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Reinterpretation of Force Integral Control Considering the Control Ability of System Input

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Abstract— **In the paper, the new force control, which is called the D'Alambertian force Error based Force Integral Control (DEFIC), is proposed based on the force integral control by considering the ability of the system input. From the system input point of view, the external force and system acceleration cannot be distinguished from each other. Thus, the best solution is to handle those quantities together. DEFIC is motivated from this observation. The external disturbance robustness and the plant/model mismatch compensation of DEFIC are explained based on the passivity-based control and Disturbance OBserver(DOB). Furthermore, it is illustrated how DEFIC can be extended to n-DOF manipulator control. The performance of DEFIC is verified with simulations, and the conclusion is followed directly.**

I. INTRODUCTION

Many robotic tasks involve interactions between the robot end-effector and the environment. Necessary to the performance of these tasks are the basic capabilities of pushing, grinding, polishing, twisting, etc. The development of successful strategies and implementations for force control is seen as a crucial step in enabling robots to perform such tasks. Several researches have been studied in this field [1] [2] [3]. Some of them focuses on the compensation for the uncertainties in both robot dynamics and the environment(position and stiffness) by using the impedance control [4], and others are designed to implement force regulation or accurately force tracking based on the integral action [5] [6]. In this paper, we focus on the latter.

The objective of the force regulation is to make the external force applying to the system follow the desired value. It seems to be relatively easy because the external force can be measured and the system input be generated from lots of novel force control algorithms developed so far. However, when the system dynamics is involved in the analysis, the problem is not easy as expected. Because the system input, the external force, and the system inertial force(e.g. the inertial force due to the system acceleration) are coupled in the system dynamics, the system input cannot figure out the external force itself from them. In other words, the external force on the system dynamics cannot be controllable by the system input port when the system is in dynamic situation. Therefore, the best thing we can do seems to control the sum of the external force and the system inertial force. So, a force control algorithm, i.e., DEFIC based on the ability of the system input will be proposed and the property and meaning of DEFIC will be illustrated by comparing it with other force controls developed so far.

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This paper is organized as follow. In section II, the traditional force integral control and DEFIC will be explained for a single DOF system. Section III discusses the robustness of DEFIC with the passivity-based control structure and DOB and the meaning of the integral gain. In section IV, the meaning of the active damping will be reinterpreted by comparing DEFIC with the force integral control with an active damping. Section V extends DEFIC to the n-DOF manipulator control. In section VI, simulation results and analysis are given to verify the proposed method. Finally, section VII concludes the paper.

II. THE CONCEPT OF CONTROL USING A SINGLE DOF SYSTEM MODEL

In this section, a aingle DOF system will be used to illustrate the basic concept of the force integral control and DEFIC. In the model as mentioned in Fig. 1, f, f_{ext}, m, $\ddot{x}$ means the control input, the measurable external force, the system inertia, and the system acceleration in order. Thus, the system dynamics will be expressed as follows:

$$f + f_{\text{ext}} = m\ddot{x} \tag{1}$$

A. The Force Integral Control

The force integral control has been commonly used in the explicit force control [1] [5] [6]. To control the external force, the following integral control with feedforward command will be applied to the system:

$$\begin{aligned} \varepsilon_F &= f_{\text{des}} - f_{\text{ext}} \\ f_{\text{ref}} &= f_{\text{des}} + K_I \int \varepsilon_F \, dt \\ f &= -f_{\text{ref}}, \end{aligned} \tag{2}$$

where f_{ref} is an intermediate reference force and the f_{des} is a desired force which f_{ext} is to be followed to.

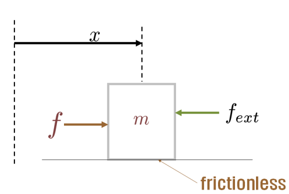

Fig. 1. The 1 DOF system model

This type of control has been widely used in the force regulation field due to it's simple structure, good control performance, and disturbance rejection property [7] [8]. However those features may not be maintained as the system dynamics becomes important. Suppose that the force integral control is applied to the system. Then, the closed loop dynamics will be given as follows (by combining (1) with(2)):

$$\varepsilon_F + K_I \int \varepsilon_F \, dt = -m\ddot{x} \tag{3}$$

From (3), it is easily expected that the force error, ε_F, cannot be zero when the system acceleration is not vanished, i.e., the system moves dynamically. Therefore, the force integral control will have some limit and may lead to an unstable system response under the dynamic situation. To overcome it, an active damping term is usually added to the controller [1].

B. The Concept Of DEFIC

From observing the system dynamics, it is obvious that the external force f_{ext} itself is not controllable with the system input f. Suppose that the single DOF system dynamics is transformed as follows:

$$f = -\left(f_{\text{ext}} - m\ddot{x}\right)$$

From the system input point of view, f cannot access to f_{ext} without altering $m\ddot{x}$ whether f_{ext} is measurable or not. This means that f cannot control the external force itself directly. Thus, the best thing under this system dynamics is to control the summation quantity, $f_{\text{ext}} - m\ddot{x}$[1], to a desired level. Hence, with the redefined force error,

$$\varepsilon_D \triangleq f_{\text{des}} - \left(f_{\text{ext}} - m\ddot{x}\right),$$

the force control is calculated as follows:

$$\begin{aligned} f_{\text{ref}} =&\ f_{\text{des}} + K_I \int \varepsilon_D \, dt \\ =&\ f_{\text{des}} + K_I \int \left(f_{\text{des}} - f_{\text{ext}}\right) dt + K_I m\dot{x} \\ f =&\ -f_{\text{ref}} \end{aligned} \tag{4}$$

This is the basic structure of DEFIC. It is noticeable that the linear momentum is fed back to the system. Applying (4) to the system, the system closed-loop dynamics is transformed to the following form:

$$\begin{aligned} f + f_{\text{ext}} &= \left\{-f_{\text{des}} - K_I \int \left(f_{\text{des}} - f_{\text{ext}}\right) dt - K_I m\dot{x}\right\} + f_{\text{ext}} \\ &= -\left(f_{\text{des}} - f_{\text{ext}}\right) - K_I \int \left(f_{\text{des}} - f_{\text{ext}} + m\ddot{x}\right) dt = m\ddot{x} \\ \therefore\ & \left(f_{\text{des}} - f_{\text{ext}} + m\ddot{x}\right) + K_I \int \left(f_{\text{des}} - f_{\text{ext}} + m\ddot{x}\right) dt \\ &= \varepsilon_D + K_I \int \varepsilon_D \, dt = 0 \end{aligned} \tag{5}$$

Hence, the integral equation is maintained whether the acceleration exists or not. Due to the structure of the integral equation, the system closed-loop dynamic will be described eventually as $f_{\text{ext}} - f_{\text{des}} = m\ddot{x}$ as time goes to infinity.

[1]this means a D'Alambertian force of the system driven by f_{ext}.

III. The Effect and Meaning of the Integral Gain K_I

Since DEFIC is based on the force integral control, the performance is tuned only by adjusting K_I. By increasing the K_I properly, not only the integrand convergent rate gets more faster but also the robustness with respect to the external disturbance rejection and model uncertainty are guaranteed as illustrated below.

A. The Robustness aganinst the External Disturbance

From (5), it is expected that the closed-loop system dynamics without the external disturbance is finally expressed as $f_{\text{ext}} - f_{\text{des}} = m\ddot{x}$. In this section, we will check how the closed-loop dynamics changes when the external disturbance is applied to the system. In the last of the section, it is verified that the stability of the closed-loop dynamics is guaranteed whether the bounded external disturbance is applied to the system or not by increasing the integral gain K_I properly.

To consider the effect of the disturbance to the system, suppose that the system (1) is modified as follows:

$$f + f_{\text{ext}} + f_w = m\ddot{x}, \tag{6}$$

where f_w represents the external unmeasurable disturbance force. To handle f_w, an auxiliary input f_u is added to (4) as given below:

$$\begin{aligned} f_{\text{ref}} =&\ f_{\text{des}} + K_I \int \varepsilon_D \, dt - f_u \\ f =&\ -f_{\text{ref}} \end{aligned} \tag{7}$$

When (6) and (7) are substituted, the closed loop dynamics is expressed as follows:

$$\begin{aligned} \left(f_{\text{des}} - f_{\text{ext}} + m\ddot{x}\right) + K_I \int \left(f_{\text{des}} - f_{\text{ext}} + m\ddot{x}\right) dt \\ = \dot{S} + K_I S = f_u + f_w, \end{aligned} \tag{8}$$

where $S = \int \left(f_{\text{des}} - f_{\text{ext}}\right) dt + m\dot{x}$. As you can see in (8), this form of the system is strictly passive about the (S, f_w) pair. Thus, we can move S to zero by using f_u properly as in the passivity based control [9].

The Lyapunov function candidate is defined about the state s as given below[2]:

$$V = \frac{1}{2} S^T S > 0, \qquad \forall s \neq 0$$

By considering the strictly passive property, the auxiliary input f_u will be defined as given below:

$$f_u = -\left(\frac{1}{\gamma^2}\right) S,$$

where γ is related to $\mathcal{L}_2$ gain of the system.

[2]In this example, the dimension of s is one. But, the analysis illustrated in this section can be extended to the multi-dimensional system as well. So the state s will be treated as a multi-dimensional vector in the stability analysis.

Then, the time derivative of Lyapunov function candidate is calculated as follows:

$$\begin{aligned}
\dot{V} &= S^T \dot{S} = S^T\left(-K_I S + f_u + f_w\right) = -K_I S^T S + S^T f_u + S^T f_w \\
&= -K_I\, S^T S - \frac{1}{\gamma^2} S^T S + S^T f_w \\
&= -K_I\, S^T S - \frac{1}{\gamma^2}\left\{S^T S - \gamma^2 S^T f_w + \frac{\gamma^4}{4} f_w^T f_w\right\} + \frac{\gamma^2}{4} f_w^T f_w \\
&= -K_I\, S^T\, S - \frac{1}{\gamma^2}\left\|S - \frac{\gamma^2}{2} f_w\right\|^2 + \frac{\gamma^2}{4}\left\|f_w\right\|^2 \\
&< -K_I\, S^T\, S + \frac{\gamma^2}{4}\left\|f_w\right\|^2 \le -\gamma_1(\|S\|) + \gamma_2(\|f_w\|),
\end{aligned}$$

where $\gamma_1(\cdot)$ and $\gamma_2(\cdot)$ are the class $\mathcal{K}_\infty$ functions. Since the RHS of the above equation is an unbounded function for s and f_w, the closed-loop system using DEFIC with the auxiliary input is disturbance input-to-state stable(ISS). Thus, we expect that when unknown bounded disturbances exist on systems, the behavior of the system will remain bounded, and when the set of inputs, including the control and disturbance, goes to the zero, the behavior of system moves toward the equilibrium point($s = 0$) [9].

Now, consider the derived control input to overcome the disturbance. DEFIC with the auxiliary input (7) will be summarized as follows:

$$\begin{aligned}
f_{\text{ref}} =&\ f_{\text{des}} + K_I \int \varepsilon_D\, dt + \left(\frac{1}{\gamma^2}\right) S \\
=&\ f_{\text{des}} + \left(K_I + \frac{1}{\gamma^2}\right)\int \varepsilon_D\, dt \\
&(\because \int \varepsilon_D\, dt = \int (f_{\text{des}} - f_{\text{ext}})\, dt + m\dot{x} = s) \\
f =&\ -f_{\text{ref}}
\end{aligned}$$

Therefore, the disturbance can be rejected with the same controller as (4) by just increasing the integral gain. This is the good property of DEFIC.

B. The Plant/Model mismatch compensation

When DEFIC is expressed as a block diagram, it will be expressed as Fig. 2. After some block diagram operation, Fig. 2 can be transformed to Fig. 3. As you can see in Fig. 3, DEFIC is essentially the same structure as the DOB. Compare to the traditional DOB [10], the only difference is that the desired input is entered with negative sign, and the external force is added and subtracted in the middle of the diagram. Thus, by using DEFIC, low frequency disturbances are canceled and plant/model mismatch is compensated in the low frequency range. It is note that the equivalent $Q(s)$ filter used in the control is the first-order one. That is,

$$Q(s) = \frac{R(s)}{1 + R(s)} = \frac{\frac{K_I}{s}}{1 + \frac{K_I}{s}} = \frac{K_I}{s + K_I} = \frac{1}{\frac{1}{K_I}s + 1} \tag{9}$$

It is quite interesting that the integral gain K_I of DEFIC is directly related to the cut-off frequency of the $Q(s)$ filter of the DOB. The region which $Q(s)$ remains unity will be wider and wider as K_I is increased more and more. So, DEFIC becomes more robust to wide frequency disturbance signals and it will appears as the disturbance robustness property becomes enhanced when increasing K_I. The disturbance robustness property illustrated in section III-A can be explained in such a different way.

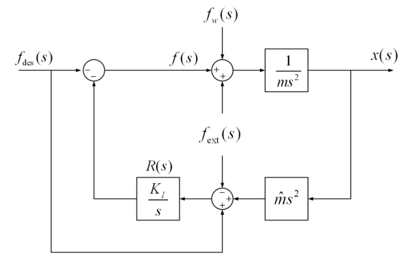

Fig. 2. Block diagram of the modified force control

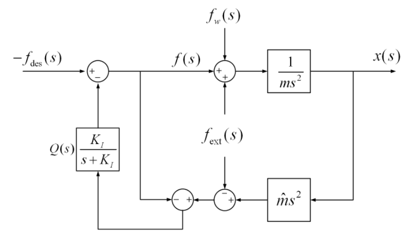

Fig. 3. Block diagram transformed to the DOB like form

Another important feature of DOB is plant/model mismatch compensation. Because DEFIC is equivalent to DOB, the compensation is also realized naturally. The nominal model implemented in Fig. 3 can be summarized as given below:

$$f_{\text{ext}} - f_{\text{des}} = \widehat{m}\ddot{x}, \tag{10}$$

where $\widehat{m}$ represents the nominal/estimated value of the inertia of the system. In fact, the control represented in (4) is not desirable to implement because the feedback momentum term cannot be defined a priori due to the lack of information of the system inertia. This ambiguity is now removed since DOB tends to compensate the mismatch between the real inertia and the nominal one in the low frequency range($Q(s) \approx 1$). Thus, all the quantity in (4) is available so that DEFIC can be realized without difficulty. Through this, the system dynamics converges to the nominal system dynamics and the force regulation will be executed with the nominal plant.

IV. Reinterpretation of force integral control with active damping

After applying DEFIC, the system moves according to (10). In (10), the external force will follow the desired force when the system acceleration decreases to zero (e.g. grinding, deburring, polishing, etc), and a force error will occur when the system acceleration exists during the operation. This does not seem to be different from the traditional force integral control case. However, there is some difference between them.

Consider (4) with nominal inertia as follows:

$$\begin{aligned} f_{\text{ref}} &= f_{\text{des}} + K_I \int \varepsilon_F \, dt + (K_I \widehat{m}) \dot{x} \\ &= f_{\text{des}} + K_I \int \varepsilon_F \, dt + K_V \dot{x} \\ f &= -f_{\text{ref}} \end{aligned} \tag{11}$$

In many cases, the force integral control is used with an active damping term to suppress the rapid velocity change [1]. It is note that the force integral control with active damping is the same form as (11). From this observation, we can guess the following two interesting things. Fist, DEFIC has the active damping naturally which is not intended at the control design step. Due to this damping factor, the system performance is more stable than that of the traditional force integral control[3]. Second, this is more important than the former, the method used so far for the active damping seems to alter the system inertia rather than to add the damping effect to the system. The velocity gain K_V is directly related to the system nominal inertia so that the effect of changing K_V will appear in the change of the system inertia. In the physical sense, the larger the system inertia is, the less sensitive to the force variation the system is. The slow motion due to the enlarged inertia seems to be interpreted that the active damping is added more and more to the system when K_V increases. This is also supported with the fact that a velocity bound of the system is not observed. If the damping exists in the system, the velocity bound such as the terminal velocity of free-falling in the air should be observed. As discussed in section VI later, however, the velocity bound is not observed by changing K_V. In summary, the active damping term in (11) can be reinterpreted with the system inertia increasing concept.

Above discussion suggests that another method will be needed if the system requires a damping effect. In this case, the desired closed-loop dynamics may be expressed as follows:

$$f_{\text{ext}} - f_{\text{des}} = \widehat{m}\, \ddot{x} + \widehat{b}\, \dot{x},$$

where $\widehat{b}$ represents the nominal damping coefficient. To obtain the above closed-loop dynamics, the controller in (4) should be changed as given below:

$$\begin{aligned} f'_{\text{des}} &= f_{\text{des}} + \widehat{b}\dot{x} \\ \varepsilon_{DA} &= f'_{\text{des}} - (f_{\text{ext}} - \widehat{m}\ddot{x}) \\ f_{\text{ref}} &= f'_{\text{des}} + K_I \int \varepsilon_{DA} \, dt \\ &= f_{\text{des}} + K_I \int \varepsilon_F \, dt + (K_I \widehat{m} + \widehat{b})\, \dot{x} + (K_I \widehat{b})\, x \\ &= f_{\text{des}} + K_I \int \varepsilon_F \, dt + K_D \dot{x} + K_P x \\ f &= -f_{\text{ref}} \end{aligned} \tag{12}$$

In (12), the position feedback as well as the velocity feedback is required to implement the active damping to the system. The position feedback gain K_P and velocity feedback gain K_D will be set as in (12). This type of control is also known as the position-based force/torque control [11] [12]. With the control, the closed-loop dynamics has the active damping in operation.

V. Applying to the manipulation control

In this section, the outline of how to apply DEFIC to the n-DOF manipulator will be illustrated.

The dynamic equation of motion for an n-DOF manipulator can be expressed in the following form [13]:

$$\boldsymbol{\tau} + \mathbf{J}^T(\mathbf{q})\mathbf{f}_{\text{ext}} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}), \tag{13}$$

where $\mathbf{q}$ is the $n \times 1$ vector of joint coordinates, $\mathbf{M}(\mathbf{q})$ is the $n \times n$ inertial matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the $n \times 1$ vector of torques due to centripetal and Coriolis effects, $\mathbf{g}(\mathbf{q})$ is an $n \times 1$ vector of gravitational torques, $\boldsymbol{\tau}$ is the $n \times 1$ vector of joint input torques, $\mathbf{J}(\mathbf{q})$ is the $m \times n$ Jacobian matrix from the $n \times 1$ joint space to the $m \times 1$ task space, and $\mathbf{f}_{\text{ext}}$ is the $m \times 1$ external force/moment vector.

This equation is now transformed to define the D'Alambertian force error as in the following form:

$$\boldsymbol{\tau} = -\left\{ \mathbf{J}^T(\mathbf{q})\mathbf{f}_{\text{ext}} - \mathbf{g}(\mathbf{q}) - (\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}}) \right\}$$

Hence, the control input $\boldsymbol{\tau}$ cannot access to $\mathbf{f}_{\text{ext}}$ directly without compensating the dynamics so that the D'Alambertian force error should be defined by considering it. Before further discussion, we assume that the gravity compensation is executed a priori without loss of generality[4]. Also, assume that the plant/model mismatch is not considered in this step. We will discuss this problem at the end of this section.

Then, the error is defined as given below:

$$\boldsymbol{\varepsilon}_\tau \triangleq \boldsymbol{\tau}_{\text{des}} - \left\{ \mathbf{J}^T(\mathbf{q})\mathbf{f}_{\text{ext}} - \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} - \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} \right\} \tag{14}$$

Then, DEFIC will be derived automatically as given below:

$$\begin{aligned} \boldsymbol{\tau}_{\text{ref}} &= \boldsymbol{\tau}_{\text{des}} + K_I \int \boldsymbol{\varepsilon}_\tau \, dt \\ &= \boldsymbol{\tau}_{\text{des}} + K_I \int \left(\boldsymbol{\tau}_{\text{des}} - \mathbf{J}^T(\mathbf{q})\mathbf{f}_{\text{ext}} \right) dt \\ &\quad + K_I \int \left(\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} \right) dt \\ \boldsymbol{\tau} &= -\boldsymbol{\tau}_{\text{ref}} \end{aligned} \tag{15}$$

In (15), most of the terms except for the joint acceleration $\ddot{\mathbf{q}}$ are available. Thus, the second integral in (15) should be

[3]This will be discussed in detail in section VI.

[4]It is also interpreted that the desire torque contains the gravity term so that the gravity is eliminated eventually in the closed-loop dynamics. In any case, the gravity compensation is not hard to perform.

modified properly to realize the control. With the property of the manipualtor [13],

$$\mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) = \dot{\mathbf{M}}(\mathbf{q},\dot{\mathbf{q}}) - \frac{1}{2}\left[\frac{\partial \mathbf{M}}{\partial \mathbf{q}^T}\dot{\mathbf{q}}\right]$$

the second integration in (15) can be calculated by using the integration by parts as follows:

$$\begin{aligned}
\int \left(\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\right) dt &= \int \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}}\, dt + \int \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\, dt \\
&= \left\{\mathbf{M}(\mathbf{q})\dot{\mathbf{q}} + \overline{\mathbf{M}} - \int \dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}}\, dt\right\} + \int \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\, dt \\
&= \mathbf{M}(\mathbf{q})\dot{\mathbf{q}} + \overline{\mathbf{M}} - \int \left(\dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}} - \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\right) dt \\
&= \mathbf{M}(\mathbf{q})\dot{\mathbf{q}} + \overline{\mathbf{M}} - \frac{1}{2}\int \left(\left[\frac{\partial \mathbf{M}}{\partial \mathbf{q}^T}\dot{\mathbf{q}}\right]\dot{\mathbf{q}}\right) dt \\
&= \mathbf{M}(\mathbf{q})\dot{\mathbf{q}} + \overline{\mathbf{M}} - \frac{1}{2}\int \left(\dot{\mathbf{M}}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\right) dt,
\end{aligned}$$

where $\overline{\mathbf{M}} = \mathbf{M}(\mathbf{q}(0))\dot{\mathbf{q}}(0)$.

Now, quantities in the above equation are all available so that (15) can be summarized as given below:

$$\begin{aligned}
\boldsymbol{\tau}_{\text{ref}} &= \boldsymbol{\tau}_{\text{des}} + K_I \int \left(\boldsymbol{\tau}_{\text{des}} - \mathbf{J}^T(\mathbf{q})\mathbf{f}_{\text{ext}}\right) dt \\
&\quad + K_I \left\{\mathbf{M}(\mathbf{q})\dot{\mathbf{q}} - \frac{1}{2}\int \left(\dot{\mathbf{M}}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\right) dt\right\} \\
\boldsymbol{\tau} &= -\boldsymbol{\tau}_{\text{ref}}
\end{aligned} \tag{16}$$

Note that the integral constant term $\overline{\mathbf{M}}$ is omitted in (16) for simplicity since the plant/model mismatching compensation property of DEFIC will finally eliminate this constant term.

When applying (16) to n-DOF manipulator (13), the closed-loop dynamics will be transformed to the following form:

$$\begin{aligned}
\mathbf{J}^T(\mathbf{q})\mathbf{f}_{\text{ext}} - \boldsymbol{\tau}_{\text{des}} &= \mathbf{J}^T(\mathbf{q})\left(\mathbf{f}_{\text{ext}} - \mathbf{f}_{\text{des}}\right) \\
&= \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}
\end{aligned} \tag{17}$$

Then, the external force/moment vector will be tracking the desired force/moment according to (17) when applying $\mathbf{f}_{\text{des}}$ or $\boldsymbol{\tau}_{\text{des}}$ to the control. Note that the dynamical coefficient matrices $\mathbf{M}(\mathbf{q})$ and $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})$ can be replaced with the nominal ones. Due to the property as DOB, the manipulator will behave the nominal manipulator model. The matrices $\mathbf{M}(\mathbf{q})$ and $\dot{\mathbf{M}}(\mathbf{q},\dot{\mathbf{q}})$ can be selected according to its purpose. For example, the inertia matrix $\mathbf{M}(\mathbf{q})$ can be just set to the diagonal matrix to decouple the joint variables [14], or the precisely defined inertia model to handle the nonlinear dynamics of the system [15]. In both case, the same control algorithm can be applied.

VI. SIMULATION RESULTS

DEFIC was simulated with 1 DOF system as shown in Fig. 4. In the configuration, the inertia slid along the guide rail without friction. A F/T sensor was equipped at the right side of the inertia and the distance between the tip of the F/T sensor and the wall was 0.28[m]. The rigid contact was assumed but the relative coefficient of restitution(e) was set by referring the values of metal. Parameters used in the simulation is summarized in Table I. The simulation was executed with the RoboticsLab simulator which is the articulated multi-body system simulation software platform [16]. The simulation results will be presented in this section.

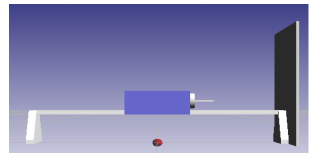

Fig. 4. the system configuration of the simulation

TABLE I
SIMULATION PARAMETERS

Parameters	Values
$\hat{m}$	5.0[kg]
$\hat{b}$	25.0
K_I	115.0
f_{des}	-5.0[N]
e(Coeff. Of Restitution)	0.5970
dT	0.001[sec]

A. Force Integral Control vs. DEFIC

In section IV, It is mentioned both the force integral control and DEFIC have excellent performance of force regulation when in contact with the static wall but the behavior of DEFIC is more stable due to its natural damping term. This expectation will be verified in Fig.5. As you can see in Fig. 5, both can control the external force to the desired force, $f_{\text{des}} = -5[N]$.

Whereas the motion produced by using the force integral control has some bounces until at rest, there is little bounce motion when applying DEFIC. It is understood that the inertia used in the simulation is large $(5kg)$ so that the rapid motion changes were suppressed naturally in motion. Therefore, we can conclude that the previous discussion is correct.

B. DEFIC With And Without The Active Damping

In section IV, DEFIC with active damping was proposed. the simulation results of the original control and the one with active damping is illustrated in Fig. 6. As mentioned in section IV, there will exist a velocity bound in free motion when the system damping force is balanced on the applied force to the system. The terminal velocity of free-falling is an example of such phenomena. This is well illustrated in Fig. 6. Note that the velocity of the system produced by (4) increased until the inertia hit the wall while the velocity produced by (12) converged a limit before collision with the wall. Therefore, we can conclude that the active damping is actually added to the system as in (12).

It is also noticeable that DEFIC with active damping can suppress the peak actuator force as a damper. Since (4) produce the unbound motion with heavy inertia, the

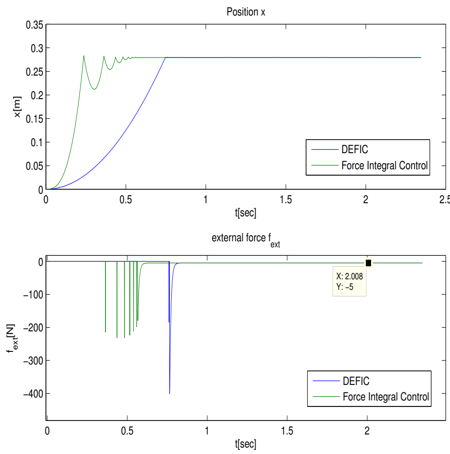

Fig. 5. Simulation results of the force integral control and DEFIC

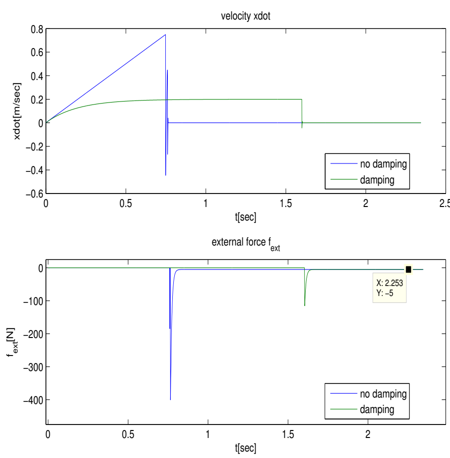

Fig. 6. Simulation results of DEFIC with and without the active damping

control input required tends to increase drastically as in Fig 5 and Fig. 6 when the system collides. This behavior is not advantageous to actual implementation of DEFIC. As in Fig. 6, active damping proposed in (12) can control the peak torque below a desired level.

VII. CONCLUSIONS AND FUTURE WORKS

In the paper, the new force control algorithm was proposed by considering the ability of the system input. From the system input point of view, the external force cannot be handled without affecting the system dynamics so that controlling the external force itself without compensation of the system dynamics with the system input is actually impossible. Hence, the best thing using the system input may be to control those quantities together. In this reason, the D'Alambertian force error was defined and the new force integral control using it was proposed.

It was also verified that DEFIC is a kind the of passivity-based control and DOB. As a result, the robustness of the external disturbance and the plant/model mismatch compensation was accomplished automatically as increasing the integral gain. It was illustrated as well that the momentum feedback loop contained in the control contributes the stable motion performance during operation. Related to it, the different version of control was proposed to add the active damping explicitly. Finally, DEFIC was applied to the control of the n-DOF manipulator to show that DEFIC can be extended to a multi-DOF system, if its closed-form dynamics is known.

Simulations were also performed to support the discussions mentioned in the paper. In the future, experiments will be executed to verify the performance of the proposed control for a single DOF and n-DOF system.

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