Robust Tracking and Human-Compliance Control Using Integral Sliding Mode Control and T-S Fuzzy Disturbance Observer

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***Abstract*—In recent years, as robots and humans have started to work together more frequently in the same space, robots must be controlled under the consideration of human safety. For the safety of human, robots must comply with human force. On the contrary, to be robust, robot control requires high impedance against nonhuman disturbances. The proposed controller aims to achieve compliance and high impedance in a control scheme. The proposed structure consists of an integral sliding mode control (ISMC) and a human disturbance observer (HDOB). For compliance, the human force is identified by HDOB and given to ISMC. If the sliding mode dynamics are affected by human disturbances, then compliance with humans is achieved. For high impedance, disturbances outside the human frequency range are decoupled by the ISMC, so robust tracking is achieved. A novel T-S fuzzy DOB is introduced to the ISMC to decrease the maximum nonlinear gain, and this leads to lower chattering by the SMC.**

***Index Terms*—integral sliding mode, disturbance observer, compliance, robust robot control, human-compliance control, T-S fuzzy observer.**

I. Introduction

With the rapid development of robot technologies, robots are now present not only in the industrial field but also in our everyday life [1–3]. Around humans, robots must have low impedance to not cause harm to humans [4–6]. When the robots' work is far from humans, high impedance is needed for a better control performance [7–10]. To cope with these situations, a disturbance observer (DOB) that changes its impedance depending on the disturbance frequency was proposed in [7]. Compared to the usual DOBs in [11–13], this DOB considers robustness and safety together. However, it does not guarantee exact compliance, but only safety. We propose a novel control scheme that considers robustness and compliance at the same time to achieve control performance and safety together. A band-pass filter is designed for the human motion, and its output is reflected to the sliding surface of an integral sliding mode controller for compliance. The basic control scheme of this paper is PD-type impedance control, and integral sliding mode control (ISMC) is added to improve its robustness. The ISMC is a special SMC that can have the nominal dynamics of another control system and has no reaching phase [14–17]. In the SMC, a sliding surface is usually designed not to be affected by disturbances. However, in this paper, the surface is designed to be affected by human motion and, as a result, to achieve human compliance. This is the novel idea of this paper. A novel DOB is also used with the ISMC to decrease the maximum nonlinear gain. It is based on a T-S fuzzy model of a nonlinear system. A T-S fuzzy state observer is designed using linear matrix inequality (LMI), which considers both stability and pole placement [18, 19]. The observer gain must be designed to make the error dynamics converge to equilibrium considerably fast, with the time constant much lower than the frequency of the disturbance. In the equilibrium state, the disturbance is simply calculated algebraically using the error dynamics. With the proposed T-S fuzzy DOB, the overall ISMC has a lower nonlinear gain, and this leads to a decrease in chattering. In Chapter II, the problem is formulated, and the main controller scheme is followed in Chapter III. The simulation results are shown in Chapter IV and conclusions are given in Chapter V.

II. Problem Formulation

Consider the following robot manipulator:

$$\mathrm{A(q)}\ddot{q} + b(q,\ddot{q})\dot{q} + g(q) = \tau + \tau_{env}, \tag{1}$$

where $A(q)$ is the inertia matrix, $b(q,\ddot{q})\dot{q}$ is the centrifugal and Coriolis force, $g(q)$ is the gravity, and τ and τ_{env} are the input torque and environment torque, respectively. t_{env} includes the human torque. In this paper, torques are estimated by the DOB while allowing the passing of forces with the frequency of human motion.

When robots cooperate with humans, safety and robust control performance are required at the same time. These two requirements are contradictive. In this paper, ISMC and DOB are implemented to work together for these objectives. The tracking performance is described by the following error equation:

$$\ddot{e} + B\dot{e} + Ke = 0, \tag{2}$$

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where B and K are the damping ratio and spring constant, respectively, which determine the impedance. With the above tracking performance, compliance with humans is the same as

$$\ddot{e} + B\dot{e} + Ke = c\tau_h, \tag{3}$$

where c is the parameter that determines the degree of compliance and τ_h is the torque introduced by the human. The human force is reflected to the sliding surface, and ISMC makes the system robust for nonhuman disturbances.

III. Robust Tracking Control and Compliance Control

A. *Robust Impedance ISMC*

In Eq. (1), τ_{env} is assumed to consist of two torques as follows:

$$\tau_{env} = \tau_d + \tau_h, \tag{4}$$

where τ_d is the disturbance torque. The unknown τ_d is assumed to be bounded as

$$|\tau_d| < \tau_{max}. \tag{5}$$

The first step is to design the impedance controller, and then ISMC is added for robust tracking. The torque input for the desired impedance is determined as follows.

$$\tau = \mathrm{A(q)}(-B\dot{e} - Ke + u_n) + b(q,\ddot{q})\dot{q} + g(q), \tag{6}$$

where u_n is the input of ISMC that will need to be designed. With this input, the following error dynamic is obtained:

$$\ddot{e} + B\dot{e} + Ke = u_n + \tau_{env}. \tag{7}$$

The state space description for the above is

$$\dot{e}_a = A_a e_a + B_a(u_n + \tau_{env}), \tag{8}$$

where $e_a = \begin{bmatrix} e \\ \dot{e} \end{bmatrix}$, $A_a = \begin{bmatrix} 0 & 1 \\ K & B \end{bmatrix}$, and $B_a = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

To have the tracking performance of Eq. (2) even in the case of existing disturbances, the sliding surface is determined as

$$S = e_a + z = 0, \tag{9}$$

where $\dot{z} = -A_a e_a$.

The error dynamics on the sliding surface are as follows:

$$\dot{S} = \dot{e}_a + \dot{z} = 0, \tag{10}$$

$$\dot{e}_a = A_a e_a. \tag{11}$$

If the error states are on the sliding surface, then the error dynamic satisfies Eq. (11). This means that the sliding surface is not affected by disturbances and achieves a robust tracking performance. The SMC input that makes the states converge to the sliding surface is determined as follows. First, the Lyapunov candidate function is selected as

$$V = \frac{1}{2}s^T s,$$

and its time derivative is

$$\begin{aligned} \dot{V} &= \tfrac{1}{2}s^T\dot{s} \\ &= s^T(A_a e_a + Bu_n +_a (u_n + d) - A_a e) \\ &= s^T B_a(u_n + d). \end{aligned}$$

The following u_n satisfies $\dot{V} < 0$:

$$u_n = -\frac{B_a^T s}{|s^T B_a|}\tau_{max}. \tag{12}$$

The condition $\dot{V} < 0$ makes the error states converge to zero asymptotically. This causes s to converge to zero, and the states become on the sliding surface.

B. *Robust Compliance Control*

To design a robust compliance controller, the human force is estimated by robust DOB and fed to the sliding surface of the ISMC. Compliance control is achieved using a sliding surface with the reflected human force.

The sliding surface for compliance control in Eq. (9) is proposed to have the following virtual state:

$$\dot{z} = -A_a e_a - B_a u_n - c\hat{\tau}_h. \tag{13}$$

The estimated human force $\hat{\tau}_h$ is the output of human DOB (HDOB) as follows:

$$\hat{\tau}_h = Q_{HFB}(s)P^{-1}(s)(\tau + \tau) - Q_{HFB}(s)\tau, \tag{14}$$

where the band-pass Q-filter $Q_{HFB}(s)$ is designed as follows:

$$Q_{HFB}(s) = \left[\frac{Kw_H s}{(s + w_L)(s + w_H)}\right]^k, \tag{15}$$

where w_L and w_H are the lower cut-off and higher cut-off frequencies, respectively, k is a positive gain to raise the magnitude of the filter, and j is the order of the filter.

The structure of ISMC, which considers compliance, is shown in Fig. 1. The T-S fuzzy DOB is involved in this scheme.

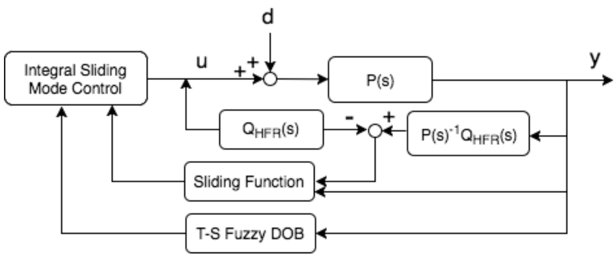

Figure 1. ISMC system with compliance control.

On the sliding surface (9), the error dynamic is

$$\dot{e}_a = A_a e_a + \tau_h. \tag{16}$$

The above equation shows the compliance control performance to human force.

The SMC input is the same as Eq. (12). By reflecting the human force to the sliding surface, compliance control is achieved. External forces, except from humans, are considered as disturbances and decoupled by the ISMC.

C. T-S Fuzzy DOB

In this paper, T-S fuzzy DOB is used as well as HDOB to decouple the low-frequency input disturbance and decrease the nonlinear gain of the ISMC.

To design T-S fuzzy DOB, the robot dynamic is described as the following state space form:

$$\dot{X} = F(X) + G(x)\tau + G(X)\tau_{env}, \quad (17)$$

where $X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$,

$F(X) = \begin{bmatrix} x_2 \\ A^{-1}(q)(b(q,\ddot{q})\dot{q} + g(q)) \end{bmatrix}$,

and $G(X) = \begin{bmatrix} 0 \\ A^{-1}(q) \end{bmatrix}$.

It is approximated by the following T-S fuzzy model:

$$\dot{X} = \sum_{i=1}^{p} \mu_i \left(A_i X + B_i \tau + B_i\, \tau_{env}\right), \quad (18)$$

$$y = \sum_{i=1}^{p} C_i X,$$

where μ_i is the membership function of the ith local linear model.

The proposed T-S fuzzy DOB is based on the nominal state observer:

$$\dot{X} = \sum_{i=1}^{p} \mu_i \left(A_i X + B_i \tau + L_i(y - C_i \hat{X}\right), \quad (19)$$

where L_i is the observer gain.

This paper does not focus on state estimation, but on the error dynamics. The estimated disturbance is algebraically calculated under the assumption that the error is already on the equilibrium state. In order to do this, the time constant of the error dynamics is set to be faster than the expected frequency of the disturbance. The error dynamics are given as follows.

The method proposed in [6] is used to achieve both stability and pole placement. In this method, the following inequality must be considered:

$$\begin{bmatrix} -rQ & qQ + QA_i^T + Y_i^T B_i^T \\ qQ + QA_i^T + Y_i^T B_i^T & -rQ \end{bmatrix} < 0, \quad (20)$$

where r and q are design parameters (radius and center of the circular region of the pole location, respectively) and Q is a positive-definite matrix.

If the error dynamics are fast enough, then the estimated disturbance is

$$\hat{d}_{TS} = \sum_{i=1}^{p} \mu_i \left((B_i^T B_i)^{-1} B_i^T (A_i - L_i C_i) e\right). \quad (21)$$

Consequently, the low-frequency disturbance is decoupled by the T-S fuzzy DOB and model uncertainty, and high-frequency disturbances are decoupled by the ISMC, and human force is reflected to the error dynamics through the sliding surface. The overall control input is determined as

$$u_s = -\frac{B_a^T s}{|s^T B_a|} d_{max} + \hat{d}_{TS}. \quad (22)$$

IV. Simulation

The proposed controller is simulated on a one-degree-of-freedom manipulator, which is the same system used in [7]. The band-pass Q-filter for human DOB is designed with a low cut-off frequency of 0.5 Hz and a high cut-off frequency of 5 Hz. The magnitude plot is shown in Fig. 2. With reference to Eq. (15), k is chosen as 4. The T-S fuzzy DOB is designed for three different observer eigenvalues (−50, −100, −200), but their frequency responses show a little difference as in Fig. 3.

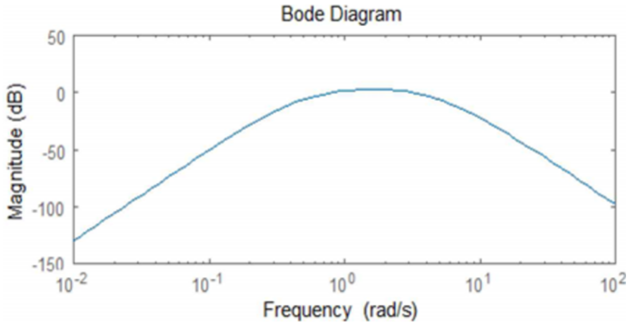

Figure 2. Magnitude plot of the band-pass Q-filter used for HDOB.

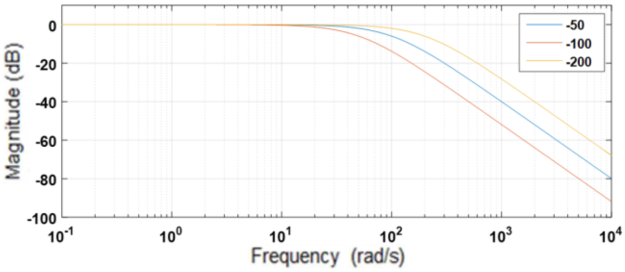

Figure 3. Magnitude plot of the T-S fuzzy LDOB.

To show the robust tracking performance for disturbances and compliance with human force, the outputs for the various frequencies are shown in Fig. 4.

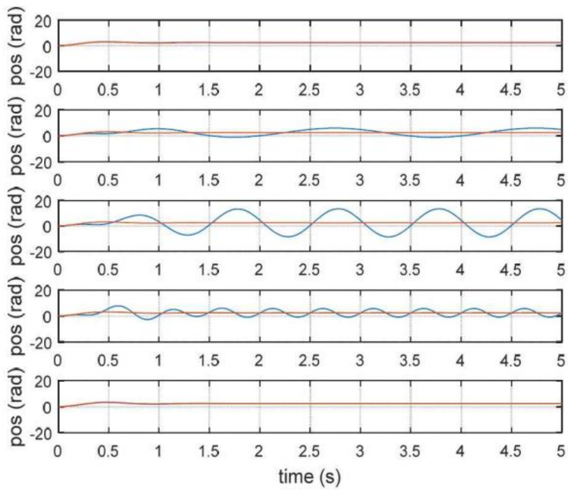

Figure 4. Output responses corresponding to input disturbance frequencies.

In Fig. 4, the red lines show the robust tracking performance of ISMC and the blue lines show the compliance with human force at 5 Hz and 5 N.

In Fig. 5, the proposed controller is simulated to show the time response for the time-varying disturbances with different frequencies. In the first 5 s, the system is given a nonhuman disturbance, and it shows a robust tracking performance. For the next 5 s, the system is given human forces and the compliance is proven by showing that the time response is affected by the human force.

Lastly, the proposed controller is simulated with the T-S fuzzy DOB and, at the same time, the controller with different ISMC gains. It is shown that, with the T-S fuzzy DOB, the ISMC gain can be reduced. As a result, the inevitable chattering caused by ISMC is lessened.

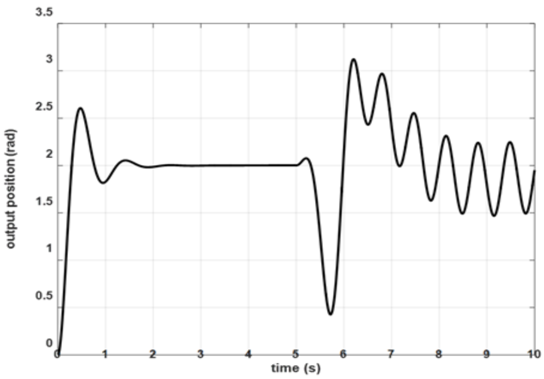

Figure 5. Output responses corresponding to input disturbance frequencies.

Table I shows the allowable nonlinear gain of ISMC for the given disturbance.

TABLE I. NONLINEAR GAIN SIZE WITH T-S FUZZY DOB.

Disturbance / DOB	5(N)	10(N)
Without DOB	6	11
With DOB	3	4

V. CONCLUSIONS

Compliance control for the safety of humans and robust impedance control for unknown disturbances are realized in a control scheme. Robust control is achieved using ISMC and compliance control is achieved by reflecting the human force to the sliding mode through a human band-pass filter. Even though robustness and compliance are contradictive control problems, they are well resolved in the proposed scheme. Additionally, a novel T-S fuzzy DOB is introduced to decrease the nonlinear gain of the ISMC for the same size of disturbance, and it lessens the input chattering caused by ISMC.

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