Robotic rehabilitation system for human upper limbs using guide control and manipulability ellipsoid prediction

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Abstract

In this paper, we propose a robotic assistive control system for rehabilitation of the human arm. The admittance control produced low stiffness in the moving direction and high stiffness in the orthogonal direction. Using the admittance control for guide control, subjects can easily move their arms in accordance with the virtual guide line. The manipulability ellipsoid is obtained by image processing and singular value decomposition of the Jacobian matrix. The major axis of the ellipse indicates the easiest direction for the operation. The proposed guide control using admittance control and the manipulability ellipsoid was confirmed to be very effective.

Keywords: admittance control; manipulability ellipsoid; rehabilitation; assistive robot; singular value decomposition;

1. Introduction

Owing to an aging society, the number of stroke patients has been increasing in recent years. The use of assistive robots has gained attention for the efficient promotion of rehabilitation from paralysis. The MIT-MANUS, which is an assistive robot, realized a learning procedure for rehabilitation with high reproducibility and good quantification [1], [2]. Most assistive rehabilitation robots use impedance control [3], in which the controllers produce force outputs such as damping and spring force in response to the movement of the arms or legs of the patient in accordance with the desired path [4], [5], [6]. To detect a self-initiated movement, triggered assistances that utilize physical sensors such as force or velocity sensors are added to the impedance controllers [7], [8]. If the signals of the muscles can be directly detected, rather than through physical sensors, the surface electromyography signals can be

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used to trigger the assistances [9], [10]. The minimum jerk and pre-recorded trajectories are often used to determine the desired path [11], [12]. Adaptation of the control parameters is also an important issue, and the efficacy of the adaptation is evaluated in [13]. An extensive review of the control strategies for robotic rehabilitation is available in [14].

Many assistive robots possess the desirable function of assisting human arm movements. However, these systems do not consider the mechanical characteristics of human arms and use representations such as the Jacobian matrix. Therefore, subjects may start moving their arms in directions that are difficult to operate with the current pose. In robotics, the manipulability ellipsoid is often used as a measure to denote the ability of manipulator arms and determine an easy direction to operate toward [15], [16].

In this paper, we propose a robotic assistive control system for human arm rehabilitation. The goal of this research was to apply the manipulability ellipsoid to the assistive robot to achieve a user-friendly rehabilitation system. From the clinical point of view, we propose the assistive robotic system for initial rehabilitation, similar to when an experienced therapist leads the arms of the patient in the easiest direction when the patient begins to move. Figure 1 shows the experimental setup of the assistive control system. This system consists of two main parts: guide control and prediction of the manipulability ellipsoid for a human arm. The guide control consists of a robotic manipulator arm with two degrees of freedom and a monitor to display the target and current position of the grip. In the rehabilitation procedure, subjects move the grip, which is attached to the end of the robotic arm, to track the target on the monitor. In order to assist the arm movement of the subjects, a force sensor is used to apply admittance control to the robotic arm. The admittance control realizes low stiffness in the moving direction and high stiffness in the orthogonal direction. Subjects can easily move their arms during the rehabilitation procedure in accordance with the virtual guide line.

Prediction of the manipulability ellipsoid for the human arm utilizes a USB camera and image processing unit. The USB camera detects human arm movement using image markers that are attached at the joints of the wrist, elbow, and shoulder. The manipulability ellipsoid is calculated in real time using the Hough transform for circles [17], [18] and singular value decomposition of the Jacobian matrix for the human arm. The major axis of the ellipse indicates the easiest direction for human arm operation. Therefore, the larger amplitude of the target displacement is set in the major axis, and the smaller one is set in the minor axis.

In the experimental results, the designed control system showed excellent assistive performance for easy operation. The guide performance using the admittance control and manipulability ellipsoid was confirmed to be very effective. In particular, because the manipulability ellipsoid could be shown on the monitor in real time, the subject was able to confirm the easiest direction and move the arm along the virtual guide line. In conclusion, the
robotic assistive control system using the guide control and predicted manipulability ellipsoid enabled the subject to execute the training procedure without excessive operation.

2. Control System Design

Figure 2 is a diagram of the entire controller. In the figure, the admittance control law based on the positional control scheme is applied to the guide control, and the tracking reference is generated from the prediction of the manipulability ellipsoid.

![Diagram of controller](image)

2.1. Guide Controller

First, a two degrees of freedom admittance controller was designed for the upper part of Figure 2. The reference displacement in the workspace $p_{ref}$ was obtained using the external force $f_{ext}$, which was measured using the force sensor.

$$p_{ref} = R^T(\theta_{rot_k}) \left[ (sD_{adm1} + K_{adm1})^{-1} \quad 0 \\ 0 \\ (sD_{adm2} + K_{adm2})^{-1} \right] R(\theta_{rot_k}) f_{ext}$$

where $R$ is the rotation matrix, $\theta_{rot,k} = 0 + (k - 1) \pi / 8$ ($k = 1, ..., 8$) is the direction of the virtual guide line, $D_{adm1}$ and $K_{adm1}$ are the damping and stiffness coefficients in the moving direction, and $D_{adm2}$ and $K_{adm2}$ are the damping and stiffness coefficients in the orthogonal direction. By applying inverse kinematics to the two degrees of freedom robotic manipulator arm, the reference displacement in the workspace $p_{ref}$ is transformed into the reference displacement in the joint space $\theta_{ref} = [\theta_1 \quad \theta_2]^T$.

Next, a guide controller was designed for the lower part of Figure 2. The controller consisted of a PID feedback controller and feed forward terms, including the inertia and friction compensations.

$$\tau_i = K_p(\theta_{rl} - \theta_i) + K_i \int (\theta_{rl} - \theta_i) \, dt + K_d(\dot{\theta}_{rl} - \dot{\theta}_i) + \bar{I}_m \ddot{\theta}_i + \bar{B}_m \dot{\theta}_i + \bar{D}_m \text{sgn}(\dot{\theta}_i), \ i = 1, 2$$

where $\tau_i$ is the driving torque of the servo motor at the $i$'th joint of the robotic arm; $\theta_i$ is the angle of the joint; $\theta_{rl}$ is the reference displacement of the joint angle; $K_p, K_i, K_d$ are respectively the proportional, integral, and derivative gains of the PID controller; $\bar{I}_m$ is the moment of inertia; $\bar{B}_m$ is the viscous friction coefficient; and $\bar{D}_m$ is the Coulomb friction coefficient. These coefficients are obtained by using the least square method [19].
2.2. Manipulability Ellipsoid Predictor and Reference Generator

Before predicting the manipulability ellipsoid, we calculated the joint angles of the human arm relative to the positions of the image markers $p_j = [p_{jx} \ p_{jy}]^T$, which were attached to the shoulder, elbow, and wrist joints, which correspond to $j = 1, 2, 3$, respectively.

$$q_1 = \tan^{-1}\left(\frac{(p_{2y} - p_{1y})}{(p_{2x} - p_{1x})}\right)$$ (3)

$$q_2 = \tan^{-1}\left(\frac{(p_{3y} - p_{2y})}{(p_{3x} - p_{2x})}\right) - q_1$$ (4)

where $q_1$ and $q_2$ are the shoulder and elbow joint angles, respectively. The positions of the image markers $p_j = [p_{jx} \ p_{jy}]^T$ are derived by applying Hough transform to the detected grayscale image and transformation of the image coordinates to the world coordinates.

$$p_j = M_{12w}T_{hough}(im_{gray}, R_{civ})$$ (5)

where $M_{12w}$ is the matrix of the coordinate transformation of the image to the world, $T_{hough}$ is the function of the Hough transform for circles, $im_{gray}$ is the grayscale image obtained by a USB camera, and $R_{civ}$ is the radius of the image marker.

From the shoulder and elbow joint angles, the Jacobian matrix of the human arm is derived as follows:

$$J_h = \begin{bmatrix}
-L_1 \sin q_1 - L_2 \sin(q_1 + q_2) & -L_2 \sin(q_1 + q_2) \\
L_1 \cos q_1 + L_2 \cos(q_1 + q_2) & L_2 \cos(q_1 + q_2)
\end{bmatrix}$$ (6)

where $L_1$ is the length of the upper arm, and $L_2$ is the length of the forearm.

Using singular value decomposition of the Jacobian matrix, the parameters of the manipulability ellipsoid are estimated as follows:

$$J_h = U_h\Sigma_h V_h^T = U_h\begin{bmatrix} \sigma_{long} & 0 \\ 0 & \sigma_{short} \end{bmatrix}V_h^T$$ (7)

where $\sigma_{long}$ and $\sigma_{short}$ are respectively the major and minor axes of the ellipse, and the first column vector of $U_h$ is the direction of the major axis.

Finally, we designed the tracking reference in the form of a sinusoidal wave with a variable amplitude using the above parameters of the manipulability ellipsoid.

$$p_{fin} = R(\theta_{rot,k})[A_r \sin(2\pi f t) \ 0]^T$$ (8)

where $p_{fin}$ is the tracking reference on the monitor, $A_r$ is the variable amplitude, and $f = 0.3$ (Hz) is the frequency of the signal. The amplitude of the sinusoidal wave varies between $\sigma_{long}$ and $\sigma_{short}$, in accordance with the summation of $\theta_{rot,k}$ and $\theta_{ellip}$.

$$A_r = \frac{\sigma_{long}\sigma_{short}}{\sqrt{\left(\sigma_{long}\sin(\theta_{rot,k} + \theta_{ellip})\right)^2 + \left(\sigma_{short}\cos(\theta_{rot,k} + \theta_{ellip})\right)^2}}$$ (9)

where $\theta_{ellip} = \cos^{-1}(U_h(1,1))$ is the inclination of the major axis.
3. Experimental Results

In this study, we used a healthy subject to evaluate the control designed in the previous section, comprising the guide control, the manipulability ellipsoid prediction, and the guide control based on the manipulability ellipsoid prediction. The evaluation was intended as a preliminary test before training application to stroke patients. The subject executed the tracking task by moving his grip in accordance with the position of the tracking reference on the monitor. The tracking reference was generated using (8) and (9).

Figure 3 shows the results of the guide control without the manipulability ellipsoid prediction. In this case, we assumed that the manipulability ellipsoid was a circle; i.e., $\sigma_{\text{long}} = \sigma_{\text{short}}$ in (9). The results revealed that the desired eight guide lines at every $\pi/B$ (rad) in the circumferential direction were achieved. Therefore, the subject could easily move his arm in accordance with the virtual guide lines. Figure 4 shows the performance of the admittance controller. The dotted and solid lines indicate high and low stiffness, respectively. In this experiment, the target high and low stiffness were 300 and 100 N/m, respectively, and the experimental values were 283 and 94 N/m, respectively. An examination of the figure confirms that the target stiffness was achieved within 10%. Here, the low and high stiffness were chosen for operations in the moving and orthogonal directions, respectively.

Figure 5 shows the performance of manipulability ellipsoid prediction for lateral movement. Figure 6 shows the performance of ellipsoid prediction for longitudinal movement manipulability.
Figures 5 and 6 show the performances of the manipulability ellipsoid prediction for lateral and longitudinal movements, respectively. For the lateral movement, the major axis of the ellipse turns in the circumferential direction of the arm movement. For the longitudinal movement, the ellipse deforms in the lateral direction when the elbow joint is stretched. The results are therefore found to be adequate.

Finally, we evaluated the guide controller that uses the manipulability ellipsoid prediction. Figures 7 and 8 show the performances of the guide controller that uses the manipulability ellipsoid prediction for the cases of left side and right side lateral movements, respectively. From these figures, we found that the larger amplitude of the target displacement was on the major axis of the ellipse, and the smaller one was on the minor axis. Therefore, the subject was able to execute the training procedure without excessive operation.

4. Conclusion

In this paper, we proposed a robotic assistive control system for rehabilitation of the human arm. The admittance control produced low stiffness in the moving direction and high stiffness in the orthogonal direction. Using the admittance control for guide control, subjects can easily move their arms in accordance with the virtual guide line. The manipulability ellipsoid is obtained by image processing and singular value decomposition of the Jacobian matrix of the human arm. The major axis of the ellipse indicates the easiest direction for the operation of the human arm. The proposed guide control using admittance control and the manipulability ellipsoid was confirmed to be very effective. In particular, because the manipulability ellipsoid could be shown on the monitor in real time, the subject was able to confirm the easiest direction and move the arm along the virtual guide line.

Along with the control performance, the proposed system achieved low cost by compensating for inertia and friction using low-cost actuators and using a USB camera for image processing. Further research will involve reducing the system cost to expand the applicability of this rehabilitation system.

References


