Admittance Control of a Multi-Finger Arm Robot Using Manipulability of Fingers

Jian HUANG, Faculty of Engineering, Kinki University, Higashi-Hiroshima, Japan 739-2116, Takayuki HORI, Nozomi TOYODA and Tetsuro YABUTA Graduate School of Engineering, Yokohama National University, Yokohama, Japan 240-8501

Abstract- Previous studies have proposed methods for admittance and impedance control for a finger-arm robot using the manipulability of the finger. Based on the previous theories, the authors have proposed an admittance control for a multi-finger arm robot using the manipulability of the fingers in this study. Two 3-DOF fingers are attached to the end-effector of a 6-DOF arm to configure a multi-finger arm robot. The averaging method and the mini-max method for two fingers were introduced to establish a manipulability criterion for generating a cooperative movement of the arm. Admittance control combined with the top search method (TSM) and the local optimization method (LOM) for the multi-finger arm robot were also studied. The stiffness control were experimentally evaluated to demonstrate the effectiveness of the proposed method.

I. INTRODUCTION

Controlling a robot that has a high degree of redundancy is a fundamental problem in the field of robotics. Many previous studies have reported methods for determining the redundant DOFs of a robot. The issues that have been studied thus far include the avoidance control of a kinematics singularity [1][2] and obstacle collisions avoidance [3]-[5] by using redundant DOFs.

To realize the dexterity comparable to that of the human hand-arm, which will greatly improve the performance of a robot, a lightweight finger can be attached at the end of a serial-linkage manipulator [6]-[10].

When performing delicate tasks, humans usually adopt a motion policy that enables them to easily move their hand. To generate an efficient motion for a finger-arm robot that emulates the movement of the human hand-arm in an unconstrained space, the authors proposed a heuristic method [11][12] and a steepest ascent method [13][14] that make use of the manipulability of the finger. Integration control of the impedance control and manipulability regulation of the finger was also attempted for a finger-arm robot to complete a contact task [15][16].

Based on a previous concept of using the finger’s manipulability as a criterion, in this study, we have proposed an admittance control for a multi-finger arm robot to complete a constrained task. However, unlike the case of a one fingered arm, in this case, algorithms that can manipulate a multi-fingered arm are required. We first introduced a mini-max method and the averaging method for two fingers to establish a manipulability criterion for cooperatively moving the arm. The admittance control algorithm was combined with the top search method (TSM) and the local optimization method (LOM) to regulate the manipulability of the fingers.

II. OVERVIEW OF THE FINGER-ROBOT

A. Configuration of the multi-finger arm robot
A 7-DOF manipulator (PA-10, Mitsubishi Heavy Industry Co.) was used in this study. Since the S3 axis of PA-10 was not used, the manipulator had 6 DOFs. Two 3-DOF finger robots (Yasukawa Co.) were attached to the end-effector of the arm as shown in Fig.1, to obtain a multi-finger arm robot with 12 DOFs. Two fingers were placed in parallel to emulate the forefinger and middle finger of a human being. To detect the contact force in a constrained task, an F/T sensor (BL AutoTech Co.) was fixed at each fingertip.

The base coordinate of the arm and the end-effector coordinate of the arm are denoted by \( \Sigma_b \) and \( \Sigma_t \), respectively, as shown in Fig.1. In this study, a contact task using the multi-finger arm is assumed. It is known that the fingers easily drop to their singularities during movement in a large space because of their small link sizes. Therefore, to avoid the singularity of the fingers, a cooperative movement of the arm is required to augment the working space of the fingers so as to simultaneously regulate the manipulability of the finger.

B. Manipulability of the Finger

The position in \( \Sigma_b \) and \( \Sigma_t \) of the \( i_{th} \) fingertip is \( p_i \in \mathbb{R}^{3\times1} \) and \( t_i \in \mathbb{R}^{3\times1} \), respectively, and the joint angle of the \( i_{th} \) finger is \( \theta_i \in \mathbb{R}^{3\times1} \). Thus, we have

\[
\dot{p}_i = J_i \cdot \dot{\theta}_i,
\]

(1)
REVIEW OF THE PREVIOUS METHODS

Before introducing the proposed control method, we briefly describe the algorithms proposed in previous studies.

A. Top Search Method (TSM)
To prevent the manipulability of the finger from continuously decreasing, a cooperative movement of the arm was generated by the top search method (TSM) [13][14]. The control sampling time is denoted as $T$ ($=5$ ms). When the manipulability $w$ is smaller than a given threshold $w_{th}$, the quantity of the expected movement of the arm end-effector $\Delta p_d(k)$ is determined as

$$\Delta p_d(k) = A(w)n(k).$$  \hspace{1cm} (3)

where $K_w$ is the gain coefficient. $n(k) \in \mathbb{R}^{3+1}$ is a unit direction vector of the desired trajectory and it is given by $n(k) = (p(k) - p_{\text{ref}}(k))/|p(k) - p_{\text{ref}}(k)|$, where $p(k)$ and $p_{\text{ref}}$ are the fingertip positions in $\Sigma_w$ and position in $\Sigma_0$ with the maximum manipulability, respectively.

B. Local Optimization Method (LOM)
The disadvantage of the TSM is that it cannot directly increase $w$. Therefore, to effectively regulate $w$, the local optimization method (LOM) was proposed [15][16]. The most important feature of the LOM is that $w$ can be increased rapidly once it is smaller than a given reference $w_{th}$.

Whenever $w$ decreases to a value below $w_{th}$, LOM is applied to increase $w$. The desired joint angle is given by

$$\theta_j(k) = \theta_j(k-1) + \lambda \frac{\partial w}{\partial \theta_j},$$  \hspace{1cm} (6)

where $\lambda$ is a predetermined gain coefficient and $\theta_j = [\theta_{j1},\theta_{j2},\theta_{j3}]^T$, the desired joint angle. According to (2), we have

$$\frac{\partial w}{\partial \theta_{j1}} = l_1 l_2 \sin \theta_1 \left( l_2 \sin \theta_2 + l_1 \sin \theta_1 \right) \left( \cos \theta_2 \cos \theta_3 - \cos \theta_1 \cos \theta_2 \right).$$  \hspace{1cm} (7)

For cooperatively moving the arm, the desired position $p_d(k)$ of the arm end-effector in $\Sigma_w$ is given by

$$p_d(k) = p_d(k) - R \cdot p(k),$$  \hspace{1cm} (8)

where $p_d(k) \in \mathbb{R}^{3+1}$ is the desired position of fingertip in $\Sigma_w$, $R \in \mathbb{R}^{3+1}$ is the rotation matrix of the arm end-effector in $\Sigma_w$, and $p(k) \in \mathbb{R}^{3+1}$ is the fingertip position in $\Sigma_0$ obtained from (9)

$$p(k) = A_j(\theta_j),$$  \hspace{1cm} (9)

where $A_j$ represents the kinematics of the finger robot.

IV. ADMITTANCE CONTROL

The impedance to be achieved at the fingertip in $\Sigma_w$ can be expressed as

$$M_\Delta \dot{p}_d + D_\Delta \dot{p}_d + K_\Delta p_d = F_k,$$  \hspace{1cm} (10)

where $\Delta p_d \in \mathbb{R}^{3+1}$ is the position difference in $\Sigma_w$ of the $i_{th}$ fingertip position; $\Delta F_k \in \mathbb{R}^{3+1}$, the force error in $\Sigma_w$ between the desired force and the force detected by the F/T sensor of the $i_{th}$ finger; and $M, D, K$, the virtual mass, virtual damping, and virtual stiffness, respectively. If the impedance performance given by (10) is configured using position-servo for the robot, it is called admittance control.

In this study, a combination of admittance control with the TSM and LOM is proposed. Block diagrams of the same are shown in Fig.3, where the $A_j$ and $A_n$ are kinematics of the finger and the arm, respectively, $F(k)$, the data in $\Sigma_w$ obtained from the F/T sensor of the $i_{th}$ finger, and $G_n, G_m$, the PID controllers of the finger and arm, respectively. This integration algorithm should enable impedance dynamics and manipulability modulation of the finger to be achieved simultaneously.

A. Mini-Max Method

Unlike the case of previous studies, two fingers are used in this study. The arrangement of the two fingers to emulate the forefinger and the middle finger of a human being allows a nearly simultaneous increase or decrease in the manipulability of the two fingers. Therefore, we consider the lesser manipulability among the two as the criterion for generating a cooperative movement of the arm.

The mini-max method is introduced to select the smaller manipulability from the two $w_i$ ($i = 1,2$); it can be expressed by

$$w_{\text{min}} = \min_{i} w_i.$$
\[ w_i = \min_1 \{w_j\} \Rightarrow \theta_{i}^{*} = \theta_{i}^{*}(k - 1) + \frac{\Delta \theta_{i}}{\Delta k} \] (15)

Equation (7) is then applied to (15) to obtain \( \theta_{i}^{*} = \theta_{i}^{*}(k) \). For cooperatively moving the arm, the desired position \( p_{\theta i}(k) \) of the arm end-effector in \( \Sigma_k \) is given by

\[ p_{\theta i}(k) = p_{\theta i}(k) - R_{\theta i} \Delta p_{\theta i}(k) = \lambda_{\theta i} p_{\theta i}(k) \] (16)

where \( R_{\theta i} \in \mathbb{R}^{3 \times 3} \) is the rotation matrix of the arm end-effector in \( \Sigma_k \) and \( p_{\theta i}(k) \in \mathbb{R}^{3 \times 1} \) is the fingertip position in \( \Sigma_k \). The desired joint angle \( \theta_{i}^{*} = \theta_{i}^{*}(k) \).

(2) For LOM

When the manipulability \( w_i \) is lesser than a given threshold \( w_{th} \), the desired joint angle \( \theta_{i}^{*} = \theta_{i}^{*}(k) \) of the finger with lesser manipulability is given by

\[ \theta_{i}^{*} = \frac{\Delta \theta_{i}}{\Delta k} \] (15)

Equation (7) is then applied to (15) to obtain \( \theta_{i}^{*} = \theta_{i}^{*}(k) \). For cooperatively moving the arm, the desired position \( p_{\theta i}(k) \) of the arm end-effector in \( \Sigma_k \) is given by

\[ p_{\theta i}(k) = p_{\theta i}(k) - R_{\theta i} \Delta p_{\theta i}(k) = \lambda_{\theta i} p_{\theta i}(k) \] (16)

where \( R_{\theta i} \in \mathbb{R}^{3 \times 3} \) is the rotation matrix of the arm end-effector in \( \Sigma_k \) and \( p_{\theta i}(k) \in \mathbb{R}^{3 \times 1} \) is the fingertip position in \( \Sigma_k \). The desired joint angle \( \theta_{i}^{*} = \theta_{i}^{*}(k) \).

B. Averaging Method

As described above, the mini-max method determines the finger having the lesser manipulability. However, switching control between the two fingers lead to an unexpected, rapid change in velocity of the arm. To avoid this problem, an averaging method is also introduced in this study; this method obtains the average of the manipulability of the two fingers. The averaged manipulability \( w_{ave} \) is given by

\[ w_{ave} = \frac{1}{n} \sum_{i=1}^{n} w_i \] (18)

(1) For the TSM

When the manipulability \( w_{ave} \) is lesser than a given threshold \( w_{th} \), the quantity of the expected movement of the arm end-effector \( \Delta p_{\theta i}(k) \) is given by

\[ \Delta p_{\theta i}(k) = \frac{1}{n} \sum_{i=1}^{n} \Delta p_{\theta i}(k) \] (n=2).

(19)

where \( \Delta p_{\theta i}(k) \) is computed using (3) and (4) for each finger. The movement direction \( n(k) \in \mathbb{R}^{3 \times 1} \) of the arm is given by

\[ n(k) = \frac{1}{n} \sum_{i=1}^{n} n_i(k) \] (n=2).

(20)

where \( n_i(k) \) is computed using (5) for each finger.

(2) For the LOM

When the manipulability \( w_{ave} \) is lesser than a given threshold \( w_{th} \), (6), (7), and (8) are applied to each finger. The desired position \( p_{\theta i}(k) \) of the arm end-effector in \( \Sigma_k \) is given by

\[ p_{\theta i}(k) = p_{\theta i}(k) - R_{\theta i} \Delta p_{\theta i}(k) = \lambda_{\theta i} p_{\theta i}(k) \] (n=2).

(21)

where the fingertip position \( t_i(k) \in \mathbb{R}^{3 \times 1} \) of the finger with lesser manipulability \( w_i \) and it is given by

\[ t_i(k) = \theta_{i}^{*}(k) \] (17)

Fig. 3. Schematic diagram of the multi-finger arm robot.
V. EXPERIMENTS

Experiments were conducted to evaluate the stiffness control and damping control using the proposed control diagram shown in Fig.3. In these experiments, the operator pushed and pulled the fingertips to apply an external force along the \( y \) axis of \( \Sigma_b \) at the fingers, as shown in Fig.4.

A. The Mini-Max Method

The parameters in (10) were empirically determined:

\[
M = 1.0 \text{ kg}, \quad D = 30.0 \text{ Ns/m}, \quad K = 150.0 \text{ N/m}.
\]

Threshold manipulability \( w_{th} = 2.0 \times 10^{-4} \).

The stiffness results obtained using TSM and LOM are shown in Fig.5; the position results of the arm end-effector using TSM and LOM are shown in Fig.6;

The stiffness effects using both the TSM and LOM are modestly completed as shown in Fig.5; therefore, the effectiveness of the mini-max method is confirmed. However, small tracking errors are detected in the position results of the arm end-effector, as shown in Fig.6. This is attributed to the rapid change in velocity of the arm movement that is induced by the control of the arm being switched between the two fingers by the mini-max method.

The manipulability results using TSM and LOM are shown in Fig.7. Although the results indicate that the LOM provided better stiffness control than the TSM, the manipulability results of the two fingers were effectively modulated around the \( w_{th} \) by both the TSM and the LOM. However, unlike the case of one finger in the previous studies [13][14], \( w \) of two fingers using LOM cannot be completely regulated above \( w_{th} \).

B. The Averaging Method

Experiments were also conducted to evaluate the stiffness control and damping control using the averaging method. Because the arm moved roughly when using the LOM, admittance control using only the TSM was used in the experiments.

The parameters in (10) were empirically determined:

\[
M = 1.0 \text{ kg}, \quad D = 30.0 \text{ Ns/m}, \quad K = 150.0 \text{ N/m}.
\]

Threshold manipulability \( w_{th} = 2.0 \times 10^{-4} \).

The stiffness results and position results are shown in Fig.8. As compared to the results obtained by the mini-max method, shown in Fig.5, the stiffness results obtained by the averaging method are more accurately completed. This is because the cooperative movement of the arm using the averaging method is always determined by the average manipulability of the two fingers instead of switching control between the two fingers, as...
in the case of the mini-max method. Therefore, the averaging method provides stable movement for a multi-finger arm.

The manipulability results are shown in Fig.9. As compared to the results shown in Fig.7, it was found that manipulability occasionally decreased considerably. This fact indicates that it is difficult to simultaneously regulate the manipulability around the given threshold for the two fingers using the averaging method.

VI. DISCUSSIONS

The obtained experimental results indicate that for a multi-finger arm robot, the proposed admittance control with TSM exhibits a better admittance effect than that using the admittance control with LOM.

To deal with the problem of how to generate a cooperative motion for a multi-finger arm, the mini-max method and the averaging method were proposed in this study. The mini-max method considers the finger with lesser manipulability as a reference to generate a cooperative movement of the arm. This lead to the switching of control between the two fingers, and this in turn resulted in a rapid change in velocity of the arm. In contrast to the mini-max method, the averaging method considers the average manipulability of the two fingers as a reference to cooperatively move the arm. Therefore, the motion of the arm is completed smoothly, whereas the manipulability of the two fingers cannot be simultaneously regulated above the threshold manipulability.

VII. CONCLUSIONS

In this study, admittance control combined with the TSM and the LOM have been proposed for a multi-finger arm robot. The mini-max method and the averaging method were introduced to deal with the manipulability of two fingers. The features of the proposed control algorithms have been investigated by experimentally evaluating the stiffness control and the damping control. The experimental results indicate that when the averaging method combined with the TSM was applied, the arm moved smoothly and the admittance effect could be greatly improved by selecting an appropriate threshold of the manipulability.

ACKNOWLEDGMENT

This work was supported by the Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Research (B) (20300075) and (C) (No. 21500208).
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