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Trajectory Control of Biomimetic Robots for Demonstrating Human Arm Movements

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Abstract: This study presents the trajectory control of biomimetic robots by developing human arm trajectory planning. First, the minimum jerk trajectory of joint angles is analytically produced, and the trajectory of elbow joint angle is modified by time adjustment of joint motion of the elbow relative to the shoulder. Next, experiments in which gyro sensors are utilized have been conducted, and produced trajectories are compared with observed ones. According to the results, the validity of this proposed trajectory control for demonstrating human arm movements has been evaluated.

Keywords: biomimetic robot, human arm movement, trajectory planning, gyro sensor

I. INTRODUCTION

It is an important issue for biomimetic robots not only to design appearance resembling a human arm but also to move its arm along humanlike trajectories. An effective method for controlling biomimetic robots along such trajectories is to apply human arm trajectory planning. Here, the criteria such as joint torque change[1] and consumed energy[2] are proposed for characterizing human arm trajectory. The optimal trajectories minimizing these criteria have good agreements with human arm trajectories if movement duration and arm parameters are properly set up. This optimal trajectory is sensitively influenced by the change of movement duration or external load. In contrast, the hand path and velocity profile of human arm trajectory is kept invariant when the movement duration or the external load is changed[1]. In addition, numerical calculations for producing optimal trajectories become extremely difficult to converge under specific movement conditions. Consequently, such criteria have difficulty with these problems for the trajectory planning of biomimetic robots.

Meanwhile, it is possible to formulate humanlike trajectories which satisfy with the invariant property, if we assume the trajectory planning geometrically determined. Here, the criteria defined by derivative of the hand position including jerk in Cartesian coordinates have been proposed[4]. The produced hand velocity profile is always bell-shaped and shows property of human arm trajectory. However, curved hand paths occasionally observed in human arm movements can not be demonstrated, since the produced path is consistently straight. Such curved paths can be represented by supposing a linear relationship between the shoulder and the elbow angles in joint angle coordinates. Furthermore, this idea leads to an important fact that most of human hand paths can be duplicated by adequately setting a time delay of joint motion onset of the elbow relative to the shoulder[5]. However, there remains a crucial problem that a hand trajectory can not be produced unless the human trajectory to be duplicated is given.

This study presents the trajectory control of biomimetic robots. At the beginning, the minimum jerk trajectory of joint angles is analytically produced, and the trajectory of elbow joint angle is modified by time adjustment of joint motion of the elbow relative to the shoulder. As regards time adjustment, a newly provided case in addition to a case reported in a past literature[5] is taken into account. This time of elbow joint motion to be adjusted is numerically determined so as to reach the maximum hand velocity at the midpoint of movement. Consequently, the hand trajectory derived from the joint angle trajectories can be uniquely produced once the initial and target positions and movement duration are given. Subsequently, experiments have been conducted in which gyro sensors are utilized for measuring angular velocities with high accuracy and high resolution. Then, trajectories are numerically produced by use of the movement condition observed by experiments, and they are compared with observed ones in joint angle coordinates and Cartesian coordinates. Finally, it is shown that the proposed trajectory control is reasonable for biomimetic robots to demonstrating human arm trajectories.

II. METHODS

A. Trajectory formation

Human trajectories sometimes show a linear relationship between a shoulder and an elbow angles in joint angle coordinates[3],[5]. With respect to this relationship, the trajectory planning, so called "staggered interpolation" has been proposed. According to this method, most of hand paths can be reproduced if a linear relationship between these two angles is initially supposed, and a time delay of joint motion onset of the elbow relative to the shoulder is appropriately provided. However, this time delay can not be determined unless the human trajectory to be duplicated is given. Besides, the hand velocity profile, in some movement conditions, becomes distorted bell-shape. In our study, these problems are overcome by newly developed trajectory planning which reflects properties of human arm trajectory in Cartesian coordinates.

At the beginning, the performance criterion of a minimum jerk in a joint angle space is defines as

$$J = \frac{1}{2}\int_0^{t_f} (\dddot{\theta}_1(t)^2 + \dddot{\theta}_2(t)^2)dt \quad , \qquad (1)$$

where $\theta_1(t)$ and $\theta_2(t)$ are shoulder and elbow angles, and t_f is a movement duration. When the initial condition of movement is given by

$$\begin{cases} \theta_i(0) = \theta_{is}, \dot{\theta}_i(0) = 0, \ddot{\theta}_i(0) = 0 \\ \theta_i(t_f) = \theta_{if}, \dot{\theta}_i(t_f) = 0, \ddot{\theta}_i(t_f) = 0 \end{cases} \quad i = 1,2 \,, \qquad (2)$$

the optimal trajectory becomes

$$\theta_i(s) = \theta_{is} + (\theta_{is} - \theta_{if})(15s^4 - 6s^5 - 10s^3), \quad i = 1,2\,, \qquad (3)$$

where $s= t/ t_f$ is a normalized time. The trajectory given by Eq. (3) shows a perfect linear relationship between two angles. However, the hand velocity profile in Cartesian coordinates does not necessarily show the maximum velocity at the midpoint of movement. In other words, it does not, in a precise sense, implement the property of human trajectory. Therefore, we need to provide time adjustment which makes the hand velocity profile reach the maximum at the halfway point.

A robot arm model is shown in Fig. 1. Here, the hand position is described by

$$\begin{cases} x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{cases} \qquad (4)$$

By differentiating Eq. (4), the relationship of velocity between Cartesian and joint angle coordinates becomes

$$\begin{cases} \dot{x} = -l_1\dot{\theta}_1 \sin\theta_1 - l_2(\dot{\theta}_1 + \dot{\theta}_2)\sin(\theta_1 + \theta_2) \\ \dot{y} = l_1\dot{\theta}_1 \cos\theta_1 + l_2(\dot{\theta}_1 + \dot{\theta}_2)\cos(\theta_1 + \theta_2) \end{cases} \qquad (5)$$

Accordingly, the tangential velocity of hand is

$$v = \sqrt{\dot{x}^2 + \dot{y}^2} \quad . \qquad (6)$$

In general, this velocity does not reach the maximum at the halfway point. Hence, a time adjustment of elbow has to be taken into account. The first is the case that

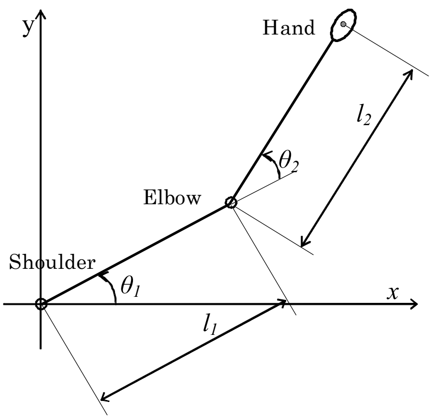


Fig. 1. Robot arm model

joint motion onset of the elbow relative to the shoulder is delayed, and only this case is considered in a past study[5]. We newly set the second case that the elbow joint motion stops before the shoulder joint motion does. In the first case, we suppose the elbow joint motion delayed time d with respect to normalized time s. Then, the elbow joint angle using Eq. (4) can be described by

$$\theta_2(s) = \theta_{2s} + (\theta_{2s} - \theta_{2f})(15p^4 - 6p^5 - 10p^3) \qquad (7)$$

where

$$p = \begin{cases} 0, & 0 \le s < d \\ (s-d)/(1-d), & d \le s \le 1 \end{cases} \qquad (8)$$

In the second case, when the elbow joint stops time d early before the shoulder joint does, p in Eq. (7) is

$$P = \begin{cases} s/(1-d), & 0 \le s < 1-d \\ 0, & 1-d \le s \le 1 \end{cases} \qquad (9)$$

When the shoulder joint angle of Eq. (3) and the elbow joint angle of Eq. (7) are substituted into Eq. (5), the hand velocity becomes function of s and d. Then, by differentiating it, we have

$$\frac{dv}{ds} = \frac{1}{2\sqrt{\dot{x}^2 + \dot{y}^2}} \frac{d(\dot{x}^2 + \dot{y}^2)}{ds} \qquad (10)$$

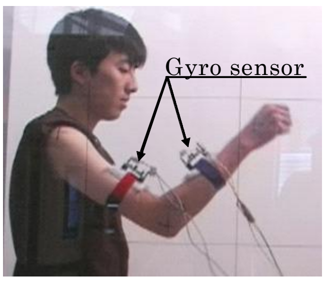
Accordingly, a condition that the maximum velocity exists at the midpoint of movement can be written as

$$\begin{aligned} \left.\frac{d(\dot{x}^2 + \dot{y}^2)}{ds}\right|_{s=0.5} &= [2l_1^2\dot{\theta}_1\ddot{\theta}_1 + 2l_2^2(\dot{\theta}_1 + \dot{\theta}_2)(\ddot{\theta}_1 + \ddot{\theta}_2) \\ &+ 2l_1l_2[(2\dot{\theta}_1\ddot{\theta}_1 + \ddot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1\ddot{\theta}_2)\cos\theta_2 \\ &- \dot{\theta}_1\dot{\theta}_2(\dot{\theta}_1 + \dot{\theta}_2)\sin\theta_2\}]]_{s=0.5} = 0 \end{aligned} \qquad (11)$$

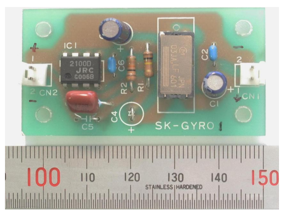
Since the time difference is uniquely decided by Eq. (11), the arm trajectory is perfectly determined once initial and target positions are given. In this study, we initially set as d=0, and time d satisfying with Eq. (11) has been searched by Newton-Raphson method.

B. Experiment

The important feature of human arm trajectory is the dynamic behavior of joint angular velocity as well as the hand trajectory in Cartesian coordinates. Therefore, the joint angular velocity has to be measured with a high degree of accuracy since a time difference of joint motion of the elbow relative to the shoulder is essential. One of the most effective methods for measuring angular velocity is to utilize gyro sensors[6]. In this study, two gyro sensors are used on the upper arm and



(a) Arrangement



(b) Circuit board

Fig. 2 Gyro sensor

the forearm of a subject, and this gyro sensor is mounted in a circuit board as shown in Fig. 2. As regards movement conditions, several sets of initial and target hand positions are provided for observing basic properties of human arm trajectories. The trajectory is measured for movements in which a subject moves a hand from the initial to the target hand positions, and this is named direct movement. Then, the initial and target hand positions are exchanged, and the trajectory is also observed for movements which is called inverse movement. Besides, the detail of experimental procedure and data processing is described in a literature[7]

III. RESULTS AND DISCUSSION

The hand path in human arm movements is either almost straight or simply curved[1]-[3]. So, these typical trajectories of direct movement are shown in Figs. 3 and 4. Results of inverse movement to each direct movement are also shown in Figs. 5 and 6. In the experiment, a subject is instructed to move his hand without concerning himself fine accuracy of the target point. As a result, a pair of hand positions of direct movement is not, in a precise sense, the same as a pair of hand positions of inverse movement.

As regards angular velocity, the observed trajectory basically shows bell-shaped profile on motion in both direct and inverse movements. Besides, most of the angular velocities overshoot near the termination time. This phenomenon is called "zero velocity crossing" as introduced in Ref. [8]. The angular velocity profile of produced trajectory well agrees with that of observed one in all movements except oscillation of angular velocity in some movements and the phenomenon of zero velocity crossing. However, these dissimilarities are not serious drawbacks for representing human arm trajectory because fluctuation within a small range of angular velocity does not seriously influence the velocity profile and the hand path.

With respect to an angular velocity, the elbow joint motion in direct and inverse movements for a pair of hand positions exhibits an interesting feature. Fig.3 indicates that the elbow joint motion starts after the shoulder joint motion does. Conversely, Fig. 5 for in inverse movement shows an opposite result that the elbow joint motion stops before the shoulder joint motion does. The same phenomenon can be seen in direct and inverse movements of condition2. This time difference between the elbow and the shoulder joint motions takes an important role of human arm trajectory planning.

The hand trajectory is one of the most important issues for biomimetic robots demonstrating human arm movements. Besides, it can be represented by the path and the velocity profile of a hand. As can be seen from Fig. 3 to Fig. 6, observed trajectories show such typical properties that the hand path is either straight or simply curved, and the hand velocity profile is bell-shaped with the maximum value in the vicinity of the halfway point. As for produced trajectories, the hand path of direct movement of condition 1 is slightly different from the path of observed trajectory. However, judging from the experimental results conducted under plural subjects[9], a variation of this degree can be considered within a range of individual difference. In all movements other than that, the hand path nearly overlapped in the

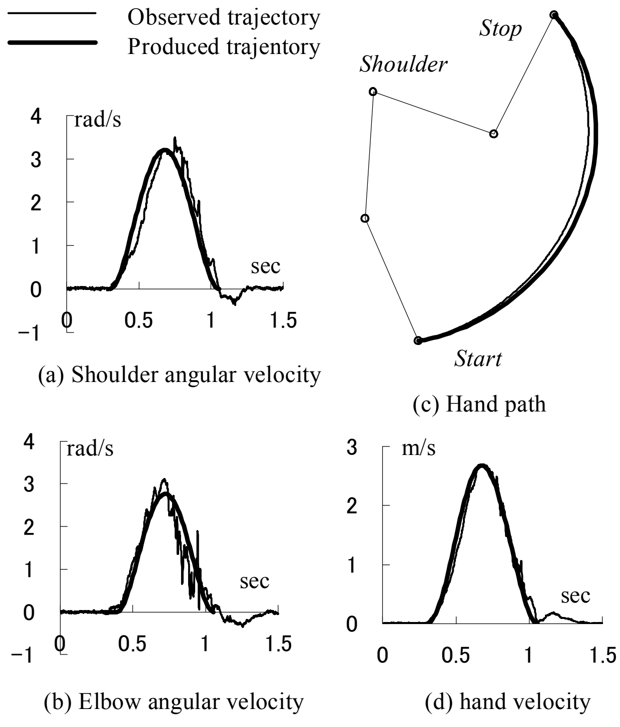


Fig. 3 Direct movement of condition 1

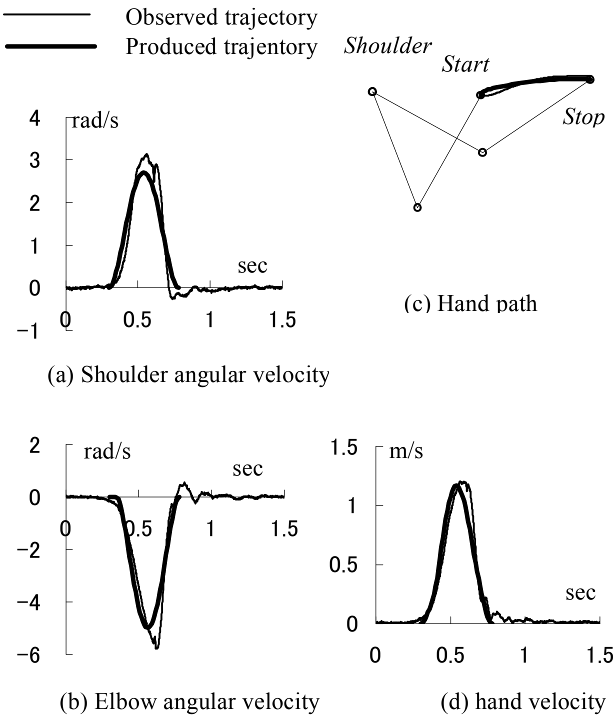


Fig. 4 Direct movement of condition 2

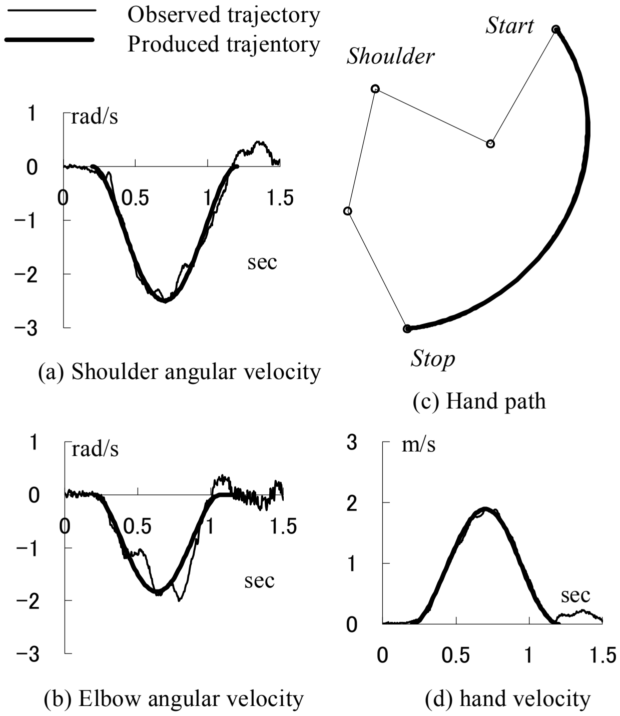


Fig. 5 Inverse movement of condition 1

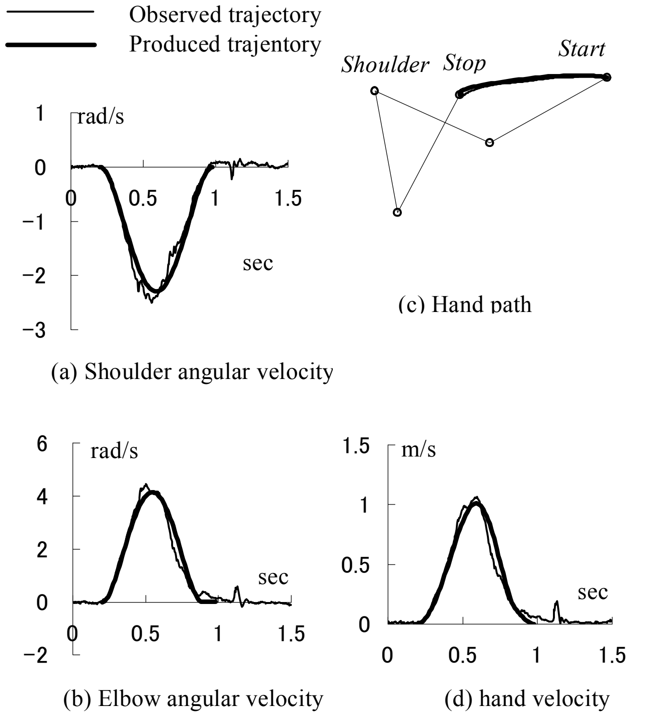


Fig. 6 Inverse movement of condition 2

produced and the observed trajectories. In addition to this consistency of the hand path, the hand velocity profile of produced trajectories is identical to that of observed trajectories in all movements. These results lead to the conclusion that trajectories produced according to the proposed trajectory planning well demonstrate human arm property.

IV. CONCLUSION

In this study, the trajectory planning for biomimetic robot has been conducted in kinematic coordinates, and produced trajectories have been compared with experimental results. Consequently, it is confirmed that the produced trajectories well demonstrate the properties of human arm trajectories. According to this trajectory planning, the trajectory can be uniquely produced if initial and target positions and movement duration are given. Furthermore, it always represents the properties of human arm trajectory even though movement duration or external load is changed. In addition to these advantages, the numerical calculation for producing trajectories is relatively simple. These features show that the proposed trajectory planning is effective for controlling biomimetic robots along humanlike trajectories.

There are, however, some problems which remain to be solved. The angular velocity of human arm trajectory fluctuates near the end of movement, and zero velocity crossing occurs especially when high angular velocity is required. This phenomenon can not be covered by our trajectory planning. Further development of trajectory planning reflecting such detail property of human trajectories is the issue to be solved in the future.

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