# Torque-sensorless Impedance Control for an Actuator with Compound Planetary Gearbox for reducing External Contact Force

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Abstract-In recent years, the demand for collaborative robots has been increasing. As collaborative robots must be safe against contact. The purpose of this research was to develop robots that can perform tasks involving contact in collaboration with humans. A torque sensor is generally used to detect the external force at contact, but can reduce the rigidity of the robot. Thus, in this paper, we propose impedance control without a torque sensor for an actuator comprising a motor and reduction gear. Position-control-based impedance control was applied to the proposed method, and the torque can be estimated without a torque sensor using a highly efficient reduction gear. In addition, an external-force feedback gain is introduced for position-control-based impedance control and an external contact force reduction method is realized based on the angular transmission error of the reduction gear. From experiments, the proposed method achieved both position control and force control. As a result, the external contact force was reduced by approximately 10%.

## I. INTRODUCTION

In recent years, there has been an increasing demand for collaborative robots that can work in environments where people are present. Safety against any risk of contact with humans is important for application of collaborative robots. Therefore, actuators used in robot joints require force control in addition to position control. Several studies have focused on force control, and include using torque sensors in robot hands to detect external torques as well as attaching torque sensors to all joints of the robot [1], [2]. However, as a torque sensor is a mechanism for detecting strain, there is a problem in that the rigidity of the robot decreases. Meanwhile, methods for controlling force without using a torque sensor have been proposed, and there is research considering a direct drive motor [3]. However, as direct drive motors with high output are large, the joints of the robot become large.

Therefore, the purpose of this study is to achieve both position and force control using angle information that is fed back from the motor and load side encoders for the robotic joint. Herein, we propose a torque sensorless impedance control method based on the motor and load side position information. A harmonic drive is used as a reduction gear for actuators [4]. However, this gear has low backdriveability, so external torque is difficult to estimate. Therefore, in this research, a compound planetary gearbox for robots is used [5]. This reduction gear can achieve high power transmission efficiency even at high reduction ratios. Furthermore, the external torque on the output shaft can be estimated from the information of the motor and load side encoder without using a torque sensor. In the proposed method, the actuator comprises a reduction gear and a motor, and a two-inertial system is modeled with the motor and load side such as the link. Then, a position-control-based impedance control [6] without a torque sensor and the acceleration control based on a disturbance observer [7] are applied. The external torque applied to the load side is estimated using the multiencoder-based disturbance observer [8]. The estimated external torque is fed back, and the virtual machine impedance is designed based on that information. Here, an approach that applies virtual machine impedance according to the estimated external force has been proposed [9]. However, this approach realizes flexible control by switching between flexible mechanisms and impedance control. Therefore, we apply an external-force feedback gain according to the external torque for the proposed torque-sensorless impedance control. This realizes position tracking for target values and flexibility against external disturbance. The external-force feedback gain increases when the non-external torque and the position tracking control become equivalent to the highly compliant control. Meanwhile, when the external torque is applied from the environment, the external-force feedback gain decreases exponentially according to the external torque, and the system becomes softer. Therefore, flexible control is possible in response to various external torques seamlessly, including contact with people and obstacles.

In addition, a method is proposed in this paper for decreasing the external contact force. Several methods for contact detection that do not use a torque sensor have been suggested. These methods use the jerk from the external force or the dither signal [10], [11]. However, none of the works incorporated an actuator that uses a reduction gear with backlash. Furthermore, a method has been proposed based on the angular transmission error of the reduction gear [12]. In this study, the backlash of the reduction gear was used to quickly detect contact and decrease the external contact force by increasing the response of compliance for the system. The proposed method assumes that the angular transmission error between the motor and load side during contact affects the load side. The influence of the external contact force based on the angular transmission error is estimated using the angular acceleration information on the motor and load side. Then, this influence is fed back as a compensation term for the external torque to assist the

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Fig. 1. Overview of the experimental device

change of the external-force feedback gain.

The remainder of this paper is organized as follows. In section II, the modeling of the actuator consisting of a motor and a reduction gear is described. Section III details the proposed impedance control method and the external contact force reduction method based on angular transmission error. Section IV presents the effectiveness results of the proposed method obtained experimentally. Finally, section V concludes this work.

## II. EXPERIMENTAL DEVICE AND MODELING

In this section, we will explain the experimental device and model of the actuator. Fig. 1 depicts an overview of the experimental device used in this research. As shown in Fig. 1, the experimental device comprises a motor, reduction gear, torque sensor, link that applies load, and two encoders that observe angle information. The torque sensor is used only for reference value. A block diagram of the actuator model is presented in Fig. 2. In the actuator, the motor and link are connected through the reduction gears. This is modeled as the following two-inertia system:

$$J_m \ddot{\theta}_m + \tau_f + \tau_{dis} = \tau_m - \frac{1}{n} \tau_s \tag{1}$$

$$J_l \ddot{\theta}_l = \tau_s - \tau_{ext} \tag{2}$$

$$\tau_s = K_s \Delta \theta \tag{3}$$

where  $J_m$  and  $J_l$  are the inertias of the motor and load sides,  $\ddot{\theta}_m$  and  $\ddot{\theta}_l$  are the angular accelerations of the motor and load sides, and  $\tau_m$ ,  $\tau_s$ ,  $\tau_f$ ,  $\tau_{dis}$ ,  $\tau_{ext}$ , n,  $K_s$ , and  $\Delta\theta$  are the motor torque, torsion torque, friction torque, disturbance torque on the motor side, external torque on the load side, reduction ratio, torsion spring constant, and torsion angle including backlash. This model considers backlash as a dead zone. Moreover, the differential term is obtained by pseudo-differentiating the angle information obtained from the encoder.

## III. PROPOSED POSITION AND FORCE CONTROL METHOD

In this section, we describe the proposed torque-sensorless impedance control, for achieving both position and force control without a torque sensor. Fig. 3 presents a block diagram of the proposed method. Each component is detailed in the following subsections.



Fig. 2. Block diagram of the actuator



Fig. 3. Block diagram of the proposed method

#### A. Acceleration control based on disturbance observer

This section describes the acceleration control based on a disturbance observer (DOB). DOB estimates disturbances such as modeling errors that are applied to the motor side [13]. In this study, a first-order lag low-pass filter is used for disturbance estimation. The equation for the estimated disturbance torque is given by

$$\hat{\tau}_{dis} = \frac{g_{dob}}{s + g_{dob}} (\tau_m^{ref} + sg_{dob}J_m\theta_m) - sg_{dob}J_m\theta_m \quad (4)$$

where  $\hat{\tau}_{dis}$  and  $g_{dob}$  are the estimated value of the disturbance torque on the motor side and the cutoff frequency of the disturbance observer, respectively. The estimated disturbance is fed back and the motor side is nominalized. Then, a method is applied to realize acceleration control as acceleration commands are provided to the nominalized system [14]. Acceleration control based on the estimated disturbance torque is performed as follows:

$$\tau_m^{ref} = n J_m \ddot{\theta}^{ref} + \hat{\tau}_{dis} \tag{5}$$

## *B. External torque estimation using multi-encoder-based observer*

This section describes the external torque estimation using a multi-encoder-based observer (MEDOB). A disturbance observer based on a multi-encoder is applied as a method to estimate the external torque applied to the load side of the actuator [8]. From (1) and (2), the external torque  $\tau_{ext}$  applied to the load side is expressed as:

$$\tau_{ext} = n\tau_m^{ref} - J_l\ddot{\theta}_l - nJ_m\ddot{\theta}_m - n\tau_{fmodel} \tag{6}$$

where  $\tau_{fmodel}$  is the friction model. The friction of the reduction gear as seen from the motor side is modeled in advance and subtracted from the external torque estimation of MEDOB. The friction model is expressed by the following equation considering viscous friction and Coulomb friction.

$$\tau_{fmodel} = D_v \dot{\theta}_m + \tau_{fc} \mathrm{sgn}(\dot{\theta}_m) \tag{7}$$

where  $D_v$  is the viscous friction coefficient and  $\tau_{fc}$  is the Coulomb friction torque. This model provides a dead zone to prevent chattering. From the relationship of (6), the MEDOB based on the motor and load side information is expressed as:

$$\hat{\tau}_{ext} = \frac{g_{medob}}{s + g_{medob}} (n\tau_m^{ref} + sg_{medob}J_l\theta_l + sg_{medob}nJ_m\theta_m - \tau_{fmodel}) - sg_{medob}J_l\theta_l - sg_{medob}nJ_m\theta_m$$
(8)

where  $\hat{\tau}_{ext}$  and  $g_{medob}$  are the estimated load-side external torque and the cutoff frequency of MEDOB.

## C. Position-control-based impedance control

This section describes the position-control-based impedance control. Position-control-based impedance control is applied as a method to maintain flexibility against external torques while performing desired motions [7]. This method applies virtual machine impedance based on external torques estimated by MEDOB. The desired impedance is achieved through the resolved acceleration control by subtracting the calculated correction value. The equation for the target virtual machine impedance is:

$$J_c \dot{\theta}^c + D_c \dot{\theta}^c + K_c \theta^c = K_f \tau_{ext} \tag{9}$$

where  $J_c$ ,  $D_c$ ,  $K_c$ , and  $K_f$  are the virtual inertia, virtual viscosity coefficient, virtual spring constant, and externalforce feedback gain, respectively;  $\ddot{\theta}^c$ ,  $\dot{\theta}^c$ , and  $\theta^c$  are correction values to achieve the desired impedance. The angular acceleration correction value determined by (9) is expressed as:

$$s^2 \theta^c = \frac{K_f \hat{\tau}_{ext} - (D_c s + K_c) \theta^c}{J_c} \tag{10}$$

where  $\ddot{\theta}^c$  is calculated as a correction value for performing an operation that satisfies the target impedance of (9) when external torque is applied. By integrating this, the angular velocity and angle correction value can be determined. The obtained  $\ddot{\theta}^c$ ,  $\dot{\theta}^c$ , and  $\theta^c$  are subtracted as a correction value from the acceleration reference of the resolved acceleration control as follows:

$$\ddot{\theta}^{ref} = -\ddot{\theta}^c + k_p(\theta_{cmd} - \theta_l - \theta^c) + k_d(\dot{\theta}_{cmd} - \dot{\theta}_l - \dot{\theta}^c)$$
(11)

where  $\ddot{\theta}^{ref}$ ,  $\dot{\theta}_{cmd}$ , and  $\theta_{cmd}$  are the angular acceleration reference, the angular velocity command, and the angle command, respectively;  $k_p$  and  $k_d$  are proportional and

differential gains, respectively. In addition, the following equation was obtained from (11) by the Laplace transform.

$$\theta_{l} = \frac{k_{d}s + k_{p}}{s^{2} + k_{d}s + k_{p}} \theta_{cmd} - \frac{\frac{K_{c}}{J_{c}}}{s^{2} + \frac{D_{c}}{J_{c}} + \frac{K_{c}}{J_{c}}} \frac{K_{f}}{K_{c}} \hat{\tau}_{ext}$$
$$= \frac{2\zeta_{p}\omega_{p}s + \omega_{p}^{2}}{s^{2} + 2\zeta_{p}\omega_{p}s + \omega_{p}^{2}} \theta_{cmd} - \frac{\omega_{\tau}^{2}}{s^{2} + 2\zeta_{\tau}\omega_{\tau}s + \omega_{\tau}^{2}} \frac{K_{f}}{K_{c}} \hat{\tau}_{ext}$$
(12)

From (12), this control method allows the position response characteristics  $\zeta_p$ ,  $\omega_p$  to the position command  $\theta_{cmd}$ , and the external torque response characteristics  $\zeta_{\tau}$ ,  $\omega_{\tau}$  to the estimated external torque  $\hat{\tau}_{ext}$ , to be designed independently by approximating the second-order system. Thus, the desired position control performance and external torque response performance can be achieved. Furthermore, the virtual machine impedances,  $J_c$ ,  $D_c$ , and  $K_c$ , and the PD gains,  $k_p$  and  $k_d$ , can be decided by comparing the coefficients from (12), and  $k_p = \omega_p^2$ ,  $k_d = 2\zeta_p\omega_p$ ,  $J_c = \frac{K_f}{\omega_{\tau}^2}$ ,  $D_c = \frac{2K_f\zeta_{\tau}}{\omega_{\tau}}$ ,  $K_c = K_f$ . In this paper,  $\zeta_p$ ,  $\zeta_{\tau}$ ,  $\omega_p$ , and  $\omega_{\tau}$  were determined experimentally.

Next, the equation for the external-force feedback gain  $K_f$  is given by

$$K_f = \frac{2J_{c\_max}}{1 + e^{a|\hat{\tau}_{ext}|}} + J_{c\_min}$$
(13)

where  $J_{c\_max}$ ,  $J_{c\_min}$ , and a are the maximum and minimum values of the virtual inertia to be changed in the externalforce feedback gain, and the gradient coefficient regarding the gain change, respectively.  $J_{c\_max}$  and  $J_{c\_min}$  were determined experimentally within a range that allows position tracking and stable flexible motion against external torque. a was also determined experimentally within a range that allows the system to operate stably and flexibly. The externalforce feedback gain given by (13) was designed to decrease as the external torque applied to the link increases. Note that analytical research is being conducted on the stability of the control system due to changes in mechanical impedance in compliance controllers [15]. In this study, the stability of the control system was considered only experimentally.

## D. External contact force reduction based on angular transmission error

This section describes the external contact force reduction based on the angular transmission error. The proposed method switches to flexible motion after the external torque applied from the environment is estimated. Therefore, the instantaneous external contact force cannot be suppressed sufficiently. Regarding this problem, the backlash of the reduction gear is used to detect contact earlier than the estimated external torque. The change of the external-force feedback gain is improved by the feedback of the detected external contact force. First, assuming that the angular transmission error between the motor and load side during contact affects the load side, and obtaining the following relational equation:

$$\frac{1}{n}\theta_m = \frac{1}{J_l s^2} \tau_{bl} + \theta_l \tag{14}$$

TABLE I PARAMETERS OF THE ACTUATOR

Motor side inertia $J_m  [\text{kg} \cdot \text{m}^2]$	$3.33 \times 10^{-6}$
Lode side inertia $J_l$ [kg · m <sup>2</sup> ]	$1.03 \times 10^{-2}$
Backlash [arc-min]	20
Reduction ratio n	75.8

TABLE II Experimental parameters

Sampling time [µs]	100.0
Cut-off frequency of Pseudo-derivation [rad/s]	1000
Cut-off frequency of DOB $g_{dob}$ [rad/s]	300
Cut-off frequency of MEDOB $g_{medob}$ [rad/s]	300
Coulomb friction torque $\tau_{fc}$ [Nm]	$\pm 0.0011$
Viscous friction coefficient $D_v$ [Nm · s/rad]	0.00002
Proportional gain $k_p$	150
Differential gain $k_d$	30
Maximum virtual inertia $J_{c_max}$ [kg · m <sup>2</sup> ]	1000
Minimum virtual inertia $J_{c_min}$ [kg · m <sup>2</sup> ]	0.0225
Coefficient of external-force feedback gain a	17

where, the influence of the angular transmission error  $\tau_{bl}$  due to the contact affecting the load side is given by the following equation using angular acceleration.

$$\hat{\tau}_{bl} = J_l s^2 (\frac{1}{n} \theta_m - \theta_l) \tag{15}$$

From the above, the influence of the angle transmission error is fedback as a compensation term of the external contact force based on the motor and load side encoder information and changing of the external-force feedback gain is assisted.

#### **IV. EXPERIMENTAL RESULTS**

As described in this section, we conducted experiments on the tracking performance and the external torque response performance to design external-force feedback gain  $K_f$ . Then, the effectiveness of the external contact force reduction using angular transmission error when the external torque applying the actuator was evaluated. Specifications of the actuator and the experimental parameters are provided in Table I and Table II, respectivly.

#### A. Design of external-force feedback gain

As detailed in this section, we designed  $K_f$  based on the tracking performance and the external torque response performance. To conduct the experiment, we created a model to be used in MEDOB. The load torque on the motor side when rotating at a constant speed was estimated using a disturbance observer, and the average torque at each speed was derived. A friction model was created based on the derived relationship between speed and torque. Fig. 4 shows the measured friction and the created friction model. As it cannot stop near 0 rad/s, a dead zone of  $\pm 3.0$  rad/s is provided.

An experiment was conducted on the tracking performance to determine  $J_{c.max}$  in  $K_f$ . In the experiment, the virtual machine impedance was changed based on the ratio of the virtual inertia  $J_c$  to the nominal inertia  $J_n$  of the actuator.



Fig. 4. Measured friction and friction model



Fig. 5. Setup of the external-torque response experiment

The conditions of the experiment are detailed in Table III. Here,  $J_n$  is given by:

$$J_n = J_l + J_m n^2 \tag{16}$$

Then, the tracking performance under each condition was evaluated using the RMSEs. In addition, the external torque response was evaluated based on the response to a similar load. The angle command  $\theta_{cmd}$  was given a trajectory that rotated from 0.0 to  $\pi$  rad in 3.0 to 10.0 s. A fifth-order time polynomial is used for the command trajectory in the experiments of this research. The experiment of external torque response performance was performed to determine  $J_{c\_min}$  in  $K_f$ . This experiment also evaluated flexibility against external torques under the same conditions as the tracking experiment. A weight, shown in Fig. 5, was used to apply the external torque, from the link in a horizontal position. A schematic of the external torque response experiment is displayed in Fig. 6.

Table III summarizes the results of both experiments. The tracking performance is depicted in Fig. 7. From Table III and Fig. 7, accurate tracking was possible in cases 5 and 6. We also confirmed an upper limit to reduction of the tracking error by increasing  $J_c$ . The angle response of the experimental results for the external torque response are presented in Fig. 8. From Table III and Fig. 8, we confirm that in terms of external torque response performance, flexible motion against external torques was possible in cases 2 to 4. In case 1, the motion was flexible in response to external torques, but the motion became unstable. At the lower limit of  $J_c$ , we confirmed that  $J_c$  in case 2 allows stable contact with

	Ratio of $J_c$ to $J_n$	$J_c  [\mathrm{kg} \cdot \mathrm{m}^2]$	RMSEs of tracking error [rad]	External torque response
Case 1	1/2	0.015	0.7669	unstable
Case 2	3/4	0.0225	0.7152	flexible motion
Case 3	1	0.03	0.6036	flexible motion
Case 4	5	0.15	0.0607	flexible motion
Case 5	10000	300	0.0014	Do not move
Case 6	100000	3000	0.0014	Do not move

TABLE III EXPERIMENTAL RESULTS OF DESIGN FOR  $K_f$ 



Fig. 6. Schematic of external torque response experiment



Fig. 7. Experimental results of the trajectory tracking

the environment. This also confirmed that it was possible to virtually control a state of inertia smaller than  $J_n$ . From the above experimental results, the upper limit  $J_{c\_max}$  and the lower limit  $J_{c.min}$  of  $J_c$  to be changed in impedance control were decided, as shown in Table II. This allows the position tracking state and external force response state to be seamlessly connected in accordance with the external torque. The relationship between the designed  $K_f$  and the external torque  $\hat{\tau}_{ext}$  is displayed in Fig. 9. Then, the tracking performance and the external torque response performance could be confirmed using the designed  $K_f$ . The experiments were conducted under similar conditions as when designing  $K_f$ . The experimental results of the trajectory tracking and external torque response are shown in Fig. 10. It is clear that the impedance control using the designed  $K_f$  can track the target trajectory. The RMSE of trajectory tracking is 0.0019 rad. As a result, the position tracking accuracy is close to cases 5 and 6. Furthermore, the behavior in response to the applied external torque was confirmed. As a result, the external force response is close to case 4.



Fig. 8. Experimental results of the external torque response







Fig. 10. Experimental results of the proposed  $K_f$ 

#### B. Verification of external contact force reduction

We further conducted a verification experiment of the proposed external contact force reduction based on the angular transmission error. In the experiment, an angular velocity command trajectory  $\theta_{cmd}$  was given in which the



Fig. 11. Schematic of external contact force reduction experiment



Fig. 12. Experimental results of external contact force reduction (Torque response)



Fig. 13. Experimental results of external contact force reduction (Angle response)

link contacted an aluminum obstacle at 2.0 rad/s during operation. Fig. 11 depicts an overview of the experiment.

As a result, the estimated value of MEDOB and the torque sensor value are shown in Fig. 12. In addition, the angle response and  $K_f$ , and angular error are depicted in Fig. 13. From Fig. 12, the proposed method can reduce the maximum value of the external contact force by approximately 10%. Moreover, from Fig. 13, the motion changes to flexible when an external torque is applied during position tracking. Therefore, the proposed method can achieve both position and force control. Moreover, regarding angle response, the application of the external contact force reduction method has little effect.

#### V. CONCLUSION

To perform tasks that involve contact, collaborative robots must be able to control both position and force. Generally, the torque sensor is used to detect the external contact force, but this has the problem of reducing the rigidity of the robot. Therefore, in this study, we applied torque sensorless position-control-based impedance control and proposed a design for external-force feedback gain. The experimental results confirmed that the proposed method can achieve both position and force control. We also proposed the contact force reduction method based on angular transmission error. Corresponding experimental results confirmed that the proposed method can alleviate the impact force. In the future, we will improve  $K_f$  regarding stability analysis and consider extending it from a single-axis joint system to a robot arm with multiple joints.

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