Control Scheme of a Two-Finger Gripper for Emulating Human Characteristics in Cooperative Tasks

Goro Obinata* Ashish Dutta**

Abstract

This paper discusses a proposed two-finger gripper for robot human cooperation, which can be a key for future assistive technology. The gripper consists of two soft fingers having a total of ten degrees of freedom. A two-finger gripper was chosen because humans perform many tasks using only two fingers and its control is simpler than a three finger hand, for robot human cooperation. The control system of the gripper was designed based on human control characteristics so that it is human friendly. An experiment was carried out in which two humans performed a task and based on it an impedance model is approximated. A dynamic control system was then designed incorporating the human impedance characteristics. During grasping both the internal forces and the motion forces applied by the fingers are simultaneously controlled. Hence, the robot can stably grasp an object and also follow the human motion. Finally a two-finger robot human cooperation simulation was carried out to demonstrate the effectiveness of the proposed control method.

Keywords: two-finger gripper, robot human cooperation, human friendly, active force closure, impedance control

1. Introduction

A recent development in life support technology is the use of robots for helping the aged and disabled persons perform everyday tasks. Industrial robots interact with machines or tools in factories, while in life support applications robots interact with humans. Hence, human friendliness, reliability of control and safety are very important issues. There are many applications where robots can be utilized for helping the aged or disabled, e.g. in eating, standing up, sitting down, walking etc. In such applications where robots are used, transfer of force or moment takes place between the robot and human during interaction. For smooth transfer of forces very good cooperation by the robot during the task is desired. The control system of robots that interact with humans should be designed based on the human control system so that humans feel at ease with them. Most industrial robots are mainly equipped with a two-finger parallel jaw gripper that can perform simple pick and place tasks. Future robots will have to be equipped with a dextrous hand having several degrees of freedom so that it can perform complicated tasks.

The main objective of this paper is to design a two finger gripper and a human friendly control system for excellent robot human cooperation. Humans perform many tasks using only two fingers and its control is simpler than a
three finger hand. In the case of robot human cooperation there are two basic cases in which a two-finger robot with soft fingertips and human can move an object together:

Case 1: The robot supports the complete weight of the object and the human just applies an external force to move the object to the desired location (Fig. 1(a)). The finger and object contact points should be such that no moment is generated due to the position of the fingers.

Case 2: The robot and human cooperate in supporting the object (Fig. 1(b)). In this case the human has to apply forces such that the conditions required for obtaining active force closure are satisfied and the object is stable.

These two cases show that most tasks in robot human cooperation can be performed with only two soft fingers. Also, the kinematics involved for object manipulation with a two finger hand is simpler in its design and is easier to manufacture. Most robot fingers are covered by some soft material, like rubber etc. and hence in practical cases the finger-object contact will be of the soft finger type (three forces and one moment at each fingertip). Due to this reason it is possible to obtain active force closure, using only two fingers with soft fingertips (provided it is possible to apply moments to the object at all positions).

In order to design a human friendly control system the characteristics of a task in which two humans move an object together was first studied, and based on it an impedance model was fitted to the experimental data. A dynamic control system was then designed which can control both the internal forces and the motion forces while manipulating an object. Finally a simulation was performed to illustrate the effectiveness of the proposed control scheme, which proved that the robot fingers can produce human like motion.

2. Background Review

Salisbury\(^1\) has shown that for dextrous manipulation, nine degrees of freedom are required for a three-finger hand with frictional point contact. Yoshikawa\(^2\) has presented various conditions for passive and active closure by constraining mechanisms, when the contact type is point contact with friction. Kerr and Roth\(^3\) have proposed a linear programming technique to determine the internal forces. Using this method the maximum forces that may be applied for a given joint motor torque are obtained. Nakamura et al.\(^4\) discuss the mechanics of coordinative manipulation by a multifingered hand in which, the resultant forces are used to move the object while the internal forces are regulated to adapt to varying friction and uncertainty. Bicchi\(^5\) has given a detailed survey on the evolution and the state of the art in the field of robot hands. Ikeura et al.\(^6\) have proposed a variable impedance control method for robot human cooperation, while Kosuge et al.\(^7\) consider a virtual impedance model for robot human cooperation. Most previous researchers have analyzed the three-finger hand, only for grasping and manipulation of objects but not for cooperation with humans. No previous study has been reported in the literature regarding the control of a gripper having several degrees of freedom for cooperation with humans.

3. Two finger robot-human cooperation

3.1 Determination of grasping forces

The structure of the proposed hand and the coordinate system of the fingers and object are as shown in Fig. 2.

The force and moment balance relation for the above finger-object system can be written as:
\[ \mathbf{F} = \mathbf{W} \mathbf{C} \]  

(1)

Where \( \mathbf{F} \) is the vector (6X1) of external forces and moments, \( \mathbf{W} \) is a (6Xn) matrix and \( \mathbf{C} \) is the vector of fingertip forces and moments. This relation is the same as the one described by several previous researchers\(^1\),\(^2\),\(^3\),\(^4\).

The finger forces can be divided into forces responsible for producing motion and internal forces, which cause compression or tension of the object.

\[ \mathbf{C} = \mathbf{C}_m + \mathbf{C}_i \]  

(2)

\[ \mathbf{C}_m = -\mathbf{W}^* \mathbf{F} \]  

(3)

\[ \mathbf{C}_i = \mathbf{N} \hat{\lambda} \]  

(4)

Where \( \mathbf{C}_m \) is the motion causing forces, \( \mathbf{C}_i \) is the internal force on the object, \( \mathbf{N} \) is an orthonormal basis spanning the null space of \( \mathbf{W} \), and \( \mathbf{W}^* \) is the generalized inverse of \( \mathbf{W} \).

The force \( \mathbf{F} \) applied by the human in equation (1), contains six components and hence, active force closure may be obtained if any resultant force and moment can be applied to the object by proper choice of actuator forces. Apart from this the following conditions must also be satisfied: there should exist nonzero internal forces, the resultant of all the external forces and moments should be zero and the friction conditions should be satisfied\(^2\). In order to control three external forces and three moments (\( \mathbf{F} \)) a total of eight actuators are required, for two fingers with soft finger contact (producing three forces and one moment per fingertip), as shown in equation (5). In addition to this in order to apply a moment on the object \((n_x, n_y, n_z)\) the axis of the last link of the finger should be parallel to the object surface normal, at the point of contact. This requires that it is possible to position the last link independent of the kinematic constraints on the other degrees of freedom, so that the last link is normal to the object surface in all positions. Hence ten actuators are required for controlling the ten degrees of freedom. The actuators are located at the respective joints and all the joints are of the revolute type.

For grasping an object of length \( L \) [m], from equation (1) we have:

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
N_x \\
N_y \\
N_z
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1/2 & 0 & 0 & 0 & -1/2 & 0 \\
0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_y \\
f_z \\
n_x \\
n_y \\
n_z
\end{bmatrix}
\]  

(5)

where \( F_x, F_y \) and \( F_z \) are the components of the applied external force [N] on the object and \( N_x, N_y \) and \( N_z \) are the moments [N-m] in the x, y and z axis directions respectively. The weight of the object is included in \( F_z \). An orthonormal basis of the null space of \( \mathbf{W} \) is:

\[
N =
\begin{bmatrix}
0.7071 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0.7071 & 0 \\
-0.7071 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]  

(6)

The generalized inverse of \( \mathbf{W} \) is given by:

\[
\mathbf{W}^* =
\begin{bmatrix}
0.5 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.5 & 0 & 0 & -1/L & 0 \\
0 & 0 & 0.5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]  

(7)

Equating the two sides of equation (5), and solving for \( f_x1, f_y2, f_z1, f_z2 \) we have:
The constraints on $f_{x1}$, $f_{x2}$ and $n_{x1}$, $n_{x2}$ for maintaining the grasp by compressing the object are given by:

$$f_{x1} \geq 0$$
$$f_{x2} \leq 0$$

$$n_{x1} \geq 0$$
$$n_{x2} \leq 0$$

The constraints on $f_{s1}$, $f_{s2}$ for maintaining the grasp by compressing the object are given by:

$$f_{s1} = -F_y/2 + N_z/L$$
$$f_{s2} = -F_y/2 - N_z/L$$

$$f_{z1} = -F_z/2 - N_y/L$$
$$f_{z2} = -F_z/2 + N_y/L$$

From equations (5) and (10) we have:

$$f_{x1} = -F_x/2 + 0.7071\mu_1$$
$$f_{x2} = -F_x/2 - 0.7071\mu_1$$

Similarly from equation (5) and (11) we have:

$$n_{x1} = -N_x/2 + 0.7071\mu_2$$
$$n_{x2} = -N_x/2 - 0.7071\mu_2$$

Assuming linear Coulomb friction conditions at the fingertip contact, the constraints for satisfying the friction requirements are given by:

$$f_{s} - \mu f_{n} \leq 0; \quad i = 1,2$$
$$f_{s} - \mu f_{n} \leq 0; \quad i = 1,2$$

Assuming the fingertips can apply a moment to the object about the surface normal, the torsion friction constraint can be written as:

$$n_{s1} = \mu \alpha \leq 0 \quad ; \quad i = 1,2$$

Considering all the friction constraints and assuming that there is no relative motion between the finger tip and object at the contact point, we have:

$$\begin{bmatrix}
\mu & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \mu & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \mu & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \mu & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \mu & -1
\end{bmatrix} \begin{bmatrix}
-F_y/2 + 0.7071\mu_1 \\
-F_y/2 + N_z/L \\
-F_y/2 - N_z/L \\
-N_x/2 + 0.7071\mu_2 \\
-N_x/2 + N_y/L \\
-N_x/2 - 0.7071\mu_2 \\
-N_x/2 - 0.7071\mu_2
\end{bmatrix} \geq \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}$$

eight inequalities are obtained from equation (16) which govern the internal force. Assuming $\mu = 0.3$ for both normal force and torsion case, we have:

$$0.7071\mu_1 \geq 0.5F_x + 3.33N_z/L - 1.67F_y$$
$$0.7071\mu_1 \geq 0.5F_x - 3.33N_z/L - 1.67F_y$$
$$0.7071\mu_1 \geq 0.5F_x$$
$$0.7071\mu_1 + 2.33\mu_2 \geq 0.5F_x + 1.66N_z$$
$$-0.7071\mu_1 \geq 0.5F_x - 3.33N_z/L - 1.67F_y$$
$$-0.7071\mu_1 \geq 0.5F_x + 3.33N_z/L - 1.67F_y$$
$$-0.7071\mu_1 \geq 0.5F_x$$
$$-0.7071\mu_1 + 2.33\mu_2 \geq 0.5F_x - 1.66N_z$$

this set of inequalities (17) shows the effect of the humans force on the internal forces required for grasping. Assuming $F_x=F_y=F_z=1 \text{ [N]}$, $N_x = N_y = N_z = 0.1 \text{[N-m]}$ and $L=0.1 \text{m}$, the minimum value of the internal force required to maintain the grasp satisfying the friction conditions is obtained as,

$$\pm 0.7071\mu_1 \geq 4.5a$$
$$\pm 0.7071\mu_2 \geq 1.44a$$

where “a” is a suitable factor of safety.

3.2 Experiment in two human cooperation

The experimental setup was as shown in Fig. 3. A leader and a follower was defined, the leader moves the object from point A to point B and the follower senses the change in shear force in his fingertips and follows the motion. The two humans moved the object between two points using their fingers only, while the rest of the arm was kept stationary. The same task was carried out 6 times for covering a distance of 36mm in approximately 1.6 sec each time. A new strain gauge based shear force sensor (Fig.4) was designed to measure the shear force applied during the task. The sensor measures the shear force as a moment about the point "A" and the normal fingertip force is balanced by the normal reaction force. It is assumed that there is no slip between the object and the fingers. The sensed shear force was amplified, passed through a LP filter and then recorded in a computer at intervals of 10ms. A laser sensor was used to measure the position of the object as it was moved by the humans, and the data was recorded in a computer at intervals of 10ms. Fig. 5 shows the variation of the humans force and object position for a...
Fig. 3. Experimental setup.

Fig. 4. The shear force sensor.

typical motion when the two humans moved the object together. It shows that the humans first start moving the object slowly and then increase the force to a maximum at the centre of motion. The force is again reduced to a minimum at the end of motion. The experiment was carried out in one dimension only, as it is very difficult to estimate human impedance parameters in three dimensions (3D). A simple task was chosen because of the limited ability of the human fingers to move in 3D, and the total number of human cooperative motions are very large.

3.3 Impedance model approximation

Humans manipulate various objects and perform different tasks by actively changing the impedance of their arms, by the coactivation of different muscles (Hogan). Kazerooni has proved the stability of the impedance control system for controlling robot manipulators. In the impedance model the identified apparent mass is modulated by neural feedback and hence both the mass and the damping parameters should be varied in the impedance model, in order to emulate human motion accurately. Ikeura et al. have mentioned that in an impedance model the spring factor resists the human motion and can be neglected. The simplified impedance model can be written as:

$$ M\ddot{x} + K\dot{x} = F \quad (19) $$

where $M$ is the mass [Kg], $K$ is the damping coefficient [Nsec/m], $\Delta x = x_d - x$ is the position and orientation error of the $i^{th}$ finger, and $F$ is the external force [N] applied by the human. The subscript "d" denotes a desired quantity. The human force and object position data obtained from the experiment was approximated by a variable impedance model, based on the average velocity, using least square approximation. Table 1 shows the variation of the impedance parameters with average velocity. We have considered the impedance parameters for the fingers only, assuming the arm to be at rest.

<table>
<thead>
<tr>
<th>$M$ (Kg)</th>
<th>$K$ (Nsec/m)</th>
<th>average velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>24</td>
<td>&lt;0.22</td>
</tr>
<tr>
<td>2.3</td>
<td>65</td>
<td>≥0.22</td>
</tr>
</tbody>
</table>

3.4 Coordinated manipulation by a robot and human

Incorporating variable impedance control into the dynamic equation of robot finger motion results in the motion of the finger being closest to that of a human. The dynamic behavior of a finger can be expressed as:

$$ D(\theta)\ddot{\theta} + B(\theta, \dot{\theta}) + J^T C_m = \tau \quad ; i = 1, 2, \ldots, 5 \quad (20) $$

where $D$ is the inertia matrix, $B$ is the matrix representing...
coriolies, centrifugal and gravity terms, \( J \) is the finger Jacobian matrix, \( C_m \) is the vector of motion forces sensed at the fingertip (from equation 3) and \( \tau_m \) is the vector of joint torques. For a given finger if \( \theta \) is the joint angle vector, \( x \) is the coordinate vector of the finger tip and \( J \) is the Jacobian matrix, then the following relation holds:

\[
\dot{\theta} = J^{-1}(\dot{x} - J\dot{\theta})
\]

Putting equation (19) and (21) in equation (20) we have

\[
D[J^{-1}(M^{-1}M\dot{x} + K\Delta \dot{x} + F)\cdot J\dot{\theta} - J\ddot{\theta}]} + B + J^TC_m = \tau_m
\]

(22)

Using this equation the required joint torque can be computed for a desired trajectory after measuring position and fingertip force. The obtained torque produces the motion of the object and not the internal forces. The finger joint torques required to apply the internal forces are obtained from the static model of the finger given by:

\[
\tau_s = J^TC_i
\]

(23)

where \( \tau_s \) is the static torque vector and \( C_i \) is obtained from equation (17). It is observed from the orthonormal basis in equation (6) that the static torque vector will contain two equal and opposite internal forces and two internal moments in the \( x \)-direction.

### 3.5 Control system

Fig. 6 shows the proposed control system. It is necessary that the fingers apply internal force continuously while moving the object in order to prevent the object from slipping. Therefore the fingers should be force controlled to hold the object and also position controlled to follow the human motion. In stage I of the control scheme, when the human moves the object the desired fingertip trajectory is obtained by numerically integrating the impedance model (19), using second order Runge-Kutta method. The current position of the finger is used as the initial condition during each integration step. Impedance parameters \( (M,K) \) used during the integration are as given in Table 1. In stage II the humans applied force is separated into the motion forces (equation 3) and internal forces (equation 17). Using the dynamic (equation 22) and the static models (equation 23) the two torques are separately calculated depending on the desired position. Using D'Alembert's principle the two torques are added to obtain the final required torque. This enables the gripper to maintain the grasp and also to follow the human motion.

### 4. Simulation and results

The dynamic equation of the object is given by:

\[
M\ddot{r} + H = WC_m
\]

(24)

where \( M \) is the inertia matrix of the object, \( H \) is the combined coriolies and gravity vector and \( r \) is the object position vector (the internal forces \( C_i \) does not produce any motion). Assuming that there is no relative motion between the fingertip and object during motion, we have the following kinematic constraint:

\[
\dot{x}_i = W^T T_r \dot{r}_o
\]

(25)

where \( x \) is the coordinate frame at the finger tip and \( T_r \) is the rotation transfer matrix. Differentiating equation (25) and combining with equation (21), substituting the result in equation (20) and then putting in equation (24), the combined finger-object dynamic equation is obtained:

\[
[M_o + W(J^T)^{-1}DJ^{-1}WM_r] \ddot{r}_o = W(J^T)^{-1}[\tau_s - B - DJ^{-1}(W^T \dot{r}_o - J\dot{\theta})]}
\]

(26)

where \( W^T \dot{r}_o \) is the time derivative. Using this equation for a desired trajectory and \( \tau_s \), the object acceleration is computed. The velocity and position of the object is computed by integrating the object acceleration \( \ddot{r}_o \). The coordinate system of the simulated object and finger system
is shown in Fig. 7. We assume that the robot and human cooperate in moving the object in one dimension only, in a straight line with no change in orientation of the object. This motion was simulated in order to compare the simulation results with the results of the two human experiments. The object was moved from (0.05, 0.144, 0) to (0.05, 0.108, 0) in 1.6 secs. The simulation force input was the force data recorded during the experiment between the two humans. Simulation was carried out following the control scheme shown in Fig. 6, at sampling intervals of 10 ms. The manipulated object was a polyhedron with six faces and all angles at right angles. Human impedance parameters as given in Table 1 were used for calculating the torque using equation (22). The simulated object and the robot finger parameters are given in Table 2. The fingers were assumed to be modeled perfectly and the contact point was soft finger type with no slip or sliding motion at the fingertip.

Fig. 7. The simulated object-finger system.

<table>
<thead>
<tr>
<th>Link</th>
<th>length (m)</th>
<th>mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0.005</td>
<td>0.1</td>
</tr>
<tr>
<td>object</td>
<td>0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Fig. 8 shows that the result of the robot human simulation was very close to the motion of two humans during the cooperation experiment. Fig. 9 shows the position errors as compared to the desired two humans’ trajectory. The main reason for the errors was that the impedance parameters in the simulation were varied based on the average velocity, while humans move objects by continuously varying the impedance parameters of their fingers. In order to reduce the error the impedance parameters should be actively varied based on smaller velocity ranges.

5. Conclusion

A two-finger gripper with ten actuators has been proposed for cooperation with humans. The gripper has only two fingers and its control is simpler than the three-fingered hand. The human characteristics have been embedded in the control system so that the gripper is human friendly. The simulation proves that the motion produced by the gripper is similar to human motion. This gripper has the potential for application in future robots used in helping the aged and disabled persons in rehabilitation applications. When a person is assisted by the proposed gripper he would feel that another person is
assisting him. This means that the proposed control scheme can be a key for future assistive technology.

Although the experiments were conducted in one dimension it is proved that in a two human cooperation task, an impedance model can approximate the followers motion. Also, it shows the validity of using shear force for controlling robot human cooperation. In order to manipulate an object in 3D the impedance parameters of humans will have to be experimentally obtained for 3D cases. This would be quite difficult since humans fingers range of motion is very small and they cannot move freely in 3D, also shear force sensors for measuring forces in 3D are still in the research stage.

References