Excess Force Reduction in Bilateral Control for Precise and Safe Operation

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This paper proposes a constrained bilateral control method to maintain a safe force limit in a remote environment in an event where the operator applies excessive force on the master system. The disturbance observer compensates system disturbances, and the reaction force observer (RFOB) estimates the external force exerted on individual. The paper introduces a force regulator called excess force reduced RFOB (EFR RFOB) to reduce the excessive force applied by the operator to the safe force limit. The amount of excess force is determined by adding the master–side RFOB output and the replica–side safe force limit. Acceleration–based bilateral control is implemented in a virtual space with a master virtual force input, virtual position response, and replica real force–position responses. It realizes transparency in the virtual space. This paper derives the relation between master–side real and virtual space variables to facilitate reproducibility between the master operator and replica environment. The restrained master force–position responses in the virtual space realize precise and safe force control on the replica–side in real space. The proposed method is verified using experiments.

Keywords: Motion control, Bilateral control, Force control, Sensorless control, Safety, Disturbance observer

1. Introduction

Japan is facing an aging society ahead of other countries and has forecasted increasing demands for caring for the elderly. As a solution, Japan has proposed to use AI and robots at nursing–care facilities to support people’s independence in the super–smart society “Society 5.0”1). The encouragement to establish an open cobotic environment highlights the importance of safety enhancement of robots because being assisted by a robot in daily tasks still seems distant. Human–friendly robots themselves should assure safety. Contacting humans or handling delicate objects with uncertain sizes and stiffness requires human interference through teleoperation. There is a possibility that the operator exceeds the bearable force limit of the remote environment and damage it due to inexperience, anxiety, tremor, and etc. Therefore, the field of teleoperation with motion constraint is merging as an essential and timely necessity because constraints on motion parameters are a must to ensure safety when robots are contacting humans or fragile objects in replica environments.

The bilateral control facilitates the artificial haptic information transmission. An operator through a master (local) robot manipulates a replica (remote) robot and as a result, work is done on the remote object. Many kinds of bilateral controllers have been proposed2)–(10) and most of them could not produce vivid tactile sensation. The vivid haptic feedback through bilateral control has been realized by achieving transparency(11). The four–channel acceleration–based bilateral control (4ch–ABC) implemented based on the disturbance observer (DOB) was the first robust bilateral communication system12). The DOB based 4ch–ABC has realized high transparent haptic communication13), and the law of action and reaction14) that are crucial for implementing a physical agent. This method has extended successfully in the fields of micro–macrow manipulation, time–delayed systems, motion copying and reproduction, skill abstraction and reproduction, and multilateral control.

This paper focuses on excess force reduction in bilateral control for precise and safe operation. An application like robotic surgery that includes minimally invasive surgery, brain surgery, cell manipulation, and telesurgery applies teleoperation techniques subject to operative or safety constraints. Casavola et al. have proposed constrained teleoperation based on predictive control technique and master–replica command governors for accuracy constraints by putting bounds on the maximum end–effector tracking error concerning the nominal path and constraints on the maximum contact force15). Grippers with constant–force mechanism which passively maintains a constant prespecified contact force have been studied for robotic automation, precision manipulation, and overload protection16)17). Arevalo et al. have demonstrated the variable stiffness actuator provides compliance and improves the safety features of Cobots in robot–assisted doppler sonography18). Intending to avoid undesired excessive contact forces, Chen et al. have proposed an adaptive hybrid impedance controller in which a self–adjusting selecting scheme updated the subspaces for hybrid control, adaptive bilateral controller synchronized the position, and replica–side locally controlled contact force by sliding mode impedance controller19). Sakaino et al. have implemented position constrained bilateral controllers20)21) based on oblique coordinate transformation which was designed by definition of the saturation coordinates where replica–side position constraint has influenced the master system once with the force regulation and other with the replica position tracking. Pil-

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Iai et al. have proposed a bilaterally controlled force limiting surgical tool based on a virtual spring–damper model to control the movement of primary surgical tool insertion during laparoscopic surgery \cite{18}. Because it has applied a torsional spring between the master–replica systems for force limiting, the system has lost the transparency that is crucial for perceived impedance by the operator. Ruwanthika et al. have proposed force constrained bilateral controller with high impedance reproducibility that is vital for replica environmental impedance perception on the master–side \cite{19}. It has imposed a safe force limit on the replica, and the operator applied excessive force has been modeled through a virtual impedance which requires environment models. The 4ch–ABC has switched to a force controller on the replica–side and a virtual impedance controller on the master–side during excessive force application by the operator.

This paper proposes a constrained bilateral control method that maintains a precise and safe force limit on the replica–side while the operator applies excessive force on the master system. Fig. 1 illustrates the overview of the proposed method. The excessive force applied by the operator is identified, and is regulated with excess force reduced reaction force observer (EFR RFOB). The EFR RFOB removes the excessive force considering it as a disturbance force similar to the reaction force observer (RFOB). Then EFR RFOB maintains master–side force input to the controller \( f_{m}^{ref} \) at the corresponding limit value imposed at the replica–side. The master position response to the controller \( x_{m}^{ref} \) is different from real position response \( x_{m} \) and the relation between two delivers the remote object impedance \( Z_{r} \) to the operator during constrained motion. The constrained bilateral controller implements DOB based 4ch–ABC in the virtual space. As a result, common mode force control, differential mode position control, and transparency realize in the vitual space. The restrained master force input and position response in the control space (virtual space) deliver precise and safe force–position responses to replica in real space. When operator applies safe force on the master system, the 4ch–ABC realizes in the master–replica real space similar to conventional method.

The proposal achieves with few designing efforts. It is an original method that differed from the above DOB based constrained bilateral controllers \cite{16,19}. The proposed method can implement to existing 4ch–ABCs with less effort once the force limit on the replica environment is identified in advance. The paper consists of six sections. Section 2 describes the force restraint with the EFR RFOB, and section 3 describes the constrained bilateral control system. Section 4 derives transparency in virtual space and relation between master position response in real–virtual spaces. Section 5 gives experimental results with discussion to verify the proposed method and the comparison with literature. Finally, section 6 concludes this paper.

2. Force Restraint with Excess Force Reduced Reaction Force Observer

This paper applies motion control schemes based on acceleration control. Table 1 shows parameter definitions in this paper. Linear motion of a one–degree–of–freedom (1 DOF) robot is considered.
With the DOB, the system is possible to treat as a nominal model. Thus, motion control systems are designed in an outer loop considering only the nominal plant model and robust motion control is attained \([22]\). By attaching an auxiliary gain element \(M_s/K_{fe}\) in front of the current controller, the input to the system becomes the acceleration. The robust motion controller makes a motion system to be an acceleration control system \([22]\). Part of Fig. 2 illustrates the DOB.

### 2.2 RFOB

The RFOB \([23]\) that is an extension of the DOB estimates externally applied force without any force sensors as in (4). For that disturbances except external force \(f_{0\text{est}}\) need to identify beforehand \([24]\).

\[
f_{\text{est}} = \frac{g_{\text{rob}}}{s + g_{\text{rob}}} (K_{j\text{fr}} x_{\text{fr}} + M_n g_{\text{rob}} x_{\text{res}} - f_{\text{dis}}) - M_n g_{\text{rob}} x_{\text{res}} (4)
\]

The cut–off frequency of the RFOB determines the bandwidth of force sensing. With wide bandwidth, both stability and response of force sensing are improved \([20]\). In general, the cut–off frequencies of the RFOB and the disturbance suppression set to the same value \([20]\). Sarayildiz et al. \([20]\) have shown that setting \(g_{\text{rob}} > g_{\text{dob}}\) improves the performance and stability of the RFOB based force control system.

### 2.3 Excess Force Reduced Reaction Force Observer

This aims to regulate operator applied excess force to the corresponding safe limit assigned on the replica–side during bilateral control. The paper assumes that the environmental object safe force limit has been identified in advance through experiments/ experiences/database. Firstly, it identifies the operator applied excess force amount \(\Delta f\) on the master system as in (5).

\[
\Delta f = f_{\text{est}} + f_{\text{limite}} \quad \text{.................. (5)}
\]

Here, \(f_{\text{limite}}\) is the force limit assigned on the replica–side, and (5) has considered the sign convention of the master–replica action–reaction forces. We aim to maintain a safe force limit. Therefore, \(\Delta f\) is a disturbance force. We remove it from master RFOB output as in (6).

\[
f_{mfr}^{\text{est}} = f_{\text{est}} - \Delta f = -f_{\text{limite}} \quad \text{.................. (6)}
\]

The notation \(f_{mfr}^{\text{est}}\) denotes the estimated value of regulated force on the master after reducing operator applied excessive force. We named it the Excess Force Reduced Reaction Force Observer (EFR RFOB). When operator applies safe force, \(\Delta f = 0\) and \(f_{mfr}^{\text{est}} = f_{\text{est}}\).

Fig. 2 shows the block diagram of master–side DOB, RFOB, EFR RFOB and its output variation with operator applied force on master. The EFR RFOB regulates master–side force input with corresponds to the given replica force limit. We use the EFR RFOB output as master side force input when implementing DOB based 4ch–ABC in virtual space. As a result, the operator applied excessive force on the master system in real (working) space does not transmit to the bilateral controller in control (virtual) space.

### 3. Constrained Bilateral Control

We focus on bilateral control in virtual space regardless operator applies safe force or excessive force on the master. The master–side force input and position response to the virtual space are different from that of real space and replica–side force–position responses are similar in both real and virtual spaces as illustrated in Fig. 3. The behavior of \(f_{mfr}^{\text{est}}\) with \(f_{mfr}^{\text{est}}\) was described in section 2.3. The relation of \(x_{mfr}^{\text{est}}\) with \(x_{mfr}^{\text{est}}\) will be described in section 3.3.

#### 3.1 Control Objectives

We have not applied a scale between master–replica systems. Therefore, in virtual space, the replica follows the master. The master–replica needs to follow the same changes in position as in (7) and needs to satisfy the law of action and reaction as in (8) in virtual space.

\[
\begin{align*}
    x_{mfr} - x_{mfr}^{\text{ext}} &= 0 \quad \text{.................. (7)} \\
    f_{mfr}^{\text{est}} - f_{mfr}^{\text{ext}} &= 0 \quad \text{.................. (8)}
\end{align*}
\]

#### 3.2 Controller Design

The control goals in (8) and (7) represent the common mode force control command \(f_{mfr}^{\text{cmd}}\) and the differential mode position control command \(x_{mfr}^{\text{cmd}}\) in virtual space \([20]\). The virtual space master–replica force–position responses convert into differential mode and common mode as in (9) and (10) using the second order quarry matrix \(Q_2\) in (11) \([20]\).

\[
\begin{align*}
    [x_{mfr}^{\text{est}}] & = Q_2 [x_{mfr}^{\text{est}}] \\
    [f_{mfr}^{\text{est}}] & = Q_2 [f_{mfr}^{\text{est}}] \quad \text{.................. (9)}
\end{align*}
\]

\[
\begin{align*}
    [x_{mfr}^{\text{est}}] & = Q_2 [x_{mfr}^{\text{est}}] \\
    [f_{mfr}^{\text{est}}] & = Q_2 [f_{mfr}^{\text{est}}] \quad \text{.................. (10)}
\end{align*}
\]

\[
Q_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad \text{.................. (11)}
\]

The first element of (9) gives the common mode force control response, and the second element of (10) gives the differential mode position control response. The virtual space common mode and differential mode acceleration references are calculated by a force controller (proportional controller) and by a position regulator (proportional derivative controller) as in (12) and (13). The term \(C_f(s)\) is defined as in (14).
If the inverse quarry matrix \( (n_f, m_m) \) then
\[
\begin{align*}
\dot{x}_m^{\text{ref}} &= C_f (f_m^{\text{cmd}} - f_m^{\text{res}}) = -C_f f_m^{\text{ext}} \\
\dot{x}_m &= K_f (x_m^{\text{cmd}} - x_m^{\text{res}}) = -C_p (s + g_{pd}) x_m^{\text{ext}} \\
C_p(s) &= K_p + \frac{s g_{pd}}{s + g_{pd}} K_d
\end{align*}
\]
These acceleration references are transformed into the master–replica acceleration references in virtual space using the inverse quarry matrix \( \mathbf{Q}^{-1} \) as
\[
\begin{bmatrix} \dot{x}_m^{\text{ref}} \\ \dot{x}_r^{\text{ref}} \end{bmatrix} = \mathbf{Q}^{-1} \begin{bmatrix} \dot{x}_m \\ \dot{x}_r \end{bmatrix}
\]

The master–replica simultaneous force–position control realized in the common dimension of acceleration. These deliver master–replica acceleration references in real space as (16) and (17).

\[
\begin{align*}
\dot{x}_m^{\text{ref}} &= -\frac{1}{2} C_f (f_m^{\text{cmd}} + f_m^{\text{ext}}) - \frac{1}{2} C_p(s)(x_m^{\text{cmd}} - x_m^{\text{ext}}) \\
\dot{x}_r^{\text{ref}} &= -\frac{1}{2} C_f (f_m^{\text{cmd}} + f_m^{\text{ext}}) + \frac{1}{2} C_p(s)(x_m^{\text{cmd}} - x_m^{\text{ext}})
\end{align*}
\]

When comparing with the literature, (16) and (17) represent similar equations to the DOB based 4ch–ABC. Therefore, we can say that the proposed constrained bilateral controller follows the 4ch–ABC control structure.

### 3.3 Relation between \( x_m^{\text{ext}} \) and \( x_m^{\text{efr}} \)

Let’s assume transparency between master and replica is achieved in virtual space. Then, reproducibility in virtual space satisfies (18).

\[
Z_r(s) = \frac{x_m^{\text{efr}}}{x_m^{\text{ext}}} = -Z_r(s) \quad \text{Where} \quad Z_r(s) = \frac{x_m^{\text{ext}}}{x_m^{\text{efr}}}
\]
It means that the master receives replica object impedance in virtual space. The impedance perceived by the operator is given by (19).

\[ Z_b(s) = \frac{\hat{f}_{\text{ext}}}{\hat{x}_{\text{ext}}} = Z(s) \]  

(19)

We aim to facilitate replica object impedance to the operator throughout the operation. Then, virtual space master impedance given by (18) needs to deliver to real space as in (20).

\[ Z_b(s) = \frac{\hat{f}_{\text{ext}}}{\hat{x}_{\text{ext}}} = \frac{\hat{x}_{\text{fr}}}{\hat{x}_{\text{fr}}} = Z(s) \]  

(20)

It derives the relation between real space and virtual space master position responses as (21).

\[ x_{m}^{fr} = \frac{\hat{x}_{\text{fr}}}{\hat{x}_{\text{fr}}} \]  

(21)

Case 1: When operator applies safe force, \( \hat{f}_{\text{fr}} = \frac{\hat{f}_{\text{ext}}}{\hat{x}_{\text{fr}}} \) from section 2.3 and from (21), \( \alpha = 1.0 \). Both real and virtual spaces share the same master position response (i.e. \( x_{m}^{fr} = x_{m}^{fr} \)).

Case 2: When operator applies excessive force, \( \hat{f}_{\text{fr}} = -\lim_{s \to \infty} \frac{f_{\text{fr}}}{\hat{x}_{\text{fr}}} \) from section 2.3 and from (21), \( \alpha = (-\lim_{s \to \infty} \frac{f_{\text{fr}}}{\hat{x}_{\text{fr}}} \). The master position response in virtual space is different from that in real space. (i.e. \( x_{m}^{fr} = \alpha x_{m}^{fr} \)).

The control block diagram of the constrained bilateral controller is shown in Fig. 4. In summary, the EFR FOB regulates operator applied excessive force to the safe limit, the controller artificially satisfy the law of action–reaction and position tracking in virtual space. The proposed method is similar to the DOB based 4CH–ABC in the virtual space. The relation between \( x_{m}^{fr} \) and \( x_{m}^{fr} \) continuously delivers replica object impedance to the operator. Then, control goals of constrained bilateral controller are summarized as follows.

1. \( \hat{f}_{\text{fr}} + \hat{f}_{\text{ext}} \neq 0 \) and \( \hat{f}_{\text{fr}} + \hat{f}_{\text{ext}} = 0 \)
2. \( x_{m}^{fr} - x_{m}^{fr} \neq 0 \) and \( x_{m}^{fr} - x_{m}^{fr} = 0 \)
3. \( Z_b(s) = -Z(s) \)

4. Analysis

Starting with virtual space acceleration references given in (16) and (17), and considering the inner loop DOB effect given in (3), the virtual space master force input and position response can be derived as in (22) and (23) respectively. In replica–side, substitute \( \hat{f}_{\text{fr}} = g_l(s) \hat{x}_{\text{fr}} \) to consider the RFOB low pass filter effect. Where \( g_l(s) = g_{\text{rob}}/(s + g_{\text{rob}}) \)

\[ \frac{\hat{x}_{\text{fr}}}{\hat{x}_{\text{fr}}} = \frac{-2s^2}{C_f G_{pc} \hat{x}_{\text{fr}} - g_l(s) \hat{x}_{\text{fr}}} \]

\[ \frac{f_{\text{fr}}}{f_{\text{fr}}} = \left( \frac{G_s}{C_f G_{pc} + (2s^2 + C_p(s)G_{pc})f_{\text{fr}}} \right) \frac{f_{\text{fr}}}{f_{\text{fr}}} 

(22)

\[ \hat{x}_{m}^{fr} = \frac{\hat{x}_{\text{fr}} + \frac{G_s}{M(s^2 + C_p(s)G_{pc})}(f_{\text{fr}} - f_{\text{fr}})}{s} \]  

(23)

Here \( f_{\text{fr}} = \left( f_{\text{fr}} + f_{\text{fr}} \right) \) and \( f_{\text{fr}} = \left( f_{\text{fr}} + f_{\text{fr}} \right) \) represent total load force acting on master–replica systems. Those are suppressed by the DOB and affect the controller through the sensitivity function \( G_{s} = \frac{s}{s + \text{pol}} \). \( G_{pc} = \text{pol} \) denotes the effect of phase compensation. Equations (22) and (23) are represented in matrix format as in (24).

\[ \begin{bmatrix} \hat{f}_{\text{fr}} \\ \hat{x}_{\text{fr}} \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \hat{x}_{\text{ext}} \\ -f_{\text{fr}} \end{bmatrix} + \begin{bmatrix} D_{11} \\ D_{21} \end{bmatrix} f_{\text{fr}} \]  

(24)

where

\[ H_{ij} = \frac{-2s^2}{C_f G_{pc} \hat{x}_{\text{fr}} - g_l(s) \hat{x}_{\text{fr}}} \]

\[ D_{ij} = \frac{G_s}{C_f G_{pc} + (2s^2 + C_p(s)G_{pc})f_{\text{fr}}} \]  

(25)

\[ \gamma = \frac{G_s}{M(s^2 + C_p(s)G_{pc})} \]  

(27)

4.1 Effect of Disturbances

First, the effect of DOB parameter variations (\( \beta \)) and DOB cut–off frequency (\( g_{\text{rob}} \)) is analyzed. We fixed the values of \( C_f = 1.0, M = 1.0 \), and \( g_{\text{rob}} = 900 + 60 \). When consider the transfer functions in (26), each element in disturbance matrix (\( D_{11} - D_{22} \)) has three common poles and a common zero at the origin.

Fig. 5 shows the bode diagrams of the disturbance matrix. As \( \beta \) grows, the disturbance magnitude is reducing, and frequency bandwidth is slightly increasing. With \( g_{\text{rob}} = 50 \), the value of \( \beta \) lower bellow 1.0, a peak point is appearing. It means lower the value of \( \beta \), a complex conjugate pole pair is moving towards the imaginary axis with shrinking real part of the root locus. The stability deteriorates and the \( \beta \) value behaves similar to the damping factor of a second–order system with complex roots in the range \( 0 < \beta < 1 \). By increasing cut–off frequency of the DOB, the stability is improved because peak value is reduced or removed for the same \( \beta \) value. The \( \beta = 1.0 \) corresponds to critically damped value. Therefore, at \( \beta = 1.0 \), complex conjugate poles converge to a common point on the negative real axis in the root locus plot, corresponding to a repeated simple pole. The \( D_{12} \) has a fixed simple pole at \( g_{\text{rob}} \) and a complex zero pair before the complex pole pair. The \( D_{21} \) and \( D_{22} \) gave identical magnitude diagrams and phase diagrams shift by 180°.

Therefore, only \( D_{21} \) is shown. Increasing \( g_{\text{rob}} \) and \( \beta \) result in increasing frequency bandwidth and reducing the overall disturbance matrix magnitude. Therefore, from the results of the Fig. 5 we selected \( g_{\text{rob}} = 500 \) rad/s. Since \( \beta \) behaves as damping constant, we selected \( \beta = 1 \) for further analysis.

Next, the effect of \( C_f \) and \( C_p(s) \) is analyzed. Only the \( D_{11} \) and \( D_{12} \) is considered because \( D_{21} \) and \( D_{22} \) have a zero at the origin and the same denominator as \( D_{11} \). The variation of \( C_f \) affects only the magnitude of the transfer function. It does not change frequency bandwidth or phase response. Therefore, Fig. 6a shows only the bode magnitude diagrams. As \( C_f \) grows, the magnitude is reducing. The \( C_f \) does not affect the pole–zero or the stability of the disturbance matrix.

Finally, the effect of \( C_p(s) = K_p + K_d s \) is analyzed. We select \( K_p = 2 \sqrt{K_p} \) with relationship for critical damping. Figs. 6b and 6c show the bode diagram. Since we consider the relationship for critical damping, the \( C_p(s) \) creates a repeated simple pole, and it is growing as \( C_p(s) \) is increasing. The disturbance magnitude is increasing until it reaches this simple
pole. A fixed simple pole is available at \( g_{dob} \) causing magnitude to reduce in Fig. 6b and constant in Fig. 6c as frequency grows. A complex zero pair in \( D_{12} \) which is growing as \( C_p(s) \) grows cause the middle part behaviour of Fig. 6c. The poles are larger than the zeros. Therefore, the magnitude became constant as frequency grows. The \( C_p(s) \) does not make the system unstable.

![Diagram](https://via.placeholder.com/150)

In summary, increasing \( \beta \) and \( g_{dob} \) increase the frequency bandwidth/stability and reduce the disturbance magnitude. Increasing \( C_f \) further reduces the disturbance magnitude. Increasing \( C_p(s) \) increase the disturbance magnitude. The \( C_f \) or \( C_p(s) \) do not make the system unstable. We need to minimize the effect of disturbances for the better performance of the controller. Therefore, selecting higher \( g_{dob}, C_f \) values, \( \beta = 1.0 \), and lower \( C_p(s) \) value that can successfully maintain the master–replica position tracking are suitable.

### 4.2 Reproducibility and Operationality

The performance of the constrained bilateral controller is analyzed with reproducibility and operationality \(^{(27)} \). The reproducibility \( (P_{rep}) \) determines how accurately environmental object impedance is reproduced on the master–side. The operationality \( (P_o) \) corresponds to the operator experienced extra operational force. The ideal condition that satisfies perfect reproducibility \( (P_{rep} = 1.0) \) and operationality \( (P_o = 0) \) is called transparency \(^{(1)} \).

The first part of the right–hand side in (24), the \( H \) matrix elements are similar to the system derived by Iida et al. \(^{(27)} \) for DOB based 4ch–ABC performance evaluation. The re-
The denominator of (31) contains three poles that decide stability. We analysed the pole variation using root locus by varying \( \text{g}_{\text{rob}} \), \( C_f \), \( K_c \) and \( D_c \). Fig. 7 illustrates the results. The direction of the pole movement as the selected parameters were increasing has shown with the arrows. The cut-off frequency of the RFOB \( \text{g}_{\text{rob}} \) mainly influences the stability. The system becomes unstable for narrow bandwidth. The soft environment becomes stable with a lower bandwidth compared to the hard environment as shown in Figs. 7a and 7b. Therefore, when selecting the \( \text{g}_{\text{rob}} \) we need to consider the environment type. The \( \text{g}_{\text{rob}} > 100 \text{ rad/s} \) is recommended for the selected soft environment and \( \text{g}_{\text{rob}} > 1000 \text{ rad/s} \) is recommended for the selected hard environment. Next, the effect of force gain \( C_f \) is analyzed. As illustrated in Fig. 7c, the \( C_f \) does not make the system unstable as long as the bandwidth of force sensing \( \text{g}_{\text{rob}} \) is properly selected considering the environment type. The imaginary parts of the complex conjugate poles are growing as the \( C_f \) increases. Finally, the effect of environmental property is analyzed. As illustrated in Fig. 7d, the environment with higher damping properties is stable compared to the environment with lower damping properties because increasing damping coefficient moves the poles to the stable region. Changing \( D_c \) from 1 \( \rightarrow \) 10 Ns/m caused stable stiffness region to rise from 500 \( \rightarrow \) 5000 N/m. Increasing \( C_f \) only makes complex poles grow along the imaginary axis. In summary, wideband force sensing makes the proposed controller stable, and the environment with higher damping property instinctively makes the system stable.

5. Experiments, Results, and Discussion

5.1 Experiments

Experiments conducted to verify the proposed method using 3 DOF calligraphy robots shown in Fig. 8. A sponge was used as a replica environmental object. The control parameters are listed in Table 2. The schematic view of a manipulator is shown in Fig. 9. The direct drive (DD) motors (m1, m2, r1, r2) are equipped with encoders. The angle resolution is 6.0415x10⁻⁶ rad and can be obtained at the sampling rate of 10 kHz. The end effector position response is estimated as in (32).

\[
\begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix} = \begin{bmatrix}
\text{lcosh} \theta_2 + \text{lcos} \theta_1 \\
\text{lcos} \theta_2 + \text{lcos} \theta_1
\end{bmatrix}
\begin{bmatrix}
\text{aco} \\
\text{aco}
\end{bmatrix}
\]

(32)

Here \( x, y, \theta_1, \theta_2, \) and \( l \) denote the end effector x coordinate, the end effector y coordinate, the angle of the upper motor, the angle of the lower motor, and the length of a link respectively. We applied the initial conditions to shift the position response to the origin as in (33).

\[
\begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix} = \begin{bmatrix}
\text{lcos}(\theta_2 - \pi/2) + \text{lcos} \theta_1 - 0.3 \\
\text{lcos}(\theta_2 - \pi/2) + \text{lcos} \theta_1 + 0.3
\end{bmatrix}
\begin{bmatrix}
\text{aco} \\
\text{aco}
\end{bmatrix}
\]

(33)

The cartesian space velocity was derived as in (34).

\[
\begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix} = J_{\text{aco}}(\theta) \begin{bmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2
\end{bmatrix}
\]

(34)

where

\[
J_{\text{aco}}(\theta) = \begin{bmatrix}
-\text{lcos}(\theta_1 - \pi/2) & -\text{lcos} \theta_1 \\
-\text{lcos}(\theta_2 - \pi/2) & -\text{lcos} \theta_2
\end{bmatrix}
\]

(35)

The reaction torque observer (RTOB) estimated the external torque applied on each DD motor. The cartesian space force
was derived as in (35) \cite{maheshi2021}.

\[ \hat{\mathbf{p}}_{\text{ext}} = J_{\text{abc}}(\theta)^T \hat{\mathbf{p}}_{\text{rob}} \]  \hspace{1cm} (35)

We implemented the proposed constrained bilateral control method between DD motor pair 1 (m1, r1), imposing a torque limit of -1.5 Nm on replica motor r1. The m1 and r1 acceleration references were obtained using (16) and (17). The \( f_{m1}^{\text{eff}} \) and \( x_{m1}^{\text{eff}} \) are modified according to the section 3.3, Case 1 within the torque limit and Case 2 beyond the torque limit. The 4ch–ABC implemented between DD motor pair 2 (m2, r2) was derived as in (35) \cite{maheshi2021}.

\[ \hat{\mathbf{p}}_{\text{ext}} = J_{\text{abc}}(\theta)^T \hat{\mathbf{p}}_{\text{rob}} \]  \hspace{1cm} (35)

We implemented the proposed constrained bilateral control method between DD motor pair 1 (m1, r1), imposing a torque limit of -1.5 Nm on replica motor r1. The m1 and r1 acceleration references were obtained using (16) and (17). The \( f_{m1}^{\text{eff}} \) and \( x_{m1}^{\text{eff}} \) are modified according to the section 3.3, Case 1 within the torque limit and Case 2 beyond the torque limit. The 4ch–ABC implemented between DD motor pair 2 (m2, r2), imposing a torque limit of -1.5 Nm on replica motor r2. The m2 and r2 acceleration references were obtained using (16) and (17). The \( f_{m2}^{\text{eff}} \) and \( x_{m2}^{\text{eff}} \) are modified according to the section 3.3, Case 1 within the torque limit and Case 2 beyond the torque limit.
Initially, the replica is in contact with the environmental object. The operator moved the handle attached to the m3 along the y–axis to exert force on the replica environment.

The excess torque reduced reaction observer (ETR RTOB) suppressed the excess torque on DD motor m1 to the controller. We conducted two experiments as follows to illustrate the significance of the ETR RTOB, and the master position response scaling in virtual space for constrained bilateral control.

1. Force restraint with ETR RTOB and no position scaling in virtual space ($\alpha = 1$)
2. Force restraint with ETR RTOB and scale master position response in virtual space ($\alpha = -f_{limit}/f_{m}^{ext}$)

5.2 Results
Figs. 10 to 13 illustrate the results.

5.2.1 Force restraint with ETR RTOB and no position scaling in virtual space
The joint space responses in the experiment (1) are illustrated in Fig. 10. As illustrated in Fig. 10a, the ETR RTOB successfully delivered regulated torque ($T_{m}^{ext}$) to virtual space by removing the excess torque applied by the operator on m1. The ETR RTOB response was used as the master (m1) torque input to the constrained bilateral controller. Following the ETR RTOB response, the replica (r1) maintained the safe torque limit (-1.5 Nm) in real space. The torque error ($T_{m}^{ext} + T_{r}^{ext}$) is nearly zero. The ETR RTOB response and the replica–side reaction torque have satisfied the virtual space common mode force control objective. In this experiment, the virtual space master position scaling coefficient was set at 1.0 to illustrate the significance of it. The m1 position response restricted to r1 as in Fig. 10a. The position error ($\alpha \theta_{m} - \theta_{r}^{ext}$) is nearly zero. The differential mode position control objective has been realized in both virtual and real spaces. When considering the rotational stiffness response, m1 has experienced higher impedance than real r1 impedance as in Fig. 10a due to restricted m1 position response in real space. It confirms that master position scaling in virtual space is necessary for high environmental impedance reproducibility.

Fig. 10b shows 4ch–ABC bilateral control results of the DD motor pair 2 (m2,r2). The replica (r2) followed torque–angle responses of master (m2) as there was no torque constraint on r2. The torque error ($T_{m}^{ext} + T_{r}^{ext}$) and the position error ($\theta_{m}^{ext} - \theta_{r}^{ext}$) are almost zero. The common mode force control and differential mode position control objectives have successfully achieved in both real and virtual spaces.

The cartesian space responses of the experiment (1) that were derived using (33) and (35) are illustrated in Fig. 11. We focused to limit joint space torque. The limit imposed on m1 has affected replica–side y–axis motion. As a result, a restrained force along the y–direction of the contact environment was delivered as shown in Fig. 11a. Setting $\alpha = 1$ for m1 has restricted the operator movement along the y–axis. Therefore, the operator experienced higher impedance than real object impedance as in Fig. 11a. The x–axis motion demonstrated the conventional bilateral control motion. The replica force–position responses along the x–axis followed that of the master as in Fig. 11b. No constraints are observed along the x–axis.

5.2.2 Force restraint with ETR RTOB and scale master position response in virtual space
The DD motor pair 1 responses in the experiment (2) are illustrated in Fig. 12. As illustrated in Fig. 12a the ETR RTOB successfully delivered regulated torque by removing the excess torque applied by the operator on m1. The ETR RTOB response was used as the master–side torque input to the constrained bilateral controller. Following the master virtual torque input, the replica r1 maintained safe torque limit (-1.5 Nm). The master position response in real space was not restricted to replica position response and was changing with operator applied force. With variable $\alpha$ derived in section 3.3, the master–replica position tracking in virtual space was obtained. The torque error ($T_{m}^{ext} + T_{r}^{ext}$) and position error ($\alpha \theta_{m}^{ext} - \theta_{r}^{ext}$) are nearly zero. Therefore, common mode force control and differential mode position control objectives have been realized in virtual space. When considering the rotational stiffness response, m1 has experienced real r1 impedance as in Fig. 12a. Therefore, the master position response scaling in virtual space is necessary for high impedance reproducibility. The relation between $x_{m}^{ext}$ and $x_{m}^{ext}$ derived in section 3.3 is verified. The variation of virtual space master position scaling coefficient is shown in Fig. 12b.
The y-axis responses in the experiment (2) were derived using (33), (34) and (35) are illustrated in Fig. 13. The restraint torque on r1 resulted in a regulated force along the y-axis of the replica environment. The operator position response along the y-axis changed with operator applied force. The operator could freely maneuver the master system. We performed experiment (2) at high velocity to show the stability and robustness of the proposed method experimentally. We have applied force in the range of 7 N to 14 N at the contact velocity varied from -8 cm/s to -30 cm/s. Throughout the experiment (2), the replica has successfully maintained the restrained force around 5 N. We have released the master grip at velocity varied from 5 cm/s to 25 cm/s. The replica has successfully followed that release velocity, and the system remained stable. Therefore, the proposed method has demonstrated stable and robust performances experimentally. When considering the stiffness, the operator has experienced remote object impedance throughout the operation. Therefore, the impedance reproducibility is high. It confirms that the master position response scaling in virtual space results in high environmental impedance reproducibility. The results of DD motor pair 2 (m2, r2), and along the x-axis are not presented because behavior is similar to Figs. 10b and 11b with 4ch-ABC.

Both experiments have clearly illustrated that the replica is following the master virtual space restrained torque-angle commands, and as a result, the replica maintains the safe torque limit in the real space. The constrained bilateral control with reproducibility has successfully been achieved with the ETR RTOB and scaling master position response in virtual space.

### 5.2.3 Discussion

This paper has experimentally validated the proposed method by assigning joint space torque limits. Figs. 10a and 12a have clearly illustrated that the ETR RTOB successfully delivered regulated torque at a defined value to the master virtual space when the operator exerts excessive torque on real space. The bilateral control implemented with master-side ETR RTOB delivered constrained torque-angle output to the replica-side. As a result, the replica maintained the precise and safe torque limit on the joint space. The constrained torque-angle responses resulted in restricted replica-side cartesian space force-position responses. Therefore, the proposed method is applicable to precise and safe operation of environmental object in bilateral operation.

The virtual space master position response scaling has delivered reproducibility which is crucial for real environmental impedance perception throughout the operation. In both experiments, common mode force control and differential
mode position control objectives have been realized in the virtual space because those errors were nearly zero. The law of action and reaction with the force constraint has successfully been satisfied in virtual space with the ETR RTOB. The master–replica position tracking has been realized in virtual space. Therefore, the proposed constrained bilateral controller performs similar to the 4c–ABC in the virtual space.

5.3 Comparison with existing methods In this section, the proposed method was compared to the constrained bilateral control by oblique coordinate control proposed by Sakaino et al. The conventional methods have considered position limit and have controlled virtual position \( \bar{x} \) and virtual force \( \bar{f} \) using saturation coordinates instead of replica position–force responses.

Simulations were conducted considering single DOF identical linear motor pair. The reaction force of the object was calculated by a spring–damper model (spring coefficient \( K_r = 1000.0 \text{ N/m} \) and damping coefficient \( D_r = 10.0 \text{ Ns/m} \)). The reaction force was estimated by the RFOB. Disturbances were eliminated by the DOB. The simulation parameters are shown in Table 3. The control input of the conventional methods are (36) and (37).

![Simulations were conducted considering single DOF identical linear motor pair. The reaction force of the object was calculated by a spring–damper model (spring coefficient \( K_r = 1000.0 \text{ N/m} \) and damping coefficient \( D_r = 10.0 \text{ Ns/m} \)). The reaction force was estimated by the RFOB. Disturbances were eliminated by the DOB. The simulation parameters are shown in Table 3. The control input of the conventional methods are (36) and (37).](image)

\[
\begin{pmatrix}
\dot{x}^e_r \\
\dot{f}^e_r
\end{pmatrix} =
\begin{pmatrix}
\frac{1}{2M_r} & 1 & -M_mC_p(x^e_r - x^e_m) - C_f(f^e_m + f^e_r) \\
1 & 1 & -C_f(f^e_m + f^e_r)
\end{pmatrix}
\begin{pmatrix}
x^e_r \\
\dot{x}^e_r \\
\dot{f}^e_r
\end{pmatrix}
\begin{cases}
\text{if}(x^e_r < a) \\
\text{if}(x^e_r \geq a)
\end{cases}
\tag{36}
\]

where

\[
c = e^{b(x_{\text{limit}} - x^e_r)},
\]

\[
b = \frac{1}{x_{\text{limit}} - a},
\]

\[
\begin{align*}
\bar{x}_1 &= (a - x_{\text{lim}1}) \ln \left( \frac{x_{\text{lim}2} - x^e_r}{x_{\text{lim}1} - a} \right) + a, \\
\bar{f}_1 &= c\bar{x}_1, \\
\bar{x}_2 &= x^e_r, \\
\bar{f}_2 &= (2c - 1)\bar{f}_2, \\
a &= 0.004m \\
x_{\text{lim}1} &= 0.005m
\end{align*}
\]

The operator applied force \( \bar{f}^e_r \) is same for all simulations. Fig. 14 illustrates the results of the proposed constrained bilateral control method. The EFR RFOB has successfully delivered regulated force \( \bar{f}^e_r \) by removing the excessive force applied by the operator on the master system. The acceleration references were obtained using (16) and (17). Following \( \bar{f}^e_r \), the replica–side has successfully maintained force limit \( f_{\text{lim}} \) at 5.0 N in Fig. 14a. As illustrated in Fig. 14b, the real space master position response freely changed with the operator applied force, and it did restrict to replica position response. Master–replica force–position tracking was satisfied in the virtual space. The master–side has experienced replica impedance through the operation as illustrated in Fig. 14c.

Fig. 15 illustrates the results of conventional methods. The replica position is 5.0 mm when \( f_{\text{lim}} = 5 \text{ N} \). We selected \( x_{\text{lim}1} = 5 \text{ mm} \) and threshold value \( a = 4 \text{ mm} \) from this result. The method in (36) restricted the replica position below 5 mm in Fig. 15b and reaction force below 5 N in Fig. 15a. The master has satisfied bilateral control with virtual force–position responses \( (\bar{f}_r, \bar{x}_r) \). Similarly, the method in (37) restricted the replica position below 5 mm in Fig. 15e and reaction force below 5 N in Fig. 15d. The master has satisfied bilateral control with virtual force–position responses \( (\bar{f}_r, \bar{x}_r) \). The difference between the two conventional methods is latter ensures the limitation of the replica position and position tracking. In conventional methods, the impedance reproducibility is poor during constrained bilateral control as in Figs. 15c and 15f. The master–side impedance is higher than the replica–side impedance.

Table 3. Simulation Parameters

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( M_r \) | 0.25 kg | \( K_{rs} \) | 4.55 N/A |
| \( K_r \) | 1600.0 | \( K_f \) | 80.0 |
| \( C_r \) | 10.0 | \( q_{sh} \) | 5000.0 rad/s |
| \( g_{sh} \) | 500.0 rad/s | \( D_r \) | 10.0 Ns/m |
| \( f_{\text{lim}} \) | 5.0 N | \( a_t \) | 100.0 ms |

![Table 3. Simulation Parameters](image)
The conventional methods have focused on the replica position limitation. Therefore, the \( x_{c,\text{limit}} \) determines the force applied to the replica environment. If we select \( x_{c,\text{limit}} > 5 \) mm replica will experience a force larger than 5 N. The method proposed by us focuses on the replica force limitation. The replica position rests where the reaction force is equal to the safe force limit. Therefore, the proposed method can apply to objects with different sizes and need not consider position coordinates in space.

All three methods have satisfied common mode force control and differential mode position control objectives in virtual space because virtual space force–position errors are nearly zero. As in Fig. 14c, the proposed method has successfully delivered replica–side object impedance to the operator throughout the operation. Thus, reproducibility is high. Conventional methods have not satisfied reproducibility because in Figs. 15c and 15f operator has experienced higher than real object impedance. The proposed method effectively reproduces replica–side environmental object impedance compared to the conventional methods.

\[ \text{(a) Force response} \]

\[ \text{(b) Position response} \]

\[ \text{(c) Stiffness variation} \]

Fig. 14. The responses of the proposed method.

\[ \text{(a) Force response of (36)} \]

\[ \text{(b) Position response of (36)} \]

\[ \text{(c) Stiffness variation of (36)} \]

\[ \text{(d) Force response of (37)} \]

\[ \text{(e) Position response of (37)} \]

\[ \text{(f) Stiffness variation of (37)} \]

Fig. 15. The responses of the conventional methods.

6. Conclusions

This paper proposed a constrained bilateral control method with reproducibility. It precisely maintains replica–side force during excess force applied by the operator in bilateral operation. The validity was experimentally and analytically verified. The master–replica force–position simultaneous control is realized in the common dimension of acceleration. The paper introduced EFR RFOB that is an extension of the sensorless technique of RFOB, for the excess force regulation. The reproducibility is realized with a master position response scaling in virtual space. There is no master–replica force–position tracking in real space. The operator applied excessive force and the following master position response do not influence the 4ch–ABC in the virtual space with the introduced EFR RFOB and the master position response scaling. The 4ch–ABC common mode force control and differential mode position control objectives realize in the virtual space. Following the virtual space master force–position responses the replica maintains a safe and precise force limit on the contact object in the real space.

The proposed method has several benefits. The operator experiences real environmental object impedance throughout the operation. It does not require an environmental object impedance model or estimation of object parameters to deliver the object impedance to the operator during constrained bilateral control. This method can apply to actuator saturation, to handle objects with different sizes and does not require object position coordinates in space. Given the force limit in advance, the system is easily designed by the EFR RFOB and master position response scaling. Therefore, the method can apply to existing bilateral control systems with few efforts.

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