresis models that can be found in literature, but one of the most important hysteresis models found nowadays are the Bouc-Wen model [30, 31, 29, 11]. The Bouc-Wen Model consists of a bending flexion force implementing an extra variable that is resolved by numerical integration. The Bouc-Wen model is important to be mentioned because a multi-variable Bouc-Wen model is used in this research. Other interesting studies found in literature related to hysteresis in robotics are explained in [20] where a control strategy is implemented to solve the performance deterioration of servo elastic drive systems, and in [25] where a torsion-angular velocity feedback is used to solve the vibrations of the tip of a robotic arm.

Force/position control has been extensively implemented for the control of different kinds of elastic robots [10, 17, 1, 33, 24, 8, 15]. For example, in [28], a hybrid force and position adaptive fuzzy sliding mode control for robotic manipulators is shown where the robot dynamics is decomposed in the force and position parts taking into account the environment and dynamic structure properties. In [27], another adaptive hybrid position control of robot arms with a rigid surface is proposed where the controller is designed in such a way constraints and uncertainties are considered to obtain a zero force and position error. In [15], a position/force controller for robotic arms in a flexible surface is implemented considering resistance and environment elasticity.

Sliding mode control (SMC) is an effective robust control strategy which has been successfully applied to a wide variety of complex systems and engineering [1, 16, 12, 5, 36, 22, 23, 2, 7, 37]. The SMC system has various attractive features such as fast response, good transient performance, and robustness with respect to uncertainties and external disturbance and so on

[6]. A major undesired phenomenon faced by SMC is the high frequency oscillations known as chattering which can cause instability and damage to the system. Other works have added an integral term to the sliding surface (ISMC) in order to reduce the steady-state error (SSE) compared to SMC [13, 38]. Sliding mode control and its variation such as second order, integral and terminal sliding mode has been extensively used in the position and force control of robotics manipulator of any kind [32, 26, 39, 18, 9, 21, 40]. For example, in [19], the unknown dead-zone and disturbance phenomenon has been considered to design a finite-time sliding surface controller for robot manipulators something that is very important for this study considering that the dead-zone non-linearity has some similarities with the hysteresis treated in this work. Other examples can be found in [14, 35], where a second order integral sliding mode controller for experimental applications and a guidance law for a missile intersection with impact angle constraint are shown.

In this study, an adaptive terminal-integral sliding mode controller is designed and implemented for the force control of flexible robotic manipulators in the presence of hysteresis. As explained before, a multi-variable Bouc-Wen hysteresis model is used to represent the flexion structure. The adaptive terminal-integral sliding mode force controller is designed by selecting an appropriate sliding surface with a suitable switching law and a control law and then by selecting an appropriate Lyapunov function, the adaptive laws for the controller gains can be obtained. Finally, an illustrative example is proposed where this strategy is tested in a two-links robotic manipulator.

The paper is organized as follows. In section 2 presents the hysteresis modeling. In Section 3, the terminal-integral sliding mode force controller design is discussed. In section 4, numerical experiments and discussions are presented. Finally, conclusions are drawn in Section 5.

2 Hysteresis modeling

This section presents the hysteresis modeling process used in this study. In Fig. 1, a rotary actuator and joint with a longitudinal flexion are shown in which the phenomenon of hysteresis occurs yielding a difference in the rotation angle of $q - x$ difference that influences in the position and force exerted at the tip of the structure [29].

The hysteresis model used in this study is the Bouc-Wen model which is defined as [30, 31, 29, 11]:

$$f(x, \dot{x}) = d\dot{x} + h(x) \tag{1}$$

where $f()$ is the restoring force, d is the linear damping and h is the hysteresis restoring force. $h(x)$ is given by [29]:

$$h(x) = \omega\eta x + (1 - \omega)\eta z \tag{2}$$

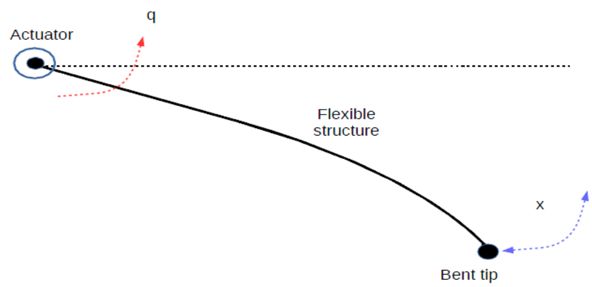

Fig. 1: Joint flexion

where η is a position dependent map and $0 \leq \omega \leq 1$ is the ratio of linear to nonlinear restoring force [29]. The hysteresis state z is defined by the following differential equation [29]:

$$\dot{z}(t) = \dot{x}(t) - \beta|\dot{x}(t)||z(t)|^{n-1}z(t) - \gamma\dot{x}|z(t)|^{n} \tag{3}$$

where β, γ, n determine the shape of the hysteresis. These equations are transformed in a multi-variable form considering that a robotic manipulator has several degrees of freedom. In the next section, this will be explained with more details.

3 Dynamic model equations of the flexible robotic manipulator

The dynamic model of the flexible manipulator represented in Euler-Lagrange form with a flexible environment is presented in this section and is given by: [27, 15, 28]:

$$\mathbf{M}(q)\ddot{q} + \mathbf{C}(q, \dot{q})\dot{q} + \mathbf{G}(q) = \tau - \mathbf{J}^{T}(q)\bar{\mathbf{F}} \tag{4}$$

where $q \in \mathbb{R}^n$ is the actuators position and/or orientation vector, $\mathbf{M} \in \mathbb{R}^{n \times n}$ is the inertia matrix, $\mathbf{D} \in \mathbb{R}^{n \times n}$ is the coriolis matrix, $\mathbf{G} \in \mathbb{R}^n$ is the gravity vector, $\tau \in \mathbb{R}^n$ is the input control vector, $\mathbf{J} \in \mathbb{R}^{m \times n}$ is the Jacobian matrix and $\bar{\mathbf{F}} \in \mathbb{R}^m$ is the interaction force between the end effector and the environment. $\bar{\mathbf{F}}$ is given by:

$$\bar{\mathbf{F}} = \mathbf{F}(\mathbf{X}, \dot{\mathbf{X}}) - \bar{\mathbf{K}}\mathbf{X}_e \tag{5}$$

where the force $\bar{\mathbf{F}}$ is given by the difference between the forces of the flexible end effector and the flexible surface, $\mathbf{F}(\mathbf{X}, \dot{\mathbf{X}})$ is the hysteresis non-linear restoring force in vector form as shown in (1), $\mathbf{X}_e$ is the position and orientation of the deformable environment, $\mathbf{X}$ is the position and orientation of the end effector and $\bar{\mathbf{K}}$ is the environment stiffness matrix [28]. $\mathbf{F}(\mathbf{X}, \dot{\mathbf{X}})$ is given by:

$$\mathbf{F}(\mathbf{X}, \dot{\mathbf{X}}) = \mathbf{D}\dot{\mathbf{X}} + \mathbf{h}(\mathbf{X}) \tag{6}$$

So, (6) is the vector form of (1) where $\mathbf{D}$ is a matrix of appropriate dimensions and $\mathbf{h}(\mathbf{X})$ is a vector of appropriate dimensions. Substituting (6) and (5) in (4) yields:

$$\mathbf{M}(q)\ddot{q} + \mathbf{C}(q, \dot{q})\dot{q} + \mathbf{G}(q) = \tau - \mathbf{J}^T(q)\mathbf{D}\dot{\mathbf{X}} - \mathbf{J}^T(q)\mathbf{h}(\mathbf{X}) + \mathbf{J}^T(q)\bar{\mathbf{K}}\mathbf{X}_e \tag{7}$$

The difference of forces obtained by the difference in the position and orientation of the end effector when this structure is in flexion is given by:

$$\mathbf{K}_q q - \mathbf{K}_x\mathbf{X} = \mathbf{F}(\mathbf{X}, \dot{\mathbf{X}}) \tag{8}$$

where $\mathbf{K}_q$ and $\mathbf{K}_x$ are matrices of appropriate dimensions. Now substituting (6) into (8) and using the vector form of (3) yields:

$$\begin{aligned} \mathbf{D}^{-1}\mathbf{K}_q q - \mathbf{D}^{-1}\mathbf{K}_x\mathbf{X} - \mathbf{D}^{-1}\mathbf{h}(\mathbf{X}) &= \dot{\mathbf{X}} \\ \dot{\mathbf{Z}} = \dot{\mathbf{X}} - \mathbf{B}\|\dot{\mathbf{X}}\|\|\mathbf{Z}\|^{n-1}\mathbf{Z} &- \mathbf{C}\dot{\mathbf{X}}\|\mathbf{Z}\|^n \end{aligned} \tag{9}$$

where $\mathbf{B}$ contains all the parameters β and $\mathbf{C}$ contains all the parameters γ, both matrices must be of appropriate dimensions. The whole dynamic model is given by (7) and (9). Before deriving the adaptive integral-terminal sliding mode controller it must be considered that the force error is given by:

$$\mathbf{e} = \bar{\mathbf{F}} = \mathbf{F}(\mathbf{X}, \dot{\mathbf{X}}) - \bar{\mathbf{K}}\mathbf{X}_e \tag{10}$$

4 Terminal-integral sliding mode force controller design

The terminal-integral sliding mode force controller for an elastic joint robot in the presence of hysteresis in a flexible environment is discussed in this section. The proposed controller is based on [40, 21] by designing the variable s and σ with an appropriate switching law. Consider the following integral sliding variable:

$$s = \mathbf{e}(t) + \int_0^t \mathbf{e}(\tau)d\tau \tag{11}$$

where $\mathbf{e}$ is the error variable defined in (10). Now the following sliding variable is designed [40]:

$$\sigma = \dot{s} + k_1 s + k_2\lambda(s) \tag{12}$$

where $k_1, k_2 \in \mathbb{R}$ are the sliding gain variables adjusted by the adaptation law and $\lambda(s)$ [40]:

$$\lambda(s) = [\lambda(s_1)...\lambda(s_m)]$$
$$\lambda(s_i) = \begin{cases} s_i^{a/p} & if\ \bar{\sigma}_i = 0\ or\ \bar{\sigma}_i \neq 0\ |s_i| \geq \mu \\ \gamma_1 s_i + \gamma_2 sign(s_i) s_i^2 & if\ \bar{\sigma}_i \neq 0 \qquad , \quad |s_i| < \mu \end{cases} \tag{13}$$

All the constants are explained in detail in [40]. The terminal-integral sliding mode control law is obtained by making $\sigma = 0$ as shown below:

$$\begin{aligned} \dot{s} + k_1 s + k_2 \lambda(s) &= 0 \\ \dot{e} + e + k_1 s + k_2 \lambda(s) &= 0 \end{aligned} \tag{14}$$

the error in (10) is equivalent to the following equation:

$$\begin{aligned} \mathbf{e} = \bar{\mathbf{F}} = \mathbf{J}^{T(-1)}(q)\tau - \mathbf{J}^{T(-1)}(q)\mathbf{M}(q)\ddot{q} - \mathbf{J}^{T(-1)}(q)\mathbf{C}(q,\dot{q})\dot{q} \\ - \mathbf{J}^{T(-1)}(q)\mathbf{G}(q) \end{aligned} \tag{15}$$

Therefore, the control law is:

$$\tau = -\mathbf{J}^T(q)\dot{\mathbf{e}} + \mathbf{M}(q)\ddot{q} + \mathbf{C}(q,\dot{q})\dot{q} + \mathbf{G}(q) - \mathbf{J}^T(q)k_2\lambda(s) + \mathbf{J}^T(q)k_2 s \tag{16}$$

The adaptive gains laws for the terminal-integral sliding mode force controller for an elastic robotic manipulator are given in the following theorem:

Theorem 1. *The adaptive gains laws k_1 and k_2 given by:*

$$\begin{aligned} \dot{k}_1 &= -\sigma^T \dot{s} \\ \dot{k}_2 &= -\sigma^T \dot{s} \end{aligned} \tag{17}$$

are obtained by selecting an appropriate Lyapunov function in order that the system must be globally asymptotically stable.

Proof. *First, substitute the torque input control variable (16) in (12) obtaining the following result:*

$$\begin{aligned} \sigma &= k_1 s + k_2 s \\ \dot{\sigma} &= k_1 \dot{s} + k_2 \dot{s} \end{aligned} \tag{18}$$

and selecting the following Lyapunov function:

$$V = \frac{1}{2}\sigma^T\sigma + \frac{1}{2}k_1^2 + \frac{1}{2}k_2^2 \tag{19}$$

Taking the derivative of (19) yields:

$$\dot{V} = \sigma^T k_1 \dot{s} + \sigma^T k_2 \dot{s} + k_1 \dot{k}_1 + k_2 \dot{k}_2 \tag{20}$$

obtaining the following adaptive laws that makes the system stable:

$$\begin{aligned} \dot{k}_1 &= -\sigma^T \dot{s} \\ \dot{k}_2 &= -\sigma^T \dot{s} \end{aligned} \tag{21}$$

concluding that the Lyapunov derivative meets the following condition:

$$\dot{V} \leq 0 \tag{22}$$

with this conclusion, the system is stable with the control law (16) and the adaptive laws (21).

in the following section a numerical example is shown to test the validity of the theoretical results.

5 Simulation Results and Discussions

In this experiment, a two links robotic manipulator is implemented with their parameter values as shown in Table 1 [34]. A comparative analysis is done using MATLAB for which the results and performances of the strategies shown in [15, 29] are compared with the proposed control strategy. In Fig. 2, it can be seen that the force error $\bar{\mathbf{F}}$ approximates zeros as times goes to infinity so it is proved that the force controller provides an excellent performance. It is important to notice that the force error approaches zero as time goes to infinity in contrast with the results obtained by the other two strategies [15, 29] that do not approaches zero as time goes to infinity.

Then in Fig. 3, it can be seen how the sliding variables σ and s reach zero as times goes to infinity proving the optimal performance of this terminal-sliding mode controller. Finally in Fig. 4, the torque variable τ_1 for the actuator 1 is shown where it can be noticed that the torque provided by the proposed control strategy tends to decrease in comparison with the comparative approaches [15, 29]

The most important issue that was considered in this study is that a suitable hysteresis mathematical model is selected taking into account that the Bouc-Wen model provides an efficient mathematical representation of hysteresis. Another important point is that this model is relatively simple and it can be implemented in a real experimental setup, so for these advantages this hysteresis model was used for the restoration forces modeling. The Bouc-wen model used in this study is extended to a multi-variable system for an

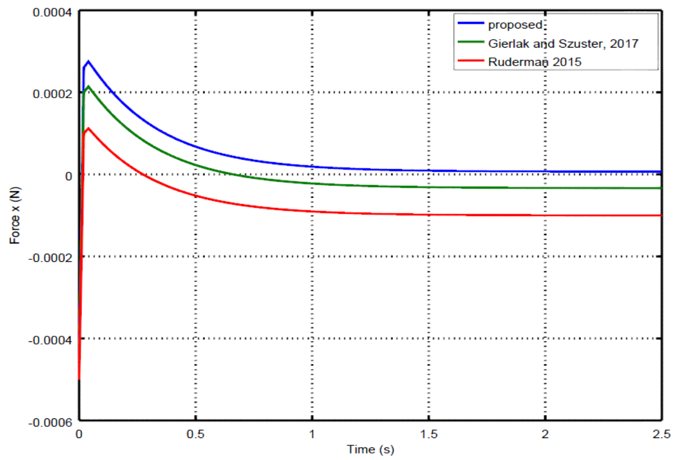

Fig. 2: Force variable $\bar{\mathbf{F}}_1$

Table 1: Two links robot parameters

Parameter	Value
m_1 Kg	0.0006
m_2 Kg	0.0006
l_1 m	0.5
l_2 m	0.5
l_{c1} m	0.25
l_{c2} m	0.25
I_1 $Kg.m^2$	0.6
I_2 $Kg.m^2$	0.6
g m/s^2	9.81

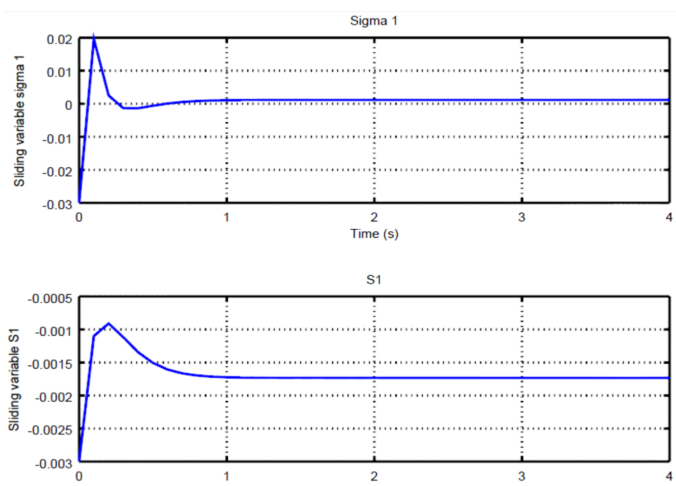

Fig. 3: Sliding variables σ and s

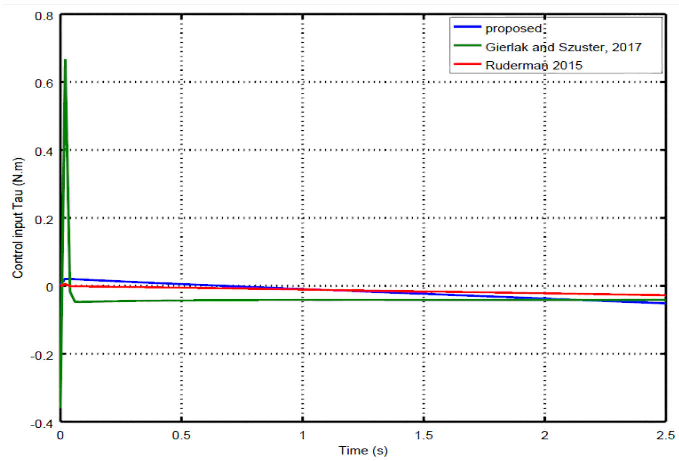

Fig. 4: Torque variable τ_1

efficient computation and then the derivation of the terminal-integral sliding mode control is eased by this multi-variable hysteresis model. Simulation results prove the superior performance of other force control robots in the presence of hysteresis and flexible environment.

6 Conclusion

In this paper, the design of an adaptive terminal-integral sliding mode force control for robotic manipulators in the presence of hysteresis in flexible environments is presented. The proposed controller provides a superior performance in comparison with other similar approaches found in literature. The selection of the hybrid terminal-integral sliding mode surface is done in a suitable way in order to obtain the control and adaptive gains laws that drive the force error to zero as times goes to infinity. Using of fractional order control can be considered as a future direction. Optimizing the sliding mode controller parameters with new metaheuristic techniques to obtain the best values for the sliding mode control law parameters is also another future work of this study.

7 Acknowledgments

This work is supported by the Robotics and Internet of Things lab of Prince Sultan University, Saudi Arabia.

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