Emulating the Motion of a Human Upper Limb: Controlling a Finger-arm Robot by using the Manipulability of its Finger

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Abstract – In this paper, a 3-DOF robot finger is fixed onto the end-effector of a 6-DOF robot arm to realize a finger-arm robot. As in the case of the upper limb of a human being, the finger-arm robot possesses a high degree of freedom. This paper describes a new method to control the finger-arm robot so as to simply generate a natural motion emulating the movement of a human upper limb. To achieve this, a control method based on the manipulability of the finger is proposed. By using the proposed method, the finger primarily moves to complete a delicate local task, while the arm only moves to assist the finger when the manipulability of the finger falls below a reference value. The proposed method was applied to the task of drawing two 3D figures. The obtained results clarify the relation between manipulability and kinetic energy and also demonstrate the effectiveness of the proposed method.

Keywords – motion control; biomimetics; cooperative control; manipulability

I.  INTRODUCTION

The human upper limb possesses a high degree of freedom and its redundant structure allows for great flexibility in various dexterous manipulations. However, the emulation of the hand-arm movement by a multi-fingered arm robot with a high redundancy presents a problem of determining the degrees of freedoms of its joints.

Controlling a robot with a high degree of redundancy is a fundamental problem in the field of robotics. A large number of studies have been published on the methodology by which the redundant freedoms of a robot can be determined. One of the major concerns of these studies has been the focusing on the generation of a geometric path with kinematics singularity avoidance by using redundant freedoms [1]–[4]. The other major concern has been the charting out of a collision-free path for obstacle avoidance using redundant freedoms [5]–[16]. In order to realize desired solutions for the above mentioned problems, methods involving null space [17] and the criterion function [18]–[20] have typically been applied.

The simplest structure of a multi-fingered arm robot is constructed by fixing a robot finger onto the end-effector of a robot arm. A robot with such a structure is also called a macro-micro manipulator [21]–[24]. Generally, a finger-arm robot has a high degree of redundancy, thereby requiring a complicated control algorithm. However, unlike the typical redundant manipulators, the finger robot is usually not heavy and has a small link size as compared to those with manipulators. Therefore, it is not appropriate to directly apply the methods developed for the control of a redundant manipulator to the finger-arm robot. The human hand-arm system exhibits the same characteristics. The inertia of a human hand is obviously smaller than that of a human arm. This is why human beings always move their hand to complete a delicate task rather than moving their arm. The hand-arm coordination is well organized by the central nervous system so as to generate a natural motion. The objective of this study is to develop a control method emulating a natural movement similar to that of a human upper limb.

When humans are asked to draw a curve with one finger as shown in Fig.1, they will primarily move their finger to draw the curve, while only moving their arm to augment their finger’s movement when it cannot reach the position at which the curve needs to be drawn. In order to realize such movement by a finger-arm robot, a motion control algorithm of a finger-arm robot is proposed in this study. This algorithm is based on the manipulability of the finger. The greatest feature of the proposed method is that a natural motion of the finger-arm robot is generated rather than merely calculating a geometric path for the kinematics resolution of the robot’s redundant freedom. Using the proposed method, a complicated task such as a finger’s tip motion can be simply divided into separate motions for the arm and for the finger. Hence, like the human upper limb, the finger will primarily move and the arm will cooperate with the finger’s movement so as to maintain the finger’s manipulability at a desired level.

II.  OVERVIEW OF A FINGER-ARM ROBOT

In this study, a finger robot with three compact motors (Yasukawa Co.) and a manipulator with seven degrees of freedom (PA–10, Mitsubishi Heavy Industry Co.) are used as shown in Fig.2. However, the S3 joint of the manipulator is not used in its motion control. To emulate the human hand-arm system, the finger robot is fixed onto the end-effector of the manipulator.
The total number of joints of a robot is \( n \), and the number of degrees of freedom required for a task is assumed to be \( m \). If \( n \) is larger than \( m \), the robot is called a redundant robot. The redundant degree of freedom \( r \) is computed as

\[
 r = n - m .
\]

The finger-arm robot shown in Fig.2 has a total of 9–DOF of freedom. If a task with 6–DOF is required for the finger-arm robot in \( \Sigma_b \), then we have \( n=9 \), \( m=6 \), and \( r=3 \).

As shown in Fig.1, this paper deals with the task of drawing a desired curve with the finger’s tip. Since the size of the finger robot is comparatively smaller as compared to that of the manipulator, the finger robot easily reaches its limit. The objective of this study is to achieve the generation of a natural motion similar to that of the human upper limb for the arm to coordinate with the finger’s movement.

### III. ALGORITHM OF MOTION CONTROL

#### A. Kinematics Analysis

The end-effector and arm base coordinates are set as \( \Sigma_e \) and \( \Sigma_b \) respectively, as shown in Fig.2. The joint velocity vector \( \dot{\theta} \in \mathbb{R}^{6\times1} \) of the finger-arm robot is defined as follows:

\[
\dot{\theta} = \begin{bmatrix} \dot{\theta}_a \\ \dot{\theta}_f \end{bmatrix},
\]

where \( \dot{\theta}_a \in \mathbb{R}^{6\times1} \) and \( \dot{\theta}_f \in \mathbb{R}^{3\times1} \) are the joint velocities of the arm and the finger, respectively. The arm’s end-effector position and orientation \( p_a \in \mathbb{R}^{6\times1} \) in \( \Sigma_e \) as well as the finger’s tip position \( p_f \in \mathbb{R}^{6\times1} \) in \( \Sigma_b \) are defined as follows:

\[
p_a = \begin{bmatrix} x_a \\ y_a \\ z_a \\ \alpha_a \\ \beta_a \\ \gamma_a \end{bmatrix}^T,
\]

\[
p_f = \begin{bmatrix} x_f \\ y_f \\ z_f \\ \alpha_f \\ \beta_f \\ \gamma_f \end{bmatrix}^T.
\]

The relationship between its joint velocity \( \dot{\theta} \) and the finger’s tip velocity \( \dot{p}_f \) in \( \Sigma_b \) can be theoretically expressed as follows:

\[
\dot{p}_f = J \cdot \dot{\theta},
\]

where \( J \in \mathbb{R}^{6\times9} \) is the Jacobian of the finger-arm robot. For the robot arm, we have

\[
\dot{p}_a = J_a \cdot \dot{\theta}_a,
\]

where \( J_a \in \mathbb{R}^{6\times6} \) is the Jacobian of the arm. For the finger, it is known that

\[
\dot{p}_f = J_f \cdot \dot{\theta}_f,
\]

where \( J_f \in \mathbb{R}^{3\times3} \) is the Jacobian of the finger, and \( \dot{p}_f \in \mathbb{R}^{3\times1} \) is the finger’s tip velocity in coordinates \( \Sigma_b \).

If a non-redundant robot is used, the Jacobian \( J \) is invertible. Subsequently, the joint velocity \( \dot{\theta} \) can be obtained as follows:

\[
\dot{\theta} = J^{-1} \cdot \dot{p}.
\]

However, because a redundant robot is used in this study, the Jacobian \( J \) in (5) is not a square matrix. Therefore, its inverse \( J^{-1} \) cannot be computed.

#### B. Motion Generation Algorithm

When a human being is asked to complete a task with his finger and arm, he will manoeuvre his limb so that his hand covers as large a scope as possible and easily complete the task. This property of the moving potential is referred to as manipulability in robotics. Generally, a human will primarily move his finger, while he moves his arm to coordinate with his finger so as to maintain his finger’s movement potential at a desired level.

In robotics, manipulability is used as a criterion to describe the movement potential of a robot. Here, the manipulability \( W_f \) of the robot finger is introduced as follows [25][26] :

\[
W_f = \sqrt{\text{det}(J_f(\theta_f) \cdot J_f^T(\theta_f))} = |\text{det}(J_f)|.
\]

At time \( t = kT \), the desired trajectory is given as \( p_d(k) \in \mathbb{R}^{3\times1} \), the position of the arm’s end-effector is \( p_e(k) \) and that of the finger’s tip in \( \Sigma_e \) is \( p_f(k) \) as shown in Fig.3. We have

\[
p_d(k) = s_i p_i(k) + R_i \cdot \dot{p}_f(k),
\]

where \( R_i \in \mathbb{R}^{3\times3} \) is the rotation matrix of the arm in \( \Sigma_b \), and \( s_i \in \mathbb{R}^{3\times6} \) is a constant matrix given as follows:

\[
s_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}.
\]

If we assume that the orientation of the arm remains unchanged, the rotation matrix \( R \) is a constant. Thus, from (10), we get

\[
\Delta p_d(k) = s_i \Delta p_i(k) + R_i \cdot \Delta p_f(k),
\]
Using (7), (11) can be expressed as
\[ \Delta p_f(k) = A(W_f) s^T \Delta \dot{p}_f(k). \] (19)

In order to move the arm without instant change in velocity, parameter \( A(W_f) \) in (19) is determined as follows:
\[ A(W_f) = \begin{cases} 0 & W_f(k) \geq W_{fr} \\ K_a(W_{fr} - W_f(k)) & W_f(k) < W_{fr} \end{cases}, \] (21)

where \( K_a \) is the selected coefficient.

Compared to (15), the proposed method shown in (21) yields a smooth motion profile such that the arm moves without any instant change in velocity. Therefore, the finger can also move smoothly. Furthermore, when the generated movement of the arm given in (18) and (19) is larger than the necessary change \( \Delta p_d(k) \) of the desired trajectory given by (15), i.e.
\[ |s_1 \Delta p_d(k)| > |\Delta p_d(k)|, \] (22)
the finger will move in a direction such that the manipulability \( W_f \) increases. Therefore, we have
\[ \Delta W_f \geq 0. \] (23)

In reality, the arm will either not move or move very slowly when \( \Delta W_f = W_f - W_{fr} \) is very small because of the friction it experiences at the joint motors and gears. This implies that \( W_f \) will probably keep decreasing for a short period. However, it will definitely increase as an integral effectiveness with the assist movement of the arm.

C. Control Block Diagram
The proposed control block diagram of the above algorithm is shown in Fig.4, where \( A_f \) is the kinematics of the finger, \( A_a \) is the kinematics of the arm; and \( G_f(z) \) and \( G_a(z) \) are the finger’s and the arm’s PID controllers, respectively. \( G_f(z) \) is defined as follows:
\[ G_f(z) = K_d' + K_v' \frac{z}{z-1} + K_p'(1-z^{-1}), \] (24)
where $K_{pa}^f \in \mathbb{R}^{13 \times 3}$, $K_{pa}^a \in \mathbb{R}^{13 \times 3}$ and $K_{pa}^r \in \mathbb{R}^{13 \times 3}$ are the given gains of the PID controller. $G_{pa}(z)$ is given as follows:

$$G_{pa}(z) = K_{pa}^f + K_{pa}^a \frac{z}{z-1} + K_{pa}^r (1 - z^{-1}),$$  \hspace{1cm} (25)$$

where $K_{pa}^f \in \mathbb{R}^{6 \times 6}$, $K_{pa}^a \in \mathbb{R}^{6 \times 6}$, and $K_{pa}^r \in \mathbb{R}^{6 \times 6}$ are the given gains of the PID controller.

As shown in Fig.4, when time $t=kT$, based on the finger’s manipulability $W_f(k)$ given by (9), the desired position $p_d(k)$ of the arm’s end-effector is calculated from (19)-(21). Subsequently, the desired position $p_d(k)$ of the finger can be computed by using (10). The obtained $p_d(k)$ and $\dot{p_d}(k)$ are fed as input to each servo loop so as to generate the expected motion.

### IV. EXPERIMENTAL RESULTS

To demonstrate the effectiveness of the proposed method, two distinct desired trajectories are charted out. Since the orientation of the finger’s tip with respect to the given curve is not specified in the experiment, the orientation arm’s end-effector is determined as a constant vector. The other related control parameters are listed in Table I.

#### A. Drawing a Sinusoidal Curve in Three Dimensional Space

When the amplitude of the desired sinusoidal curve is approximately equal to the total link length of the finger, the manipulability of the finger will fall to a very small value and the drawing task would not be completed without the assist movement of the arm. In this experiment, a three dimensional sinusoidal curve with an amplitude of 0.1[m] is given in $\Sigma_6$ by

$$\begin{align*}
  x &= 0.709 + 0.1 \sin(2\pi k / N) \\
  y &= 0.079 + 0.3k / (N\sqrt{2}) \\
  z &= 0.794 - 0.3k / (N\sqrt{2})
\end{align*}$$

\hspace{1cm} (26)$$

where $N$ is the total sampling number.

**a) Experimental Results of Position and Manipulability**

The obtained positions of the finger’s tip and the arm’s end-effector are shown in Fig.5(a), and the results indicate that the arm also moves along a trajectory similar to that of the given sinusoidal curve to assist the finger to accurately draw the desired curve.

The manipulability $W_f$ and magnitude of the arm’s velocity $|\dot{p}_a|$ are drawn in Fig.5(b). In this figure, $W_f$ of the finger is higher than $W_f$ during its starting period. Thus, only the finger moves to draw the curve, while the velocity of the arm is almost zero. Once $W_f$ of the finger falls below $W_f$, the velocity $|\dot{p}_a|$ of the arm increases large to assist in the
movement of the finger. As a result, the manipulability of the finger increases.

**(b) Kinetic Energy of the Arm-finger Robot**

By the proposed method, a smaller and lighter finger would move more actively, thus, the finger-arm robot moves with a smaller kinetic energy, which is advantageous. The kinetic energy of a manipulator movement at time $t=kT$ as well as translation and rotation can be expressed as follows:

$$K_e(k) = \frac{1}{2} \dot{\theta}^T(k) \cdot M(\theta) \cdot \dot{\theta}(k),$$

where $M(\theta)$ is the mass matrix of the arm and the finger. The kinetic energy $K_e$ in the task of drawing a sinusoidal curve with different values of $W_f$ is calculated and shown in Fig.5(c). Compared with $K_e$ when moving the arm only, the kinetic energy is a small value since the only the lighter finger is used during the starting period. However, when the $W_f$ gradually decreases in the middle period, the arm moves to assist the finger so that the $K_e$ increases. When the $W_f$ reaches near to the level of $W_{fr}$ in the end period, the $K_e$ decreases since the arm stops moving and only the finger is drawing the curve. The above results reveal that when the arm is moved to develop a large moving potential for the finger, it requires a higher kinetic energy. This result agrees with the phenomenon that in order to reduce the energy consumption, a human always moves his arm only when the moving potential of his hand falls below a desired value.

**B. Drawing a Free-Hand Figure**

The task of drawing a free-hand figure is completed in the second experiment. This figure is composed of a triangle (with edge lengths of 0.03[m], 0.04[m] and 0.05[m]), a circle (with a diameter of 0.06[m]) and a straight line (with a length of 0.3[m]) to link the circle and the triangle together. When a human draws such a figure, he will naturally move his finger primarily to draw the delicate part of the figure while he moves his arm to maintain the desired moving potential of his finger. As compared to the arm movement, hand movement consumes less energy because it has a small inertia.

The control parameters used in this experiment are listed in Table I. $W_{fr}$ is set to 0.0002. The positions of the arm’s end-effector and the finger’s tip are shown in Fig.6(a), and the result of $W_f$ is shown in Fig.6(b). Unlike the movements in experiment I shown in Fig.5(a), the robot finger plays a dominant role in drawing the delicate parts of the triangle and the circle, while the arm moves along the straight line so as to maintain the desired value of the moving potential of the finger. As shown in Fig.6(b), the manipulability $W_f$ of the finger is higher in the initial stages of drawing the triangle. However, the value of $W_f$ falls gradually when the finger begins to move along the straight line toward the circle. To improve the $W_f |\dot{p}_f|$ of the arm increases resulting in an increase in $W_e$, as shown in Fig.6(b). When the finger reaches near the position where the circle needs to be drawn, the arm stops moving and the finger draws the circle. Thus, the proposed method can naturally segregate the complicated motion of the finger-arm robot into two separate motions of the arm and the finger as in the case of a human being.

**V. CONCLUSIONS**

In this study, a control method is proposed to enable a
finger-arm robot to generate a motion that emulates the movement of a human upper limb. Based on the proposed method, the finger primarily moves to draw the desired trajectory, while the arm only moves to augment the finger’s movement when the manipulability of the finger falls below a given reference value. The proposed method has been applied in the experiments involving the drawing of two 3D figures. The obtained results elucidate the relationship between the manipulability and kinetic energy and also demonstrate the effectiveness of the proposed method in generating a natural motion emulating the movement of a human upper limb.

REFERENCES