Position-based High Backdrivable Control Using Load-side Encoder and Backlash

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The demand for robots working with humans, known as collaborative robots, has increased recently. Collaborative robots must be human-friendly; they must ensure safety and flexibly follow human’s instructions. In the industry, as the cost of high-resolution encoders has decreased, the number of devices with load-side encoders has significantly increased. However, studies on control methods using load-side encoder information are limited. Therefore, in this paper, a high backdrivable control method for geared mechatronic systems is proposed using load-side encoder information and backlash. The proposed high backdrivable control method utilizes the idling characteristics of backlash, by precise position control using both motor-side and load-side encoders. The performance of the proposed method is verified and compared to impedance control. Moreover, the advantages of employing a load-side encoder to collaborative robots are demonstrated by simulations and experiments.

Keywords: backdrivability, backlash, impedance control, robot control, two-inertia system

1. Introduction

The demands for robots working with humans have increased recently\(^{(1),(2)}\). Collaborative robots possess the capability of advancing factory automation and reducing welfare work burdens. Collaborative robots must be human-friendly; they need to ensure safety\(^{(3)}\), and must flexibly follow human’s instructions, as shown in Fig. 1.

Backdrivability is an important characteristic for realizing human-machine interactive motion in collaborative robots, because it indicates the ease of moving mechatronic systems externally. The main factors that cause backdrivability deterioration are the motor-side impedance and friction, which are amplified by the gear reducer. By enhancing the backdrivability in collaborative robots, workers can move the robots easily and safely, which improves working productivity and enables safe human-machine interaction\(^{(4)}\). Especially, backdrivability is essential in wearable robots, since users cannot move arbitrarily in low backdrivable systems. Several researches have attempted to enhance the backdrivability by changing the system hardware\(^{(5)-(7)}\). For example, series elastic actuators (SEAs), which are intensively studied for wearable robot application, consist of a flexible spring to improve backdrivability\(^{(8)-(10)}\). Further, because the gear ratio amplifies the motor-side impedance and friction, direct drive actuators have been developed to enhance backdrivability and applied to flexible robots\(^{(11)}\). However, in this study, an enhancement of backdrivability is realized by changing the software control methods. Because changes in the control methods do not restrict or modify the system configuration, these enhancements can be widely applied.

Robots usually employ gear reducers for miniaturizing systems. However, low resonance frequencies caused by the low-stiffness gear reducers restrict control bandwidths in the robotic systems. Conventionally, geared systems are modeled as two-inertia system in order to consider their resonant characteristics, and several studies have been conducted to obtain higher control bandwidths\(^{(12)-(14)}\). A two-inertia system consists of the motor side, low-stiffness transmission mechanism, and load side. In addition to low stiffness, the transmission mechanisms have nonlinearities such as backlash that deteriorate the precision of positioning at the load side\(^{(15)-(18)}\). Backlash is a gap between teeth in a gear reducer, and a number of studies have been conducted to compensate for backlash in transmission mechanisms\(^{(19)-(20)}\).

To obtain high-precision positioning at the load side even with the nonlinearities, high-resolution encoders (e.g. 25 bit) are being used in an increasing number of devices that require precise positioning, such as machine tools. However, industrial robots are often difficult to equip with load-side encoders due to the lack of space available for mounting the encoder and scattering of lubricant. Therefore, our research group has proposed a novel machine structure with both the motor-side and load-side encoders for application in industrial robots\(^{(20)}\). Moreover, SEAs used in wearable robots...
contain load-side encoders for torque control. Though the expected reduction in cost of high-resolution encoders will increase the use of load-side encoders in various fields, research on control methods using load-side information has not been sufficiently conducted. Therefore, the development of novel control methods using load-side encoder information is required.

In this study, we have considered one of the most probable situations in human-machine interaction, in which a human suddenly pushes the robot during its tracking operation. Collaborative robots are required to behave safely and follow a human’s instructions all the time. First, a novel high backdrivable control method using a load-side encoder and backlash is proposed, in order to ensure the robot follows the human’s instruction. Second, by comparing a collaborative robot with a load-side encoder to a robot without a load-side encoder, the advantages of using a load-side encoder are revealed both theoretically and experimentally.

The proposed high backdrivable control method actively uses a backlash. Backlash is known to be difficult to manage as many studies on backlash compensation demonstrate (17). However, from the perspective of backdrivability, backlash has an ideal characteristic: the load side idles within the backlash width (i.e., when external force is placed at the load side, the load side does not hit the motor side within the backlash width). In other words, when a human exerts an external force on the load side, only the load-side impedance will be observed. The proposed method uses this idling characteristic by implementing precise position control of the motor side.

The existing studies for backdrivability enhancement can be categorized into two groups based on their approach: hardware change and software change. As previously mentioned, backdrivability enhancement by hardware change is effective and widely studied (9–11), but involves high cost and the application is limited. On the other hand, changing software or control methods does not restrict the system configuration. One of the most widely studied backdrivable control methods is impedance control (21). The impedance control requires external force/torque detection by force/torque sensors or sensorless estimation. Though force/torque sensors are currently used in collaborative robots, the sensors with high cost deteriorate the control performance by reducing the rigidity of robot systems. To avoid these disadvantages, the sensorless approach is widely studied, however, it is subject to modeling errors of the plant parameters and delay for estimation. The proposed high backdrivable control method addresses this problem as it does not require the external force/torque detection by its position-based control structure. The advantages of the proposed high backdrivable control method are validated by comparison with a robot using force/torque sensorless impedance control, using simulations and experiments.

The main contributions of this paper are as follows:

1. Notice of the ideal characteristic of backlash for improving backdrivability,
2. Proposal of a position control based backdrivable control method using load-side encoder and backlash,
3. Revealing the advantages of applying load-side encoders to collaborative robots.

This study improves upon our previous studies (22)(23) with additional literature reviews, simulation results for modeling error analyses, and discussions. This paper is organized as follows: The experimental setup is introduced and modeled in sect. 2. In sect. 3, the proposed high backdrivable control is explained and compared to an impedance control both by simulations and experiments. In sect. 4, the advantages of applying a load-side encoder to a collaborative robot are described by a comparison between single encoder system and double encoder system. In sect. 5, the performances of the single encoder system and double encoder system are quantitatively compared by simulations and experiments. The advantages and disadvantages of our proposals are described with comparison to conventional methods in sect. 6. Finally, the conclusion and the future work are given in sect. 7.

2. Experimental Setup

2.1 Hardware

In this study, only the motion along one axis is considered. Therefore, an experimental setup comprising two PMSM motors (TAMAGAWA SEIKI Co., Ltd., Rated power: 1.5kW) with 20-bit absolute high-resolution encoders and a low-stiffness joint is used for evaluation as in (22)(23). A photograph and a schematic of the setup are shown in Figs. 2(a) and 2(b), respectively. Backlash is introduced with a gear coupling. Therefore, the gear ratio of our setup is 1. Here, please note that the performance of our proposed high backdrivable control method does not influence by the gear ratio at all, because the proposed method enables the load side to move freely regardless of the gear ratios. Controllers are implemented in digital signal processor (Myway Plus Corporation, PE-Expert3). The control sampling of current control loop is 10kHz and the PI current controller is implemented. Current control bandwidth is experimentally confirmed as 1.2kHz. The control sampling of the motion control loop is 2.5kHz. All the controllers described in this paper are discretized by Tustin conversion and implemented with 2.5kHz sampling frequency.

2.2 Modeling

A block diagram of the two-inertia system is shown in Fig. 3(a). The inertia moment, viscosity coefficient, torsional rigidity, torque, angle, and angular velocity are described by $J, D, K, T, \theta,$ and $\omega$, respectively. Subscripts $M$ and $L$ indicate the motor side and load side, respectively. The joint torque, load-side external torque, and torsional angle are indicated by $T_s, d_1,$ and $\Delta\theta$, respectively. In this study, the backlash from the gear coupling is modeled as a dead zone, as shown in Fig. 3(a).

![Fig. 2. Two-inertia system motor bench setup](image-url)
For a successful human-machine interaction, high backdrivability is required for collaborative robots to follow human instructions. A novel high backdrivable control method is proposed using a load-side encoder and backlash. When a human exerts an external torque from the load side, the load side becomes difficult to move because the friction and impedance of the motor are amplified by the gear ratio. Within the backlash width, the human only feels the load-side impedance since the load side is not connected to the motor side. To utilize this idling characteristic, when an external torque is input, the proposed high backdrivable control method controls the motor-side position such that the motor side follows the load side within the backlash width. A schematic of the proposed high backdrivable control motion is given in Fig. 4. The motor-side position is synchronously controlled with the load-side position within backlash width.

The block diagram of the proposed high backdrivable control method is shown in Fig. 5(a). Here, $C_{PID}(s)$ indicates a PID controller and subscript $a$ denotes nominal values. The high backdrivable control method is a motor-side position control whose command value is the load-side position obtained by the load-side encoder. In the operating range of the method, the plant model becomes the only motor-side model, because the motor and load sides are separated by the backlash. Therefore, the feedforward (FF) controller and PID controller are designed only based on the motor-side plant parameters and do not require the load-side plant parameters, which makes the proposed method robust against load-side plant parameter variation. This is a strong advantage since the load-side inertia varies in robots depending on the posture.

### 3. High Backdrivable Control

#### 3.1 Proposal of Backdrivable Control Using Backlash

For a successful human-machine interaction, high backdrivability is required for collaborative robots to follow human instructions. A novel high backdrivable control method is proposed using a load-side encoder and backlash. When a human exerts an external torque from the load side, the load side becomes difficult to move because the friction and impedance of the motor are amplified by the gear ratio. Within the backlash width, the human only feels the load-side impedance since the load side is not connected to the motor side. To utilize this idling characteristic, when an external torque is input, the proposed high backdrivable control method controls the motor-side position such that the motor side follows the load side within the backlash width. A schematic of the proposed high backdrivable control motion is given in Fig. 4. The motor-side position is synchronously controlled with the load-side position within backlash width.

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#### 3.2 Impedance Control

For the improvement of backdrivability, impedance control is the most widely employed technique. Impedance control realizes the desired impedance by velocity feedback (FB) control, with respect to a velocity command value generated through model impedance expressing the desired impedance. In this study, a P controller with gain $K_p$ is implemented as the velocity controller.
controller. The block diagram of the implemented impedance control is given in Fig. 5(b). Here, \( Q_{RFOB}(s) \) is the first-order low-pass filter (LPF) used for realization.

To realize impedance control, it is necessary to detect the external torque input to the model impedance. Though force/torque sensors could be applied to detect external force/torque by human inputs, these sensors present disadvantages such as high cost, low stiffness, and nonlinearity. Therefore, sensorless estimation is preferred.

In this study, a reaction force observer (RFOB) which was proposed in (25) is applied to estimate the external torque. As described in sect. 4, unless the two-inertia system dynamics is considered, the estimation is vulnerable to resonant vibration. For a fair comparison between the proposed high backdrivable control and impedance control in terms of sensor configuration, the RFOB using both the motor-side and load-side encoders considering resonant dynamics is applied for the external torque estimation in impedance control as shown in Fig. 5(b). Here, \( Q_{RFOB}(s) \) is the first-order low-pass filter (LPF) used for realization.

Then, load-side impedance control is realized by load-side velocity control with the load-side velocity command value generated through the model impedance, which is designed to be equal to the load-side impedance. The simulation result of the impedance control performance evaluation is shown in Fig. 6(a). Because the load-side velocity, which is non-collocated information with a large phase delay, is used in the FB control, the gain \( K_a \) cannot be increased. Therefore, the velocity does not follow the command value. Because the load-side information FB with a large phase delay hinders the increase in velocity controller gain, the motor-side velocity FB control is implemented. The velocity command value and motor-side velocity response are shown in Fig. 6(b). Using information of the collocated system enables high gain, and the response is clearly improved. We define this impedance control method with the FB of the motor-side velocity as the conventional method and compare it with the proposed method.

### 3.3 Simulations and Experiments

#### 3.3.1 Conditions

The advantages of the proposed high backdrivable control method are evaluated by comparison with a conventional method: impedance control. The backdrivability is evaluated by the load-side velocity response when a step load-side external torque \( d_L \) is input between 0.05–0.25 s. A first-order LPF with a cut-off frequency of 500 Hz is implemented to the step command of the external torque. The cutoff frequency of \( Q_{RFOB}(s) \) is experimentally designed to be 150 Hz. The PID controller of the proposed method is designed using the pole placement method with only the motor-side plant. The triple poles are placed on the real axis, at 60 Hz. The frequency of the pole is determined to the fullest extent experimentally. The second-order LPF \( Q(s) = \frac{s^2 + 2\zeta\omega_n s + \omega_n^2}{s^2} \) is used for realizing the FF controller in the proposed method is tuned as \( \zeta = 0.30 \) and \( \omega_n = 2\pi \cdot 700 \). Here, \( \zeta \) is designed to be small in order to reduce the phase delay. The value of the model impedance used in the impedance control, is designed to be equal to the impedance of the load side so that only the load-side impedance is felt from the load-side external torque. The velocity controller gain \( K_\nu \) is designed to be \( K_\nu = 1.5 \), and is increased till it loses stability experimentally. Unless otherwise stated, no modeling error is given in the simulations. The experimental conditions are the same as those in the simulations.

#### 3.3.2 Validations

Figure 7(a) shows the comparison of the load-side velocity response of the impedance control method (Conv.), the proposed method (Prop.), and the plant without any controller (w/o). The model represents a reference because it indicates a response when the same external torque is applied to the load-side plant model instead of the two-inertia model. With no control, the backdrivability is low. The velocity does not significantly increase, and vibration occurs at the resonance frequency. Because the response of the proposed method and the conventional method mostly overlaps with the response of the model, the backdrivability is improved, and the impedance from the load side coincides with the load-side impedance. Figure 7(b) indicates the errors in the load-side velocity responses from the model response. It must be noted that the errors of the proposed methods are kept 0. The load-side velocity response of the conventional method has an error from the response of the model, because the gain \( K_\nu \) cannot be sufficiently increased due to the delay in external torque estimation.

Torsional angle response shown in Fig. 7(c) reveals the reason for the error. In the proposed method, the torsional angle response is within the range of backlash (dead zone width), indicated by the dotted black line, but the torsional angle response in the conventional method exceeds the backlash width. Because the model impedance is designed to be the
Backdrivable Control Using a Load-side Encoder and Backlash (Shota Yamada et al.)

(a) Load-side velocity responses. Note that Model and Prop. responses are perfectly matched.

(b) Error of the load-side velocity responses. Note that Model and Prop. responses are perfectly matched.

(c) Torsional angle responses.

(d) Joint torque responses. Note that Model and Prop. responses are perfectly matched.

(e) Load-side torque responses. Note that Model and Prop. responses are perfectly matched.

Fig. 7. Comparison of backdrivability performance. Model in dotted black line indicates the reference with the only load-side plant, Conv. in dashed red line indicates the response of impedance control, Prop. in solid blue line indicates the response of the proposed method, w/o in solid black line indicates the response of the two-inertia plant without any controller.

load-side impedance, the joint torque should be 0 Nm. However, as shown in Fig. 7(d), the joint torque is not always 0 Nm in the conventional method due to collisions between the motor and load sides. As a result, the joint torque acts as a disturbance. The load torque $T_L$ shown in Fig. 7(e) does not coincide with the input external torque, resulting in an error in the load-side velocity in the conventional method. Thus, the torsional angle can be kept within the backlash width even if a large disturbance is input in a high-frequency range.

Next, the effects of modeling error are analyzed when the load-side inertia and the viscosity, which easily fluctuate in robotics applications, become 0.80 and 1.2 times the nominal value. The load-side velocity response is shown in Fig. 8(a), and the external torque estimated in the conventional method is shown in Fig. 8(b). It is important to note that the responses in the proposed methods precisely coincide with the input external torque. The estimated external torque has an error due to modeling error. Therefore, a large error occurs in the load-side velocity response. Furthermore, since the proposed method is not required to estimate the external torque and does not require the load-side plant parameters on controller design, the performance does not deteriorate.

Figure 9(a) shows an experimental comparison of the velocity responses in the conventional method, proposed method, and the plant without control. The results are similar to the simulation results shown in Fig. 7(a). Since a modeling
error exists, the velocity responses differ between the conventional method and proposed method, especially in the response during deceleration. Vibration is observed in the load-side velocity in the conventional method, while the proposed methods demonstrate responses without vibration.

Figure 9(b) shows an experimental comparison of the torsional angle responses. The experiment is conducted for the verification of the simulation shown in Fig. 7(c). While the torsional angle is suppressed in the proposed method, the conventional method does not suppress the torsional angle within the range of the backlash, which deteriorates the load-side velocity response.

4. Human–machine Interactive Control

4.1 Procedure of Human–machine Interactive Motion

In this study, the scenario in which a human suddenly pushes a collaborative robot during its velocity tracking operation is considered. The human-machine interaction can be divided into four phases: I. tracking control, II. recognition of external inputs, III. impact attenuation, and IV. backdrivable control. In order to realize a safe and flexible operation, a double encoder (DE) control system is applied. The advantages obtained by applying a load-side encoder to a collaborative robot for human-machine interaction are revealed in each phase by comparing with a single encoder (SE) control system.

Figure 10 shows the overall procedure of human-machine interactive motion and the comparison between double encoder system and single encoder system.
The RFOB using both the motor-side and load-side encoder information, known as double encoders RFOB (DERFOB) in this paper, is utilized to consider the two-inertia resonant characteristics (26). The block diagram of the two-inertia-model-based RFOB is shown in Fig. 12(a). The transfer function from the external torque to the estimated torque is expressed as:

\[
\hat{d}_L = Q_{RFOB}(s) \frac{d_L}{d_L} \tag{1}
\]

Here, the subscript \( \hat{\cdot} \) indicates the estimated values. The equation (1) shows an ideal estimation characteristic. Also, Fig. 12(c) shows the frequency characteristic from the external torque to the estimated external torque when the cutoff frequency of \( Q_{RFOB}(s) \) is 150 Hz. DERFOB response indicated in the blue solid line shows an ideal low-pass characteristic.

### 4.2.3 Impact Attenuation

The maximum braking is the best FB-based impact attenuation method. Therefore, rapid detection of the contact is important for actuating the maximum negative torque as soon as possible, to attenuate the impact. The usage of load-side encoder enables faster detection of the contact, as shown in the gain and phase characteristics in a high-frequency range of Fig. 12(c). When the estimated value exceeds the designed threshold value (−2.0 Nm), the maximum negative torque (−5.0 Nm) is input to attenuate the impact.

### 4.2.4 High Backdrivable Control using a Load-side Encoder and Backlash

After maximum braking, when the motor-side velocity becomes zero, the proposed high backdrivable control method is turned on.

### 4.3 Single Encoder Interactive Control System

#### 4.3.1 Tracking Control

The SE control system does not contain a load-side encoder. Therefore, achieving a precise and fast tracking performance at the load side is difficult due to the low-frequency resonant modes and nonlinearities caused by gear reducers. For precise tracking control, a precise modeling of the gear dynamics including the nonlinearities are required.

However, in this paper, for proper comparison, the semi-closed controller is not applied, and the same PI-P controller, which utilizes the load-side encoder information is implemented in order to achieve the same conditions at impact.

#### 4.3.2 Recognition of External Inputs

With only a motor-side encoder, a rigid-body model expressed as Eq. (2) is used as the estimation model in RFOB, which is known as single-encoder RFOB (SERFOB) in this paper.

\[
P_{ailn}(s)^{-1} = J_{ailn}s + D_{ailn}, \tag{2}
\]

\[
J_{ailn} = J_{Mn} + J_{Lr}, \quad D_{ailn} = D_{Mn} + D_{Lr}.
\]

The block diagram of rigid-body-model-based RFOB is shown in Fig. 12(b). When it is assumed that a modeling error does not exist, the transfer function from the external torque to the estimated torque is expressed as Eq. (3). The equation (3) confirms that it has resonant characteristics even
without any modeling error.

\[
\frac{d_\text{i}}{d_\text{L}} = \frac{Q_{\text{RFBO}}(s)}{J_\text{m}J_\text{L}^2 + (J_\text{m}J_\text{L} + J_\text{m}J_\text{L})^2 + (D_\text{m}K + D_\text{L}K)^2 + (D_\text{m}K + D_\text{L}K) + (D_\text{m}K + D_\text{L}K)}
\]

Figure 12(c) shows the frequency characteristic from the external torque to the estimated external torque. While the DERFOB response indicated by the solid blue line demonstrates an ideal low-pass characteristic, the SERFOB response indicated by the dashed red line reaches a large peak at resonance, because its estimation model does not consider the two-inertia resonance characteristic. The response in the high-frequency range is important for the rapid and proper detection of contact with human, to achieve maximum attenuation of the impact. Also, the proper threshold value cannot be easily designed with the resonant characteristics in SERFOB due to a large vibration. The load-side encoders enable the robots to quickly detect contacts by humans, by considering resonant characteristics, which enable the robots to further attenuate the impulse.

4.3.3 Impact Attenuation When the estimated value exceeds the designed threshold value, the maximum negative torque is input to attenuate the impact. The impact attenuation phase in SE control system is the same as that in DE control system.

4.3.4 Turning Off After maximum braking, when the motor-side velocity becomes zero, the system is turned off (i.e., the control output becomes zero).

5. Numerical Comparisons of Interactive Control

5.1 Conditions The scenario where a human suddenly pushes a collaborative robot during its velocity tracking operation is considered. For high reproducibility of external torque inputs, a torque imitating a human’s sudden pushing action is input by the load-side motor in the experiments. Generally, collaborative robots comprise soft covers over their surface to prevent injury to human workers. Therefore, a spring and damper impedance model is used to simulate the impedance between the soft-covered robot and human. The value of torsional rigidity and the damping coefficient of impedance model are set as 1.0 Nm/rad and 1.0 Nms/rad, respectively. The impedance model is placed at a 5.0 rad distance from the initial position. The parameters of PI-P controller in tracking control are experimentally tuned to be 0.13, 12, and 1.0, respectively.

The experimental conditions are the same as those in the simulations. In the experiments, the spring-damper impedance model is implemented using the load-side motor. The input external torque is measured by the torque reference of the load-side motor. It is noted that the threshold value for contact detection is experimentally changed to -3.0 Nm.

5.2 Simulations and Experiments The step velocity reference is filtered with a first-order low-pass filter whose cutoff frequency is 50 Hz. The control performances of the DE control system are indicated by solid blue lines and the SE control system are indicated by dashed red lines. Also in the figures, each control phases defined in Fig. 10 are shown in Roman numerals in blue and red, respectively.

The load-side velocity responses are shown in Fig. 13.
practical, in order to attenuate the first impact, prediction of the contact timing is necessary by using other sensors such as cameras. Even without such kind of sensors, the DE system can attenuate the second impact, which can ease the durability requirement of the soft covering material on collaborative robots. Figure 14(b) shows the experimental verification of the simulation shown in Fig. 14(a). The DERFOB attenuates the second impact by faster contact detection than SERFOB as shown and described later.

The estimated external torque is shown in Fig. 15. By considering the resonant characteristics, DERFOB can detect the contact faster than SERFOB by about 5 ms. Moreover, SERFOB has a large vibration due to the resonance. Figure 16(c) shows the experimental verification of the simulation shown in Fig. 15(b). As in the simulation, the SE system has a large vibration due to the resonance, and the DE control system can detect the contact faster than the SE system by about 4 ms.

Figure 16(a) shows the motor torque response around the timing of the contact to the spring-damper impedance model. The motor torque in the DE system quickly reaches to the maximum negative torque (~5.0 Nm), and then, when the motor-side velocity reaches zero, the proposed high backdrivable control method is turned on. To make the motor-side angle follow the load-side angle, a positive torque is input. On the other hand, the motor torque in SE system increases gradually even after the contact because SERFOB cannot quickly detect the contact. The motor torque quickly increases to the maximum negative torque, and then, the motor torque is turned off. The motor torque response indicates that the DE control system works correctly. Finally, Fig. 16(b) shows the experimental verification of the Fig. 16(a). The experimental results are similar to the simulation results. Though the motor torque in the experiment is larger than that in the simulation due to the friction and the modeling error, we can confirm that the mode-switching algorithm for human–machine interactive motion properly works also in the experiments.
The third feature is on the limitation of the proposed method. The proposed method is superior when the desired impedance equals to the load-side plant model. However, the proposed method cannot realize the arbitrary impedance because it does not assist the load side by the motor.

The fourth feature is related to the performance of the proposed method. The proposed method actively uses the backlash for improving backdrivability. In other words, it requires some backlash. Also, in order to detect the load side movement with enough precision between backlash width, the resolution of the load-side encoder needs to be high enough. For example, in our setup, the resolution is 20 bits, which means the quantization width is about 0.0060 mrad/pulse, while the backlash width is 12 mrad. In our case, there are about 2000 pulses between backlash width. The required amount of the backlash width is difficult to be determined because it depends on the factors such as the control bandwidth and the external inputs. In practical, the controller and the backlash width are designed with simulation and experimental evaluation. When you are able to design both the backlash width and the controller, simulation analyses can be used with assumed various external inputs. For example, in our case, Fig. 7(c) shows the backlash width can be narrowed to ±1 mrad from ±6 mrad, or six times amplitude of the external input can be dealt without the contact between the motor and the load sides. When the setup is already made and you are able to design only the controller, the controller bandwidth should be tuned based on simulation and experimental results.

6.2 Human-machine Interactive Control On comparison with robots without a load-side encoder, the advantages of applying a load-side encoder to collaborative robots were presented in human-machine interactive motion. The advantages of applying the load-side encoder to collaborative robots are as follows:

- Precise tracking even with transmission nonlinearities,
- Precise and fast contact detection for impact attenuation,
- High backdrivable control by active use of backlash,
- Additional sensor at the load side.

By using the information of the encoder mounted to the load side, precise tracking control and fast detection of the contact can be achieved. Also, our proposed method can enhance the performance of backdrivability. The last feature is the structural disadvantage of the double encoder system. However, mechanical systems with load-side encoders have appeared as stated in the introduction section, and the cost is expected to decrease thanks to its developments.

7. Conclusion

Owing to the increasing use of load-side encoders in industry, a novel high backdrivable control method was proposed using the load-side encoder information and backlash. Although the system with backlash is known to be difficult to control, the backlash has an ideal characteristic for backdrivability. The proposed method effectively utilized the characteristic that the load side idles in the backlash width. Also, human-machine interactive control system is proposed using the proposed high backdrivable control method. In the comparison between the single and double encoder system in human-machine interactive motion, the advantages
of applying load-side encoder to collaborative robots are revealed. The simulations and the experiments validated the advantages of our proposals quantitatively. The discussion section described the advantages and the limitations of our proposals qualitatively.

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