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Bounded Compensation with Friction Estimation for Accurate Motion Tracking and Compliant Behavior of Industrial Manipulators

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Abstract— **This paper proposes a control structure for accurate tracking and compliant behavior of industrial manipulators without additional sensors. To achieve control objectives, friction, one of the biggest causes of performance degradation, should be compensated. For tracking performance, the estimated friction cancels most friction effects as a feed-forward, and the modified robust control structure eliminates the remaining friction uncertainty, which was originally equivalent to the disturbance observer. For compliant behavior, the compensation force fed to the real plant is bounded in contrast to the conventional disturbance observer structure. The compensation bound could be determined through the experiments. The proposed method is validated by experiments with a 6-DOF collaborative industrial manipulator.**

I. INTRODUCTION

The abilities to track motion accurately and adapt to the environment are essential features for an industrial collaborative manipulator which operates in unstructured environments. Motion tracking has been the most basic function of industrial manipulators, and compliant behavior has become gradually crucial in modern robotics. Both abilities are often required simultaneously to perform a complex task, such as an assembly scenario that includes free and contact-rich motion. In addition, those are required to avoid excessive force when incidental contact occurs, even while tracking the desired trajectory accurately in free motion.

Friction is one of the main problems for industrial manipulators to achieve such control objectives. Each joint of industrial manipulators is often actuated by a high ratio reduction drive for high payload. As a side-effect, friction is induced and critically degrades the control performance, such as tracking accuracy [1]. Hence, the robot should overcome friction while adapting to external forces to accomplish the control objectives. An additional sensor, such as an F/T sensor or joint torque sensor, can be used to measure the external force. But it always increases the cost and burden of system integration. Accordingly, it is necessary to study the sensorless friction compensation method to achieve the control objectives.

Friction estimation is one of the typical approaches by adding estimated value to cancel the real friction, which can be classified into model-based and model-free approaches. Model-based approach [2] requires a proper mathematical model that can describe the complex phenomenon of friction. Friction models can be classified again into the static friction model (Coulomb model, viscous model) and the dynamic friction model(LuGre model [3], GMS model [4]). In recent studies, temperature and external load are also incorporated into the existing model [5], [6], [7] for more accurate estimation. However, these model-based approaches may require a complicated identification procedure as the more expressive model is selected. On the other side, the model-free approach using neural network [8], [9] can estimate the friction without an analytical model. But, it requires much data and a long learning time for accurate estimation. In addition, it is difficult to estimate friction precisely because of time-varying properties caused by heat and wear.

In order to deal with time-varying and uncertain friction, intelligent friction compensation methods [10], [11] have been utilized. However, those intelligent methods often do not consider interaction. Friction observer can also counteract time-varying friction uncertainties, but those studies concentrate on the motion control [12] or require joint torque sensors [13].

The proposed method utilizes both prior knowledge of friction and robust control structure for accurate motion tracking and compliant behavior simultaneously. In the related previous studies, the model-based observer structure has been widely utilized to estimate the external force without additional sensors so that it detects collision [14], [15] or implements compliant control(or force control) [16], [17]. In order to eliminate the need for an analytical model, the learning-based inverse dynamics identification also has been suggested [18], [19]. However, in the collision detection literature, the modeling error and sensor measurement may cause false alarms, which cause unnecessary interruption and requires a proper strategy to recover the original controller. Meanwhile, the sensorless compliant control literature focused on external force estimation. Thus, accurate motion tracking cannot be guaranteed when modeling error (e.g., friction uncertainty) exists. In [20], a detuned small integral action allows estimating the transient external force for an assembly task. Still, it requires prior knowledge about specific task models for better performance and shows the

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bad performance due to friction in the absence of contact.

The main contribution of this paper is to propose a control structure that can achieve accurate motion tracking in free motion and compliant motion during contact without an additional sensor. The proposed method modifies the robust control scheme, originally equivalent to the disturbance observer (DOB) structure. Estimated friction cancels the majority of friction as feed-forward first, and the modified structure would compensate for the remaining uncertain friction for tracking accuracy. In contrast to the conventional observer, the compliant behavior is achieved by limiting the compensation input within the user-defined bound, which could be determined through an experiment. The excess compensation input is added to the nominal plant to keep it close to the real plant. Although the friction uncertainty causes the trade-off between accurate motion tracking and adaptability to the external torque, both can be accomplished using the simple static friction model in the experiment.

The rest of this paper is organized as follows. First, the problem of this paper is stated, and the preliminaries are provided in Section II. Section III explains the proposed method. In Section IV, the experimental results are validated, and the proposed method is discussed in Section V.

II. Problem Statement and Preliminary

This section provides the problem statement and research background. The proposed method is based on the nonlinear robust internal-loop compensator (NRIC) structure [21], which is equivalent to the disturbance observer (DOB) structure [22]. Therefore, the NRIC structure will be introduced briefly compared to the conventional DOB structure.

A. Problem Formulation

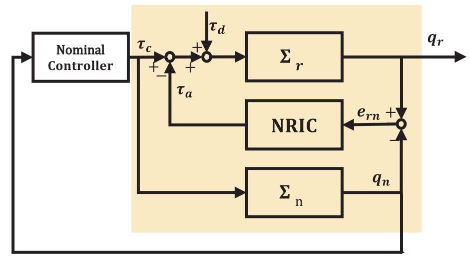
For the rigid joint manipulators, the dynamics is generally expressed as

$$M(q)\ddot{q} + C(q)\dot{q} + g(q) = \tau_m + \tau_{ext} - \tau_f \tag{1}$$

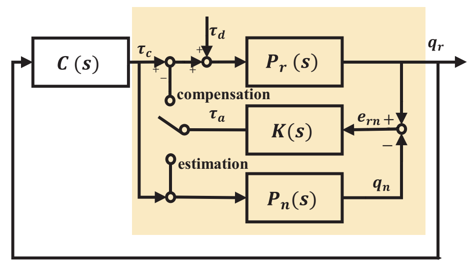
where $M(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $C(q,\dot{q})\dot{q} \in \mathbb{R}^n$ is an Coriolis/centrifugal force, $g(q) \in \mathbb{R}^n$ is the gravity force, $\tau_m \in \mathbb{R}^n$ is the input control torque, $\tau_{ext} \in \mathbb{R}^n$ is the external force when interaction occurs with environment, and $\tau_f \in \mathbb{R}^n$ is the friction at each joint.

The objective of this paper is to propose the friction compensation method without any additional sensor that satisfies the following control objectives: 1) accurate motion tracking in free motion; 2) compliant motion during contact to avoid excessive force. In order to achieve both objectives at the same time, the input torque τ_m should reject the friction τ_f but adapt to the external force τ_{ext}. The absence of the external sensor results in the difficulty of distinguishing the exact value of τ_{ext} from τ_f. The prior knowledge of friction can achieve both control objectives, but it is too difficult for the only friction estimation method to compensate for friction accurately, as stated earlier.

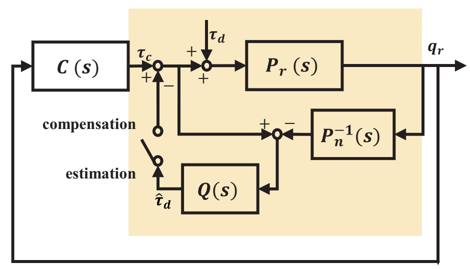
As a matter of fact, the exact robot model parameters are also necessary for more accurate position tracking. But, in this work, we assume that the model uncertainty does not exist and remains as a future work which will be discussed in Section V.



(a) NRIC Structure



(b) RIC Structure



(c) DOB Structure

Fig. 1. Three equivalent control structures are illustrated in the yellow-shaded region. The NRIC structure (a) is the nonlinear extension of the RIC structure (b). The equivalence between the NRIC and DOB is explained by the RIC structure.

B. Nonlinear Robust Internal-loop Compensator

The main philosophy of the NRIC structure is that: first, the nominal controller is designed for the nominal plant to achieve desired performance; second, the deviation from the nominal plant is attenuated by simply adding the PID-type auxiliary input. Namely, the robot controller achieves additional robustness from the auxiliary input.

Accordingly, the nominal plant is introduced newly, as shown in Fig. 1(a). Then, the dynamics of the real/nominal plant are expressed as

$$\begin{aligned} M_r\ddot{q}_r + C_r\dot{q}_r + g_r &= \tau_c - \tau_a + \tau_{ext} - \tau_f \\ M_n\ddot{q}_n + C_n\dot{q}_n + g_n &= \tau_c \end{aligned} \tag{2}$$

where the subscript "r" and "n" represent "real" and "nominal" plant, respectively, and $\tau_c \in \mathbb{R}^n$ is the output of nominal controller, $\tau_a \in \mathbb{R}^n$ is the auxiliary input. The dependency is omitted for readability. Again, by the assumption, $M_r = M_n, C_r = C_n$, and $g_r = g_n$ in this work.

Due to the various disturbances, such as friction, the error between the real plant and the nominal plant is induced. In order to attenuate the error, the auxiliary input is designed as

$$\tau_a = (K + \frac{1}{\gamma^2} I)(\dot{e}_{rn} + K_p e_{rn} + K_I \int e_{rn}), \quad (3)$$

where $\gamma > 0$, and $K, K_I, K_P > 0$ are diagonal matrices satisfying $K_p^2 > 2K_I$. By adding the τ_a to the real plant, the disturbances are rejected, and the controller achieves additional robustness [21].

When there is no additional sensor to measure τ_{ext}, the external force will be incorporated into the disturbances as follows

$$\tau_d = \tau_{ext} - \tau_f. \quad (4)$$

Therefore, the external force also will be compensated in the NRIC structure.

C. Equivalence to the DOB

As a matter of fact, the NRIC structure is the extension of robust internal-loop compensator (RIC) [23] to the nonlinear system[1] as shown in Fig. 1. Therefore, the equivalence to the DOB can be explained with the RIC structure. Likewise, in the RIC structure, the control input τ_c is added to both real plant $P_r(s)$ and nominal plant $P_n(s)$, and the error between two plants is attenuated by PID controller $K(s) = (k + \frac{1}{\gamma^2})(s + k_p + k_i \frac{1}{s})$ with Laplace variable s. Then, the transfer function from τ_c, τ_d to q_r can be derived as follows

$$q_r = \frac{P_r(s)[1 + P_n(s)K(s)]}{1 + P_r(s)K(s)} \tau_c + \frac{P_r(s)}{1 + P_r(s)K(s)} \tau_d.$$

On the other side, the well-known transfer function in the DOB structure is expressed as

$$q_r = \frac{P_r(s)P_n(s)}{X(s)} \tau_c + \frac{P_r(s)P_n(s)[1 - Q(s)]}{X(s)} \tau_d,$$

where $X(s) = P_n(s) + [P_r(s) - P_n(s)]Q(s)$. Then, the RIC structure becomes equivalent to the standard DOB by setting the low pass filter $Q(s)$ in the DOB as [23]

$$Q(s) = \frac{P_n(s)K(s)}{1 + P_n(s)K(s)}. \quad (5)$$

From the given $K(s)$, $Q(s)$ in (5) behaves as a low-pass filter as described in the section II-C of [21]. Since the NRIC structure and DOB structure are equivalent, it can be easily seen that the output of $K(s)$ in the RIC (NRIC) structure is the estimated disturbance in the DOB structure, i.e.

$$\tau_a = \hat{\tau}_d. \quad (6)$$

III. Proposed Method

In this section, the overall control structure for friction compensation is explained. The proposed controller will be introduced in three parts: nominal controller, friction compensation as a feed-forward, and modified NRIC structure.

[1]One modification is that the nominal state is fed back to outer-loop controller $C(s)$. This allows for the design of the outer-loop controller and disturbance rejection scheme separately and makes stability analysis easier [21].

A. Nominal Controller

For a given nominal plant, the nominal controller can be easily designed to satisfy the desired tracking performance. Typically, the inverse dynamics control can be employed, which is given by

$$\tau_c = M_n(\ddot{q}_d + k_v \dot{e}_{dn} + k_p e_{dn}) + C_n \dot{q}_n + g_n \quad (7)$$

where $q_d, \dot{q}_d, \ddot{q}_d$ are desired motion, $e_{dn} = q_d - q_n$, and k_v, k_p are the PD gains. Then, the inverse dynamics control shapes the nominal dynamics into the error dynamics $\ddot{e}_{dn} + k_v \dot{e}_{dn} + k_p e_{dn} = 0$ which guarantees the exponential stability.

For the case of task space motion tracking application, the inverse dynamics controller with acceleration kinematics can be obtained as

$$\begin{aligned} \tau_c &= M_n J_n^{-T}(\ddot{p}_d - \dot{J}_n \dot{q}) + C_n \dot{q}_n + g_n \\ \text{with } \ddot{p}_d &= M_d^{-1}(K_d(p_d - p_n) - B_d \dot{p}_n) \end{aligned} \quad (8)$$

where $J(q) \in \mathbb{R}^{6\times n}$ is a Jacobian matrix, and $p \in \mathbb{R}^6$ is task space pose of end-effector, and subscript "d" represents "desired". This controller also can achieve asymptotic stability in the nominal plant.

Although any motion tracking controller can be selected, the nominal controller requires one assumption for the compliant behavior as follows.

Assumption 1: The nominal controller τ_c does not include the integral action.

Considering the nominal controller output τ_c also applied to the real plant, the integral action will try to eliminate the steady-state error, and the excessive force will be induced when the robot contacts environments. Therefore, the integral action should not be used in the nominal controller for the compliance capability to the external force.

B. Friction compensation as a feed-forward input

To decrease the effect of friction, the estimated friction $\hat{\tau}_f$ is added with the nominal controller τ_c to the real plant as shown in Fig. 2. Any model-based or model-free friction estimation methods can be used [3]–[9]. Accordingly, the disturbance is defined again as follows

$$\tau_d = \tau_{ext} - \tau_f + \hat{\tau}_f. \quad (9)$$

The friction uncertainty, denoted by $\tilde{\tau}_f = \hat{\tau}_f - \tau_f$, can become small through the expressive friction model. Nevertheless, accurate friction estimation requires a complicated identification procedure and the friction uncertainty is highly likely to remain.

C. Modified NRIC structure

This subsection introduces the modified NRIC structure to achieve accurate motion tracking and compliant behavior. Before explaining it, we present the properties of the NRIC structure first. Depending on the port where τ_a is added, the NRIC structure works as either compensator or estimator, as shown in Fig. 1. When τ_a is added to the real plant, the NRIC structure compensates for the disturbance so that the real plant behaves as the nominal plant. Then finally, the

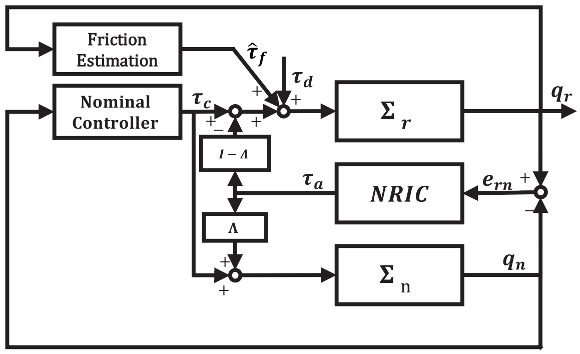


Fig. 2. The NRIC structure is modified to compensate for the disturbance partially, and the rest is added to the nominal plant. For the only real plant, the estimated friction is applied to cancel most of the friction.

robust stability and performance could be fulfilled [21]. In contrast, when τ_a is added to the nominal plant, the NRIC structure makes the nominal plant behaves as the real plant without any influence on the real plant.

From this idea, the control structures are suggested, as shown in Fig. 2. The robot dynamics can be rewritten as follows

$$\begin{aligned} M_r\ddot{q}_r + C_r\dot{q}_r + g_r &= \tau_c - (I-\Lambda)\tau_a + \tau_d \\ M_n\ddot{q}_n + C_n\dot{q}_n + g_n &= \tau_c + \Lambda\tau_a. \end{aligned} \tag{10}$$

where $\Lambda \in \mathbb{R}^{n\times n}$ is a diagonal matrix whose elements are greater than 0, less than 1, and will be determined later. In the proposed structure, the auxiliary input τ_a is divided into two parts $(I-\Lambda)\tau_a$ and $\Lambda\tau_a$, then, each term is applied to the real plant and nominal plant, respectively. When $\Lambda = 0$ (I), the proposed structure become disturbance compensator (estimator). In the case of $\Lambda \neq 0$ and $\Lambda \neq I$, the disturbances on the real plant are partially compensated, and the rest of the estimated disturbance affects the nominal plant. Under the assumption that the dynamics of NRIC structure is sufficiently fast, i.e., $\tau_a \approx \tau_d$, both real and nominal plants are affected equally by $\Lambda\tau_d$. Namely, the proposed structure attenuates the error between two plants while compensating for the disturbance partially as the ratio of $(I-\Lambda)$.

Remark 1: It is worthwhile to note that the rest of the disturbance is also fed back to the nominal plant. This prevents the nominal plant from drifting away from the real plant. Otherwise, τ_a does not work as an instantaneous disturbance anymore.

Finally, the diagonal matrix Λ should be determined appropriately. In order to achieve compliant behavior when τ_{ext} exists, each element in Λ, denoted by λ_i is set as below

$$\lambda_i = \begin{cases} 0 & \text{if } |\tau_{a,i}| \leq f_i(\dot{q}_i) \\ 1 - \frac{f_i(\dot{q}_i)}{|\tau_{a,i}|} & \text{if } |\tau_{a,i}| > f_i(\dot{q}_i) \end{cases}$$

where $f_i(\dot{q}_i)$ is the user-defined joint velocity dependent function, called compensation bound. For simple example, f_i can be defined with constant c_i, i.e. $f_i(\dot{q}) = c_i$. As shown in Fig. 3, the λ_i is determined to limit the compensation term τ_a to $f_i(\dot{q}_i)$, which is fed back to the real plant. When $f_i(\dot{q}_i)$ is determined to be larger than the magnitude of friction uncertainty $|\tilde{\tau}_{f,i}|$, the modified NRIC structure will compensate for the remaining friction uncertainty effectively in free motion where disturbance includes only friction uncertainty. Then, finally, accurate motion can be achieved. When the interaction occurs and $|\tau_{a,i}|$ becomes greater than $f_i(q_i)$, the NRIC does not reject the excess term $|\tau_{a,i}| - f_i(q_i)$ so as to make the robot adapt to the external force. As the trade-off of accurate motion tracking, this control structure will require larger external torque than the compensation bound for the compliance motion. Therefore, more accurate friction knowledge is preferred for sensitive compliance motion to set the compensation bound $f_i(\dot{q}_i)$ more tightly. Nevertheless, the simple static friction model is sufficient to show compliant behavior with human interaction or environment, which will be shown in the experiment.

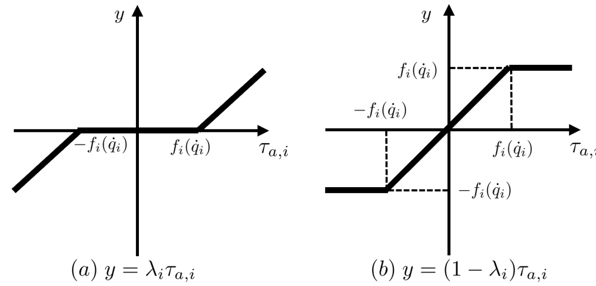


Fig. 3. The compensation term is limited according to λ_i, which are the element of Λ. The graphical view of each term is fed back to (a) the nominal plant and (b) the real plant.

Remark 2: The compensation bound's dependency on the joint velocity can help alleviate the trade-off between tracking accuracy and compliant behavior. The friction uncertainties $\tilde{\tau}_f$ can vary according to the joint velocity because many friction models, such as the LuGre model, depend on the joint velocity. The compensation bound can be set through the friction estimation results or experiment.

IV. Experimental Results

To verify the proposed method, two experiments were performed with a 6-DOF collaborative industrial manipulator (Indy7, Neuromeka). The first experiment implements task space tracking in free motion, and tracking accuracy is compared according to the compensation bound $f_i(\dot{q}_i)$. The second experiment is designed to validate accurate tracking in free motion and compliant behavior during interaction with a rigid environment(acryl plate) and human operator. The experiment results can also be found in the accompanying video.

For the friction estimation, the simple static friction model is used, which is defined as

$$\tau_f = F_c + F_{v_1}(1 - e^{-|\frac{\dot{q}}{F_{v_2}}|})$$

where F_c is Coulomb friction, F_{v_1}, F_{v_2} are the coefficients of

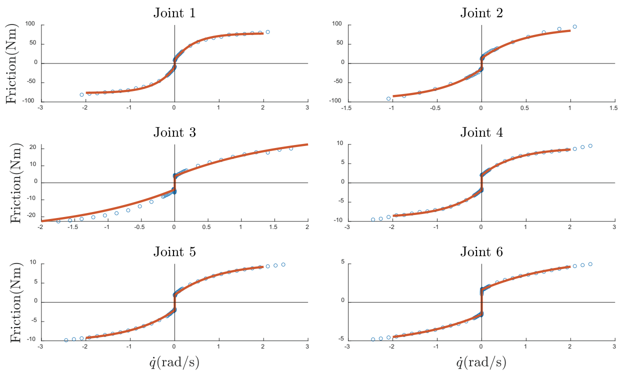
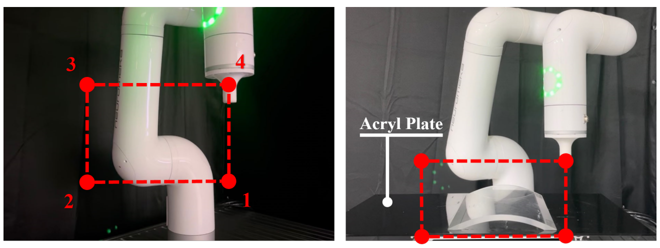


Fig. 4. The fiction data (blue) and estimated friction value (orange) by the identified parameters of the static friction model for each joint.



(a) Task space tracking (rectangle) **(b) Compliant motion**

Fig. 5. (a) The first experiment is designed to track the rectangle-shaped motion in free space. (b) On the other hand, in the second experiment, the robot is also commanded to track the rectangle-shaped motion, but the acryl plate blocks the desired motion. At the final position, human interaction is also included.

the exponential model[2]. The identification results are shown in Fig 4, and are used for all experiments as a feed-forward. The compensation bound is assumed to be a constant value as $f(\dot{q}) = \alpha(1.0, 1.0, 1.0, 0.5, 0.5, 0.5)$ where α is a constant value. The bound for each joint was selected empirically. Also, the task space PD controller (8) was used for the all experiments. Each parameter in (3) and (8) is noted in the attached video.

A. Exp1: Tracking accuracy according to the compensation bound

In the first experiment, the end-effector is commanded to track the rectangle-shape motion while desired orientation is defined to keep the initial orientation as shown in Fig. 6(a). The width and height of the rectangle is 0.24m and 0.18m, respectively. According to the compensation bound modulated by α, the tracking results are plotted in Fig. 6. Without friction compensation (green dotted line), the robot could not follow the desired motion accurately due to the friction at each joint. When $\alpha = 0.0$, meaning that the compensation term is not fed back to the real plant (i.e., estimated friction is only used to cancel the friction), the robot tried to track the desired motion closely compared

[2]If more precise dynamic friction model such as LuGre or GMS model is utilized, it is expected to improve motion tracking accuracy and adaptability at the same time.

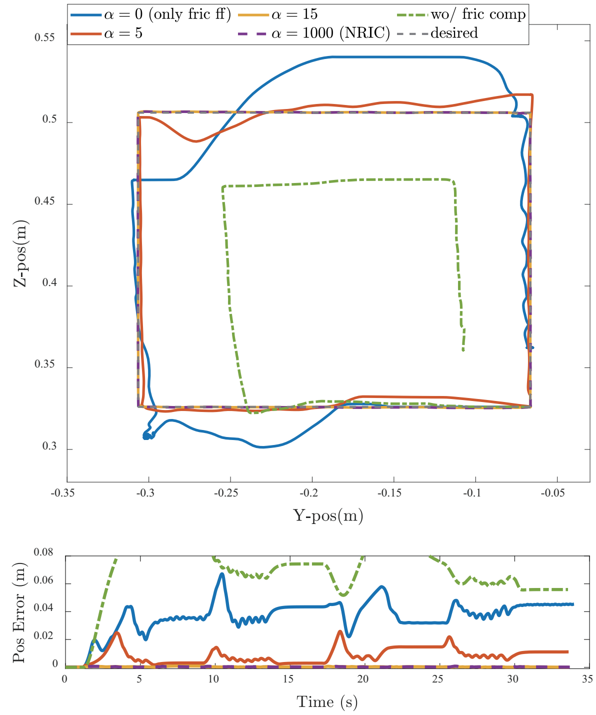


Fig. 6. The end-effector is commanded to track the rectangle shape according to α. Top: Task space tracking results. Bottom: Position error compared to the ideal motion (i.e., without any disturbance).

to the case without any friction compensation. However, the tracking performance still needs to be improved. As α increases, it is shown that the robot can effectively reject the friction uncertainty and track the desired motion more accurately. When α is extremely large, the control structure becomes the NRIC structure.

B. Exp2: Tracking with interaction

In the second experiment, the tracking scenario was also considered again, but interaction with a rigid environment (acryl plate) and the human operator was included. The compliant behavior of the proposed control structure can be checked whether the robot adapt to the acryl plate and the force exerted by human operators. Since the acryl plate obstructs desired motion in the z direction, the robot should adapt to the acryl plate not to generate excessive force. At the same time, the robot is required to track the desired motion in free space. For achieving both accurate motion tracking and compliant behavior simultaneously, α is set to 15.0 based on the result of the first experiment.

As shown in the Fig.7 (a), in the middle of tracking, the robot trajectory (blue line) conforms to the acryl plate and does not proceed in the (-) z direction, while tracking the desired motion (orange dotted line) in free space. At the end of the tracking, the end-effector is controlled to regulate the desired position. When the human operator exerted the force to the end-effector, it shows compliant motion as shown in Fig.7 (a) and (b). When the interaction occurred, the magnitude of τ_a increases and exceed the compensation

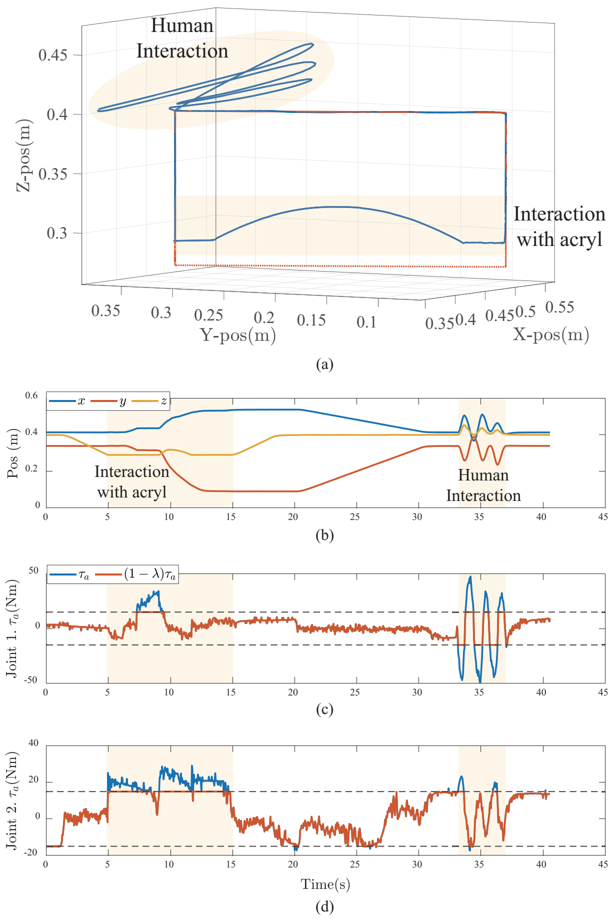


Fig. 7. Tracking scenario with α = 15.0, including interaction with the acryl plate (in the middle of tracking) and human interaction (at the end of tracking). (a) Task space tracking results (3D plot) (b) the position graph of end-effector (c) compensation term graph of joint 1 (d) compensation term graph of joint 2. The yellow-shaded region represents the interaction that occurred.

bound $f_i(\dot{q})$, as shown in Fig.7 (c) and (d). The robot adapted to the excess compensation term and showed complaint behavior. The compliant motion can be also found in the attached video.

V. Discussion

In this paper, the modified robust control structure for accurate tracking and compliant behavior is proposed. With the friction estimation and limiting the compensation with proper bound, both accurate motion and compliant behavior could be achieved at the same time. The compensation bound could be set through the friction identification results and experiment.

In the proposed structure, the exceeding compensation force $\lambda\tau_a$ is fed back to the nominal plant. This feedback prevents the nominal plant from going far away from the real plant. Otherwise, the nominal plant will follow the desired pose regardless of the real plant. Even if $\lambda\tau_a$ is not fed back to the nominal plant, compliant behavior can be achieved during the interaction. In this case, however, the real plant should follow the desired trajectory with only τ_a, whose absolute value is limited by $f_i(\dot{q}_i)$ after the interaction disappears. This is because the nominal controller τ_c relies on the nominal plant, which is already close to the desired pose. In contrast, in the proposed control structure, the nominal plant also does not follow the desired position during contact and is close to the real plant. Therefore, the real plant is driven by both τ_a and τ_c after the interaction.

Although the proposed method is validated through the experiments, the theoretical explanation, such as stability and passivity, is still insufficient. In future work, such theoretical explanations will be incorporated. Besides, since the proposed method is based on robot dynamics, the model uncertainty also should be considered in future work. The model uncertainty will work as a disturbance; thus, the large compensation bound would be necessary at the high velocity for accurate motion tracking. Nevertheless, the accurate motion tracking and compliant behavior could be achieved at the same time within the low velocity (about 0.15 rad/s).

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