Abstract—In tightly coupled cooperative manipulation of two arms, an interaction force control is one of the important issues. In this paper, a sensor-less interaction force control in a de-burring task using a dual-arm is introduced. The dual arm manipulation increases the motion dexterity in the de-burring task as compared to the single arm manipulation. A closed form interaction force control algorithm is proposed, which does not require any force sensor. In the motion planning, the 12 Lagrangian coordinates of the system are decomposed into 9 motion degrees and 3 constrained degrees. Then, the whole dual arm can be modeled as a kinematically redundant robot. The primary task is to control the 9 motion degrees and the secondary task is to control the interaction force and the relative motion between the two arms. The concept of virtual joints is employed to represent the constrained degrees, which include the interaction force and the relative motion between the two arms. Through the simulation results, we show that the smooth de-burring task can be accomplished by using the suggested interaction force control model without force sensor.

I. INTRODUCTION

There have been many researches on the dual-arm manipulation for the last two decades because many difficult tasks done by humans can be substituted by the dual-arm. Regarding the conventional de-burring task, the work-piece is held at a fixed surface and an operator or a robot performs the de-burring task. However, when using the dual arm manipulation in the de-burring task, the motion dexterity can be improved by employing the relative motion degrees between two arms. Secondly, the interaction force between the tool and the work piece [1-5] can be adjusted by using the redundant actuators inherent in the dual-arm system.

To date, most interaction force control methods make use of the reliable force sensors attached to the wrist of manipulators. In this point of view, there has been some research works related to analysis and control of the interaction forces in robotic systems. Yoshida, et al. [6] suggested the reaction management control method. Torres and Dubousky [7] proposed the path-planning method for elastically constrained space manipulator systems. Chong, et al. [8] dealt with the position control problem of collision-tolerant passive mobile manipulator with base suspension characteristics. Yun and Kumar [9] suggested the control method of trajectory and interaction force simultaneously for the planar dual arm model. Zuo and Qian [10] dealt with the equivalence problem of the internal and interaction forces in multi-fingered grasping case. Desai and Howe [11] developed a humanoid arm manipulation method by minimizing interaction forces through minimum impedance control. Wu, et al. [12] developed 12 DOF force sensor in order to measure the interaction force of robotic manipulator. Chung, et al. [13] proposed a closed form dynamic model for hybrid-type robotic systems and it was applied to the interaction force control between the two robotic modules connected in a serial manner. However, it was confined to the control of the interaction force between serially-connected modules or tightly-coupled two-arms. Most controllers related to dual-arm operation require a force/torque sensor to control the interaction forces between two arms. However, employing force/torque sensor is expensive. In light of this fact, this paper treats a force sensor-less interaction force control in a de-burring task using a dual-arm.

This paper is organized as follow: section II explains the interaction force of the de-burring task as a target task; section III introduces a closed-form dynamic model of interaction force in a viewpoint of kinematics and dynamics; section IV proposes the interaction force control method and shows its effectiveness through simulations of a given de-burring task; finally, section V draws the conclusion of this paper.

II. INTERACTION FORCES IN DE-BURRING TASK

A. De-burring Task

For the dual-arm manipulation, the mobility of robot system is decided by the contact condition. Fig. 1 shows three types of contact in the dual-arm operation. We assume that both manipulators have 6-DOF. Firstly, Fig. 1(a) shows that a dual-arm rigidly grasps the object. In this case, the mobility of this closed chain is 6 and the degree of internal loading is 6. Secondly, Fig. 1(b) shows that the left arm rigidly grasps the object and the right arm makes a friction point contact with the object. Then, the mobility of this closed chain is 9 and the degree of the internal loading is 3. Finally, Fig. 1(c) shows that both arms make a point contact with the object. In this case, the mobility of closed chain is 12 and thus there is no internal loading.

From another point of view, these three closed chains have
A de-burring task done by the dual-arm can be depicted as shown in Fig. 2. In Fig. 2(a), the end-effector of the right arm grips a de-burring tool and that of the left arm grips the work-piece to be de-burred. Also, each arm is a 6 degrees-of-freedom serial chain for dexterous manipulation, and each arm controls the 3 positions and 3 rotation angles (x, y, z, roll, pitch, and yaw). On the other hand, for the de-burring task, the de-burring tool should keep in contact with the work-piece continuously and stably as shown in Fig. 2(b). When the de-burring tool gets in contact with the work-piece, two arms can be considered as one closed chain. Then, the mobility of this closed chain is 9. This implies that there are nine variables to be controlled for operational degrees of motion. Table 1 shows that the nine operational degrees consist of 6 DOF motion of the left arm and 3 rotational DOF of the tool grasping arm. When the tool is pinned to the work-piece, three constraints can be defined as three interaction forces \((F_x, F_y, F_z)\) between the tool and the work-piece grasped by the left arm. However, when the tool just contacts the work-piece at a point with friction, the constraints can be defined as one contact force in the direction normal to the work-piece and two relative motions between the tool and the work-piece as shown in Fig. 3. Thus, the case 2 corresponds to the de-burring task of current study.

B. Virtual Joint Model

It is necessary to express the kinematic constraints by some means. We employ the concept of virtual joint to represent the relative motion and the interaction force between two arms. Fig. 4 depicts the equivalent model of the proposed dual arm. The constraints in the de-burring task are represented by the three virtual joints as denoted by three orthogonal linear joints. They are equivalent to the operational output \((x, y, \text{ and } z)\) of the right arm. Here, the physical meaning of the dynamic forces at the virtual joints is equivalent to the interaction forces between the de-burring tool and the work-piece. The dynamic model of the left arm including the virtual joints is first obtained. Then, the effective dynamic model of the right arm is represented as the sum of virtual joints’ dynamics and its own dynamic model. In the following, we discuss the kinematic and dynamic model of this dual-arm through the virtual joints in more detail.
For a de-burring task, the desired trajectory of the de-burring tool should be firstly described at the work-piece coordinate frame as shown in Fig. 3. The tool will move according to the desired de-burring trajectory with both x-directional and y-directional components on the work piece. In this case, the interaction force is mainly generated along the z-coordinate. Here, let us assume that two arms get in point contact with each other and the cutting force between the tool and work-piece are sufficiently large to accomplish the de-burring task well, then the three (x, y, z) directional cutting forces are transferred from the tool to the work-piece, but the transferred moment about the z-direction due to the rotation of the de-burring tool can be neglected in the de-burring task since it is applied at a contact point.

III. INTERACTION FORCE MODEL

A. Kinematics

When the de-burring tool gets in point contact with the work-piece, the translational output velocity \( \dot{z}_u \) of the right arm can be represented in terms of 6 joint variables \( \dot{\phi}_e \) as follows

\[
\dot{z}_u = [G_v^e] \dot{\phi}_e ,
\]

where, \( [G_v^e] \in R^{3x6} \), \( \dot{\phi}_e \in R^6 \), and \( \dot{z}_u \in R^3 \).

The output displacement \( \dot{z}_u \) of the right arm is treated as three virtual joints \( \dot{\phi}_e \in R^3 \) interfacing with the left arm.

Then, the velocity \( \dot{z}_u \in R^6 \) of the left arm including the virtual joints is given as

\[
\dot{z}_u = [G_v^e] \dot{\phi}_e ,
\]

where \( [G_v^e] \in R^{6x6} \) denotes the Jacobian and the joint variable of the left arm including the virtual joints is given as

\[
\dot{\phi}_e = \begin{bmatrix} a_{2*}^T \\ v_{2*}^T \end{bmatrix} \dot{z}_u ,
\]

where \( a_{2*} \in R^6 \) and \( v_{2*} \in R^3 \) denotes the velocity vector of the joints of the left arm and that of the virtual joint, respectively.

By substituting (1) into (2), we can obtain the velocity equation of the hybrid robot as

\[
\dot{\phi}_e = [G_v^e] \dot{\phi}_e ,
\]

where

\[
[G_v^e] = [G_v^e] \in R^{6x6} \quad I_{6x6} \in R^{6x6} \in R^{6x12}
\]

and \( D \dot{\phi}_e \in R^{12} \) given by

\[
D \dot{\phi}_e = \begin{bmatrix} \dot{z}_u^T \\ \dot{\phi}_e^T \end{bmatrix} \phi_e .
\]

(6) denotes the total Lagrangian coordinates (or all inputs) of this dual-arm, and \([0]_{6x6} \) and \( I_{6x6} \) are a \( 6 \times 6 \) null matrix and a \( 6 \times 6 \) identity matrix, respectively.

B. Dynamics

The dynamic model with respect to six joints of the right arm is obtained as

\[
\ddot{z}_u = [I_{aa}^e] \ddot{\phi}_e + \frac{2}{v_{2*}} \dot{z}_{2*} \ddot{z}_{2*} \, [P_{aa}^e] \ddot{\phi}_e ,
\]

where \( [I_{aa}^e] \), \( \ddot{\phi}_e \), and \( [P_{aa}^e] \) denotes the inertia, acceleration, and centrifugal and coriolis term of the right arm, respectively.

Now, the dynamic model of the left arm including the virtual joints is described as

\[
\ddot{z}_u = [I_{aa}^e] \ddot{\phi}_e + \frac{2}{v_{2*}} \dot{z}_{2*} \ddot{z}_{2*} \, [P_{aa}^e] \ddot{\phi}_e ,
\]

where \( \ddot{z}_u \in R^6 \) denotes the dynamic load of the left arm itself and \( \ddot{z}_u \in R^3 \) denotes the dynamic load at the virtual joints to support the dynamics of the left arm. This force is exerted on the de-burring tool of the right arm. This is in turn a reaction force exerted on the de-burring tool of the right arm. Thus, it should be supported by the right arm.

Rewriting (8), we have

\[
\begin{bmatrix} \ddot{z}_u \end{bmatrix} = [I_{aa}^e] \ddot{\phi}_e + \frac{2}{v_{2*}} \dot{z}_{2*} \ddot{z}_{2*} \, [P_{aa}^e] \ddot{\phi}_e ,
\]

where \( \ddot{z}_u \in R^6 \) and \( \ddot{z}_u \in R^3 \) denotes the nonlinear velocity term of (8).

Now, we can extract the interaction force model at the virtual joint as follows

\[
\ddot{z}_u = [I_{aa}^e] \ddot{\phi}_e + \frac{2}{v_{2*}} \dot{z}_{2*} \ddot{z}_{2*} \, [P_{aa}^e] \ddot{\phi}_e ,
\]

where \( \ddot{z}_u \) denotes the dynamics influenced by the motion of the left arm and \( \ddot{z}_u \) denotes the dynamics influenced by the motion of the virtual joint. The dynamic force given in (10) denotes the interaction forces exerted on the work piece by the de-burring tool.
IV. APPLICATIONS OF INTERACTION FORCES

A. Interaction Force Control

The interaction force between the two manipulators is controlled so that the motion of the de-burring manipulator can be controlled according to the desired trajectory. The left 6-DOF serial arm grips the work-piece to be de-burred and the right 6-DOF serial arm grips a de-burring tool. The operational output of the right arm is denoted as three virtual joints as shown in Fig. 5. The given right arm controls three rotational motions of the de-burring tool. Since the mobility of this dual arm configuration is 9, three constraint relations can be employed. Two will be used to control the relative position between the tool and the work-piece and one will be used to control the de-burring force normal to the contact surface.

![Fig. 5. Virtual joint model of the closed chain constructed by the dual-arm](image)

For the given dual-arm model, we can express the kinematic equation of the left arm in terms of the Lagrangian coordinates as follows

\[ \dot{\theta} = [^1(G)]^T \dot{\phi} + [^1(G)]^T [^1[H]]^T \dot{\phi}, \]  \hspace{1cm} (11)

where \( ^1\theta = [x, y, z, \text{roll}_l, \text{pitch}_l, \text{yaw}_l]^T \), \( ^1\phi = [\theta_l, \theta_l, \ldots, \theta_l]^T \), \( ^1[G] \) and \( ^1[H] \) denotes Jacobian and Hessian.

Similarly, the velocity \( ^2\dot{\theta} \) of the right arm can be expressed as

\[ \dot{\theta} = [^2(G)]^T \dot{\phi} + [^2(G)]^T [^2[H]]^T \dot{\phi}, \]  \hspace{1cm} (12)

where \( ^2\dot{\theta} = [\text{roll}_r, \text{pitch}_r, \text{yaw}_r]^T \). Now, the whole output of the closed chain is augmented as

\[ ^A\dot{\theta} = [^A(G)]^T \dot{\phi} + [^A(G)]^T [^A[H]]^T \dot{\phi}, \]  \hspace{1cm} (13)

where

\[ ^A\dot{\theta} = [x, y, z, \text{roll}_l, \text{pitch}_l, \text{yaw}_l, \text{roll}_r, \text{pitch}_r, \text{yaw}_r]^T, \]  \hspace{1cm} (14)

\[ ^A[G] = [^1(G)]^T [^2(G)]^T \in \mathbb{R}^{9 \times 2}, \]  \hspace{1cm} (15)

and

\[ ^A[H] = [^1[H]]^T [^2[H]]^T \in \mathbb{R}^{9 \times 12 \times 2}. \]  \hspace{1cm} (16)

Similar to (8), the dynamic equation of this dual-arm model can be expressed as

\[ ^A\ddot{\theta} = ^A[H] \dot{^A\phi} + [^A\phi]^T [^A[P']]^T \dot{^A\phi}, \]  \hspace{1cm} (17)

where \( ^A\ddot{\theta} \in \mathbb{R}^9 \), \( ^A[H] \in \mathbb{R}^{9 \times 9} \), and \( ^A[P'] \in \mathbb{R}^{9 \times 9} \) denotes the force/torque vector, the inertia, and Coriolis and centrifugal term of the robot, respectively. And \( ^A\phi \) consists of joints of the left arm and the operational positions of the right arm such as \( [\theta_l, \theta_l, \theta_l, \theta_l, \theta_l, x_r, y_r, z_r]^T \).

Now, we can extract the interaction force model \( ^A\ddot{\theta} \in \mathbb{R}^3 \) at the virtual joints connecting the right and the left arm as follows

\[ ^A\ddot{\theta} = ^A[H] \dot{^A\phi} + [^A\phi]^T [^A[P']]^T \dot{^A\phi}, \]  \hspace{1cm} (18)

where

\[ ^A[H] = [^A[H]]_{9 \times 9} \in \mathbb{R}^{9 \times 9} \]  \hspace{1cm} (19)

and

\[ ^A[P'] = [^A[P']]_{9 \times 9} \in \mathbb{R}^{9 \times 9}. \]  \hspace{1cm} (20)

Substituting (11) into (18), the interaction force is described with respect to the Lagrangian coordinates as

\[ ^A\ddot{\theta} = [^A[H]]_{9 \times 9} \dot{^A\phi} + [^A\phi]^T [^A[P']]^T \dot{^A\phi}, \]  \hspace{1cm} (21)

where

\[ ^A[H] = \begin{bmatrix} ^1[H] \\ 0_{9 \times 9} \end{bmatrix} \in \mathbb{R}^{9 \times 12} \]  \hspace{1cm} (22)

and

\[ [G^2_D] = \begin{bmatrix} ^1[G] \\ 0_{9 \times 12} \end{bmatrix} \in \mathbb{R}^{9 \times 12} \]  \hspace{1cm} (23)

Substituting (11) into (18), the interaction force is described with respect to the Lagrangian coordinates as

\[ ^A\ddot{\theta} = ^A[H] \dot{^A\phi} + [^A\phi]^T [^A[P']]^T \dot{^A\phi}, \]  \hspace{1cm} (21)

where

\[ [G^2_D] = \begin{bmatrix} ^1[G] \\ 0_{9 \times 12} \end{bmatrix} \in \mathbb{R}^{9 \times 12} \]  \hspace{1cm} (22)

and

\[ [H^2_D] = \begin{bmatrix} ^1[H] \\ 0_{9 \times 12} \end{bmatrix} \in \mathbb{R}^{9 \times 12}. \]  \hspace{1cm} (23)
When the operational acceleration \(\ddot{u}\) according to the number of mobility is given, the general solution of (13) is expressed as

\[
\ddot{\phi} = \dot{[G]}(\ddot{u} - \phi^T \dot{[H]} \dot{\phi}) + (I_{12} - \dot{[G]} \dot{[G]} \dot{\phi}) \varepsilon . \tag{24}
\]

Now, we apply two positional constraints \((c \varepsilon = \{y_2 \ z_2\})\) expressed as follows.

\[
c \dot{\varepsilon} = [c \varepsilon] \ddot{\phi} + \phi^T ([c \varepsilon] \dot{\phi}) . \tag{25}
\]

Substituting (24) into (25) yields the \(\varepsilon\) vector and re-substituting it into (25) gives the final solution as

\[
\ddot{\phi} = \dot{[G]}(\ddot{u} - \phi^T \dot{[H]} \dot{\phi}) + (I_{12} - \dot{[G]} \dot{[G]} \dot{\phi}) \varepsilon , \tag{26}
\]

where

\[
[K_2] = \varepsilon - [c \varepsilon] \dot{[G]} \ddot{u}, [K_3] = [c \varepsilon] (I_{12} - \dot{[G]} \dot{[G]} \dot{\phi}) ,
\]

and

\[
[H'] = [c \varepsilon] \dot{[G]} \dot{\phi} .
\]

Next, we apply the last constraint in terms of the interaction force \((f_i)\). The interaction force \(f_i\) to be controlled is denoted as

\[
f_i = \varepsilon \hat{f}[I']_\phi [G_D^2] \phi + \phi^T \{([\varepsilon \hat{f}[I']_\phi ][G_D^2] \phi) + ([G_D^2]^2 \varepsilon \hat{f}[P']_\phi [G_D^2] \phi) \} \varepsilon \phi . \tag{29}
\]

by selecting the first component of the interaction model given in (21). Substituting (26) into (27) yields \(\varepsilon_i\) as follows.

\[
\varepsilon_i = [K_4]^{-1} f_i - [K_3] - [K_5], \tag{28}
\]

where

\[
[K_4] = \varepsilon \hat{f}[I']_\phi [G_D^2] (I_{12} - \dot{[G]} \dot{[G]} (I_{12} - [K_2] [K_3])),
\]

and

\[
[K_5] = \varepsilon \hat{f}[I']_\phi [G_D^2] (I_{12} - \dot{[G]} \dot{[G]} (I_{12} - [K_2] [K_3]).
\]

Finally, the total solution that satisfies the given operational motion and three constraints is given by

\[
\varepsilon = \dot{\varepsilon} - \phi^T \phi + (I_{12} - \dot{[G]} \dot{[G]} \dot{\phi}) \varepsilon . \tag{29}
\]

B. Simulation study

The simulation parameters are summarized in Table II. Sometimes, it is necessary to control the de-burring force in a controlled manner. Thus, we consider three cases in simulation as shown in Table III.

In the case 1, the objective is the control of the interaction force when the touch point between the tool and the work-piece is fixed at one point. Fig. 6(a) shows that the dual-arm is stationary and the given sinusoidal interaction force is well controlled as shown in Fig. 6(b).

In the case 2, the objective is to generate a simultaneous motion of the tool and the work-piece while controlling the interaction force. Namely, there is no relative motion between the work-piece and de-burring tool. A simultaneous circular motion is given to both arms in the reference frame of the dual-arm manipulator and an interaction force of 5N is controlled. Fig. 7(a) shows that the two arms are performing a given circular motion and Fig. 7(b) shows that using the proposed motion planning algorithm, the interaction force can be controlled properly, while without using the algorithm, the interaction force between the tool and work-piece is arbitrary created.

In the case 3, the objective is to control a relative motion between the de-burring tool and the work-piece, while controlling the interaction force. The left arm is holding the work-piece and the tool grasped by the right arm moves along the desired trajectory of the de-burring tool in the x-y plane of the work-piece frame, and a sinusoidal shaped interaction force is controlled. Fig. 8 shows that the desired objective could be achieved successfully.

The video clip attached to this paper demonstrates the motions of this simulation study.

<table>
<thead>
<tr>
<th>TABLE II. SIMULATION PARAMETERS</th>
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<tbody>
<tr>
<td><strong>Property</strong></td>
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<tr>
<td>L1=L4=L5=L8=0.25, L2=L3=L6=L7=0.5 [m]</td>
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<tr>
<td>m1=m8=10, m2=m7=4, m3=m4=m5=m6=3 [Kg]</td>
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<tr>
<th>TABLE III. THREE CASES OF SIMULATION</th>
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<tr>
<td><strong>Number</strong></td>
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<td>Case 2</td>
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<td>Case 3</td>
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V. CONCLUSION

In this paper, the interaction force model was proposed to accomplish the de-burring task by using the dual-arm manipulation. A methodology to control the interaction force without using a force/torque sensor is proposed. Finally, the feasibility and effectiveness of the suggested interaction force control method were shown through simulations for the given de-burring task. Experimental work remains as the future work.

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