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Human-Robot cooperation with double stages of impedance

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***Abstract*—Studies of human-robot cooperation have been performed by many researchers because human-robot cooperation can be a good alternative to use human intelligence and the power and accuracy of a manipulator at the same time. For that reason, the author has developed a human-robot cooperative robot system with the double stages of impedance considering the contact condition during the human-robot cooperation. The research results on the double stages of impedance will be introduced in this paper.**

***Index Terms*—Human-robot cooperation, Constraint condition, Double impedances**

I. INTRODUCTION

Direct teaching is one of the easiest ways for the human-robot manipulator and it is one of the best effect ways [7-9]. Studies of human-robot cooperation have been performed by many researchers because human-robot cooperation can be a good alternative to use human intelligence and the power and accuracy of a manipulator at the same time [1-11]. In this reason, the author has developed a human-robot cooperative robot system with which the human operator can directly teach the robot manipulator in a contact condition between the manipulator and the environment (Fig. 1). It uses double stages of impedance. The research results on the double stages of impedance will be introduced in this paper. Finally, the gain effects of the two stages of impedance were shown to verify the usefulness of the developed controller structure of the double stages of impedance.

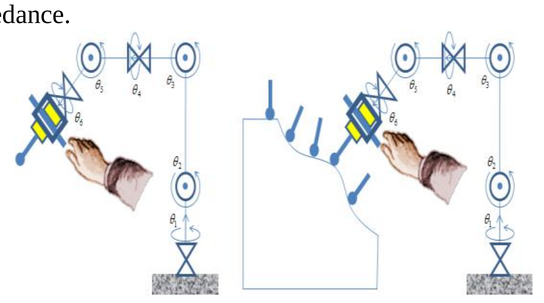

Fig. 1 Direct teaching in a non-constraint condition (left) and in a constraint condition (right)

Direct teaching is easy when the manipulator moves in the free space without contacts with the environment. But it is not easy when the manipulator has to contact and the contact has to be maintained during while the operator directly teaches the manipulator by pushing or pulling the end of the manipulator. Direct teaching process means that the operator pushes or pulls the end of the robot manipulator and the robot manipulator is controlled to comply with the operators' teaching force and the teaching moment.

II. DIRECT TEACHING IN A CONTACT CONDITION

First, the concept and the need of the direct teaching in a constraint condition have to be introduced. Fig. 2 shows how the developed human-robot cooperative robot manipulator can be operated. First, the work piece can be set-up in front of the manipulator. The shape and the dimension of the work piece are unknown. Thus the manipulator cannot handle the work piece because it does not have any information of the work piece.

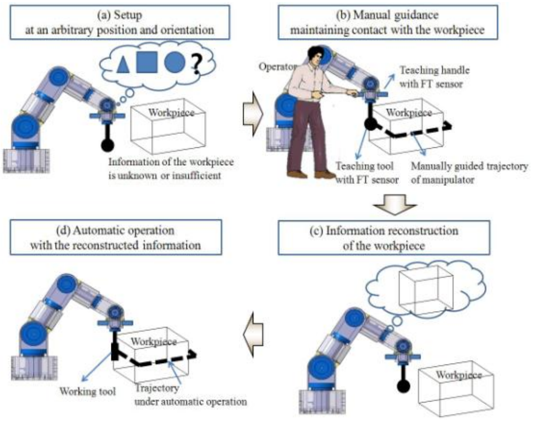

Fig. 2 Direct teaching concept of the developed human-robot cooperative robot system

Second, the manipulator manually guides (directly teaches) the manipulator to follow the surface of the work piece. In this process, the manipulator gets into contact with the work piece and the contact has to be maintained during while the direct teaching process. Thus the manipulator has to be controlled to comply with the operators teaching force and the moment and also, it has to be controlled to keep the contact force small between the manipulator and the work piece. Anyway, in this process, the controller can memorize the trajectory of the manipulator. The third, the memorized trajectory can be used to reconstruct the geometrical information (shape and curvature) of the work piece using the memorized trajectory. After that, the manipulator knows the geometrical information of the work piece in front of it. The fourth, the manipulator can handle the work piece because it knows the required information of the work piece. This is the basic concept of the direct teaching in a constraint condition. This concept is very useful for the teaching the reference trajectory for the

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deburring and grinding processes.

III. TEACHING THE POSITION AND THE ORIENTATION AT THE SAME TIME

In this research, only active impedance algorithm is used. A compliance mechanism is not used to implement compliance. If the mechanical compliance mechanism is equipped on the end of the manipulator, the safety for the contact condition is guaranteed (Fig. 3). But in this case, the actual position of the manipulator is unknown because the mechanical compliance mechanism does not have any sensors to detect the compliance motion and as a result, the manipulator cannot detect actual motion of the mechanical compliance mechanism. So, this kind of passive compliance mechanism cannot be used for the concept of the direct teaching in a constraint condition, as explained in section II.

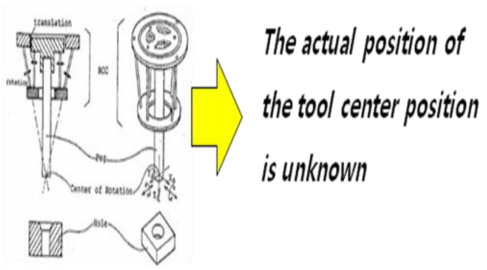

Fig. 3 A compliance mechanism

So, in this research, only active impedance algorithm is used. The teaching handle and the teaching tool are equipped on the end of the manipulator (Fig. 4). The teaching handle is used for the operator to push or pulls to teach the manipulator. The teaching tool is used for the manipulator to contact with the environment. We can consider the case that one 6-DOF force/torque sensor is equipped on the end of the manipulator. In this case, the teaching handle and the teaching tool are linked and one 6-DOF force/torque sensor is equipped on them (Fig. 4). Thus, the 6-DOF force/torque sensor can detect resultant signal of the teaching signal and the contact signal. This means that the controller has to be controlled to comply with the resultant signal of the teaching signal and the contact signal when the operator directly teaches it. In this reason, the teaching tool rotates when the teaching tool contacts with the environment because the manipulator is controlled to comply with the contact moments even though the teaching moment is 0. Thus the operator cannot manually guide the manipulator to get into contact and maintain the contact. That is, with one 6-DOF force/torque sensor, it is impossible to teach the position and the orientation of the manipulator at the same time when the contact occurs in the teaching process. To solve this problem, in this research, 2 individual 6-DOF force/torque sensors are used. In this case, one 6-DOF force/torque sensor is equipped on the teaching handle and the other 6-DOF force/torque sensor is equipped on the teaching tool (Fig. 5). Using two individual 6-DOF force/torque sensors, the teaching signal and the contact signal can be detected, separately. Thus it is possible to decouple the teaching signal by the operator and the contact signal by the contact motion. As a result, the manipulator can be controlled to comply with the operator's teaching force and moment even when the contact occurs. This means that the position and the orientation can be directly taught at the same time even when the contact motion occurs during while the direct teaching process.

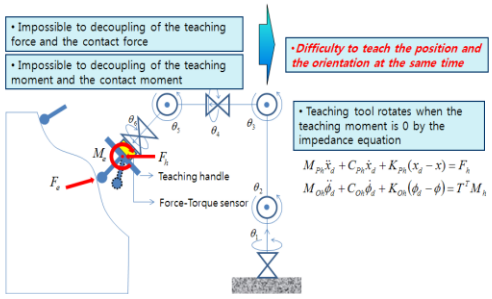

Fig. 4 One 6-DOF force/torque sensor

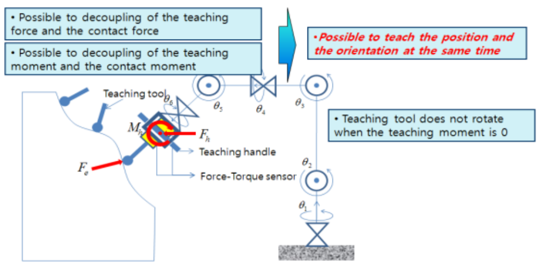

Fig. 5 Two individual 6-DOF force/torque sensors

IV. CONTROLLER STRUCTURE

As mentioned above, double stages of impedance is used in this research. The first stage of impedance is used for the teaching force and it is expressed by Eq. (1). It is shown in the figure 6, also.

$$\begin{aligned} M_{Ph}\ddot{x}_d + C_{Ph}\dot{x}_d + K_{Ph}(x_d - x) &= F_h \\ M_{Oh}\ddot{\phi}_d + C_{Oh}\dot{\phi}_d + K_{Oh}(\phi_d - \phi) &= T^T M_h \end{aligned} \qquad (1)$$

Here, M_{Ph}, M_{Oh} are 3x3 diagonal matrixes and represent the virtual inertia, C_{Ph}, C_{Oh} are 3x3 diagonal matrixes and represent the virtual damper and K_{Ph}, K_{Oh} are 3x3 diagonal matrixes and represent the virtual stiffness. The operator feels as though he pushes or pulls the virtual inertia with a virtual damper and a virtual compliance when he pushes or pulls the teaching handle. x, ϕ are 3x1 vectors and stand for the actual position and orientation, respectively. The orientation is expressed by the Euler angle and T is a 3x3 transformation matrix between the angular velocity and the time derivative of the Euler angles. The subscript d means that the variable is related with the desired trajectory. The subscripts P and O mean the position and orientation, respectively. The subscript h indicates that the parameter is related to human force and moment. The second stage of impedance is used for the contact condition between the manipulator and the environment and it is expressed by (2). It is shown in the figure 6, also.

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$$M_e(\ddot{x}_c - \ddot{x}_d) + C_e(\dot{x}_c - \dot{x}_d) + K_e(x_c - x_d) = F_e \,. \quad (2)$$

x_c is a 3x1 vector that represents the compliant frame. x_d is a 3x1 vector and means the desired position of the TCP (Tool Center Position) defined according to Eq. (2). Once the compliant frame for the TCP is determined by Eq. (2), it is used as the reference trajectory for the inner motion control loop to control the motion of the manipulator. As a result, the manipulator can accommodate the contact force between the teaching tool and the work piece. As a result, the direct teaching algorithm is divided into two stages of impedances. The first stage of impedance is for the direct teaching and the second stage of impedance is for the contact motion. When the operator directly teaches the manipulator by pushing or pulling the teaching handle, the first impedance makes the desired trajectory for the manipulator to follow. If the manipulator controlled to follow the trajectory, the operator feels the manipulator moves as he/she intends. When the contact occurs, the second impedance works, and the desired trajectory is modified to make the compliance motion considering contact situation. The final reference trajectory is a kind of a compliant frame [12-13]. Fig. 6 shows the overall structure of the controller for the developed robot manipulator system. The controller can be divided into two modules. One is called "direct teaching algorithm" and the other is called "robot & controller". The "direct teaching algorithm" makes the reference trajectory and the "robot & controller" follows it.

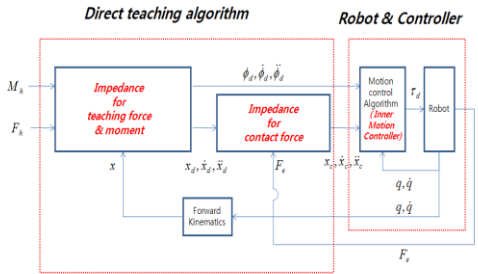

Fig. 6 The controller structure for the direct teaching algorithm in a contact condition

V. GAIN EFFECTS OF THE IMPEDANCE

In this section, the effects of two stages of impedance of Eq. (1) and Eq. (2) are analyzed. To analyze the gain effects, it is imagined that the operator pushes the teaching handle in the x-direction with step function of 10N during 2 sec, as shown in Fig 7. It is impossible for the human operator to make this step force. Thus we load the teaching signal with the step function on the teaching handle by the software program Fig. 8 shows the teaching response of the manipulator according to the various M gains. The upper figure of Fig. 8 shows the response in the case of K=200, C=200, and the lower figure of Fig. 8 shows the response in the case of K =200, C=400. In the both case, if the M gets bigger, then the response of the manipulator gets slower. And the manipulator moves the same distance even though the gain M get different value if the same teaching force of Fig. 7 is loaded. Next, the effects of the various impedance gains of Eq. (2) are analyzed. It is imagined that the manipulator gets into contact with the environment and the contact force is induced in the -x-direction with step function of 20N during 2 sec, as shown in Fig. 9. It is impossible for the contact force to be a step function of Fig. 9, thus, we load the contact force signal with the step function by the program. Fig. 10 shows the contact response of the manipulator according to the various M gains. The upper figure of Fig. 10 shows the response in the case of K=1000, C=200, and the lower figure of Fig. 10 shows the response in the case of K =1000, C=500. In the both case, if the M gets bigger, then the response of the manipulator gets slower and the overshoot gets bigger. And the manipulator moves the same distance even though the gain M get different value if the same contact force of Fig. 9 is loaded. As shown the figure 7 ~ 10, the two stages of impedance are decoupled for the 2 individual force-moment sensors which are equipped on the manipulator to detect the teaching force-moment by the operator and to detect the contact force-moment by the environment. Thus the operator can tune the impedance gains of Eq. (1) and Eq. (2) separately.

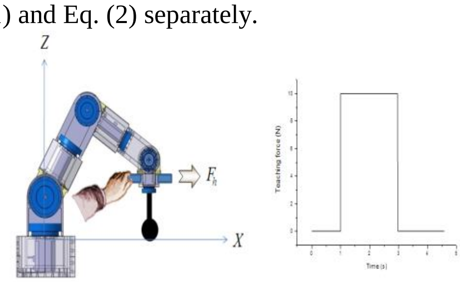

Fig. 7 teaching force (left) and its time plot (right)

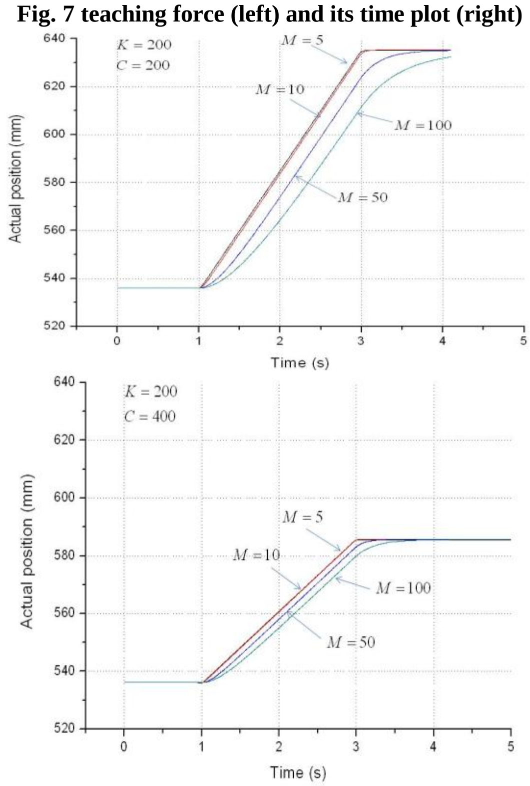

Fig. 8 The teaching response of the manipulator with various M

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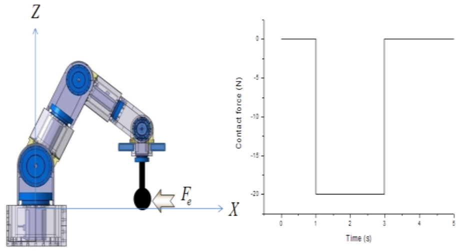

Fig. 9 Contact force (left) and its time plot (right)

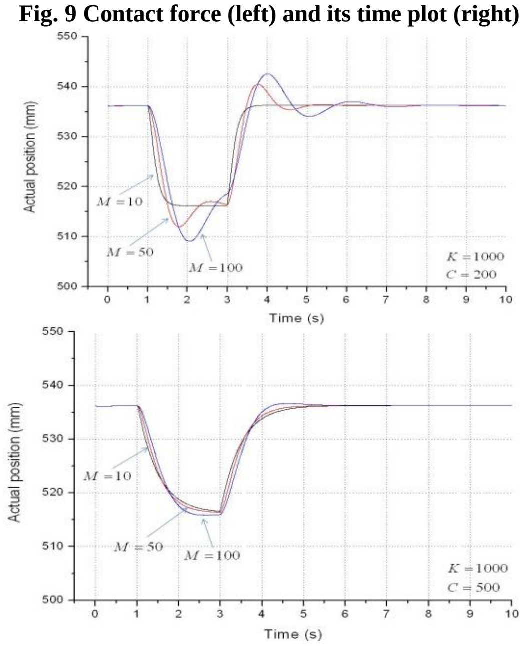

Fig. 10 The contact response of the manipulator with various M

VI. CONCLUSION

The author has developed human-robot cooperative robot system using "double stages of impedance". It is very useful when the human operator has to directly teach the robot manipulator in a contact condition between the manipulator and the environment. In this paper, the research results are introduced. The first, the mechanical compliance mechanism cannot be applied was explained. A kind of passive mechanical compliance mechanism makes the system stable when the manipulator and the work piece gets in contact, but the compliance motion cannot be detected, so it cannot be applied in this research. And why two individual 6-DOF force/torque sensors have to be used instead of the one 6-DOF force/torque sensor was explained. With two individual 6-DOF force/torque sensors, the teaching signal and the contact signal can be divided. As a result, the manipulator can be controlled to comply with the teaching signal even when the manipulator is in a contact condition with an environment. The second, the controller structure was introduced. The controller structure is composed of "Direct teaching algorithm" and "Robot & controller". "Direct teaching algorithm" is composed of the first impedance stage and the second impedance stage. The first impedance stage is used for the manipulator is controlled to comply with the teaching force/moment by the operator. And the second impedance stage is used for the manipulator to be controlled to get a compliance motion for the contact motion between the manipulator and the environment. Finally, the gain effects of the two stages of impedance were shown to verify the usefulness of the developed controller structure of the double stages of impedance. The two stages of impedance are decoupled for the 2 individual force-moment sensors which are used to detect the teaching force-moment by the operator and to detect the contact force-moment by the environment. Thus the operator can easily tune the impedance gains of Eq. (1) and Eq. (2) separately.

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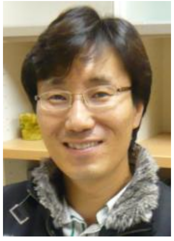

Chanhun Park received PhD degree in Mechanical Engineering from KAIST, KOREA. He has been working for Korea Institute of Machinery and Materials (KIMM), Korea, since 1996, where he is currently a principal researcher. His research fields include design and control of high speed parallel robot system. He is also interested in human-robot cooperation and design and control of dual arm robot manipulator for industrial applications.

Doohyeong Kim. received Ph.D degree in Mechanical Engineering from KAIST, KOREA. He has been working for Korea Institute of Machinery and Materials (KIMM), Korea, since 1982, where he is currently a principal researcher. His research fields includes design and control of heavy payload manipulators and a wire-driven mechanism for a light weight dual arm robot manipulator for industrial applications