Precision Grasping of a Prosthetic Hand Based on Virtual Spring Damper Hypothesis

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Abstract—A control strategy for achieving object precision grasping by a prosthetic hand is proposed. The control strategy is based on defining virtual spring-damper between two finger tips and damping force at each finger joint. It is shown that the proposed control strategy provides a satisfactory performance in precision grasping of a prosthetic hand, without the need for additional complexity regarding equations for inverse kinematics, or inverse dynamics, and the information on tactile or force sensing or even object shape.

I. INTRODUCTION

HUMAN hand is one of the most important and complex parts of the body, which has the ability to handle different tasks. Loss of hand can highly affect the quality of life; hence there is a high demand among amputees for prosthetic hands. The goal is to design an anthropomorphic prosthetic hand which is capable to be controlled through mind and has functionality close to normal human hand. The muscle movements in humans are controlled by electromyographic (EMG) signal which comes from brain to the body. In case of a lower hand amputee the remaining part of muscles are capable to measure EMG and through it find the subject’s intention.

Grasping can be categorized into two main groups: precision and power grasping. In precision grasping the object is held by tips of the fingers, while in power grasping, the whole finger is active and in contact with the object [1]. Our previous work [2] addressed the problem of power grasping and here we study the problem of precision grasping of a prosthetic hand.

Many control methods require the knowledge of the shape of the object. For humans this information is available by visual feedback from eyes, while in case of a prosthetic hand this visual information is not directly available for hand controller, and the only available information is electromyographic (EMG) signal related to patient’s arm muscle activities. However, normally the EMG signal is not available for all individual joints and besides, due to measurement noise, accessing high quality EMG signal is hard [3]. Moreover, using EMG signal to control all the movements requires lot of attention during grasping and leads to fatigue for the amputees [4]. Hence it is required for prosthetic hand to be semi-autonomous which means a part of command information will be provided by the EMG signal and the rest of the required command should be provided automatically by hand controller.

Defining finger trajectory without the knowledge of shape of object to be grasped is a challenging task for many path planning techniques. For multi DOFs robots there are two common methods for trajectory planning which are “inverse kinematics” and “inverse dynamics” [5]-[7]. Both these methods require object shape and are based on solving optimization problem which requires high computation, hence they are hard to implement for real-time applications.

To avoid solving the path planning problem for prosthetic hands, many researchers advocated under-actuated mechanisms, which are capable of adapting to object shape mechanically and without additional computation [8]-[10]. In these mechanisms, the number of actuators is less than the DOFs, and because of less number of actuators they have less weight. However fewer actuators result in less functionality, because fingers joints can’t move independently.

Arimoto et al. [11] used “virtual spring-damper hypothesis” for control of robotic arm-hand systems. A similar method called “virtual model control” is also suggested by J.Pratt et al. [12] used for walking robots, and it is based on defining virtual forces between two points. Both methods are based on the use of Jacobian matrix to relate task space movement to joint space. In [12] it is shown that any kind of force can be defined between two points and the other study [11] shows that use of spring-damper forces will result in human like movement. From physiological point of view, human skilled multi-joint reaching movement has these characteristics: 1) endpoint trajectory become a quasi-straight line and less variable, 2)velocity profiles of the endpoint has a bell-shape, and 3) joint trajectories are rather variable from trial to trial [11].

In this paper, a new control scheme is proposed that can efficiently address the problem of precision grasping without complete knowledge of the shape of the object which may be called “blind precision grasping” for prosthetic hand. The proposed method is based on the works by Arimoto et al. [11] using virtual spring-damper (VSD) hypothesis for control of robotic arm-hand systems. In our paper, we use the above mentioned hypothesis, in particular for the precision grasping of a prosthetic hand. In this method, we define a virtual spring-damper between finger tip and desired point for control of movement of fingers. Further, in this method there is no need to introduce any performance indices to solve inverse kinematics uniquely.

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and Jacobian pseudo-inverse or inverse dynamics which are common methods to define trajectories of redundant DOFs robots. Besides, in the present method, there is no need for any information on tactile or force sensing.

The paper is organized as follows. In Section 2 modeling of prosthetic hand is discussed, Section 3 covers virtual spring damper method. Section 4 describes control strategy. Section 5 analyzes the efficiency of the proposed control scheme using numerical simulation. Finally, conclusion and discussion are presented in section 6.

II. MODELING OF PROSTHETIC HAND

In this control method, controller is not designed based on dynamic model of the system. Instead, kinematics equation and Jacobian matrix are used for controller design.

A model of a robotic hand system is shown in Fig.1. The model consists of a finger with 3DOF which represents three joints of index finger, palm and a finger with 2DOF which represents thumb.

![Fig. 1. Schematic of a robotic hand system](image)

In this paper we assume the following:

1) Movement of both finger and object are confined to a 2 dimensional horizontal plane, and therefore there is no gravity effect.

2) The object is assumed to be initially stable in its position.

3) The initial movement toward object is handled by amputee, so the hand is close enough to the object before grasping.

The position of the tip of index fingers is evaluated as (see Fig. 1):

\[
x_i = l_{i1} \cos q_{i1} + l_{i2} \cos(q_{i1} + q_{i2}) + l_{i3} \cos(q_{i1} + q_{i2} + q_{i3}),
\]

\[
y_i = l_{i1} \sin q_{i1} + l_{i2} \sin(q_{i1} + q_{i2}) + l_{i3} \sin(q_{i1} + q_{i2} + q_{i3}),
\]

(1)

(2)

where, \(l_{i1}, l_{i2}, l_{i3}\) are lengths of index finger and \(q_{i1}, q_{i2}, q_{i3}\) are angles of each corresponding joint. Similarly the position of thumb finger is evaluated as:

\[
x_t = l_{t1} \cos q_{t1} + l_{t2} \cos(q_{t1} + q_{t2}),
\]

\[
y_t = l_{t1} \sin q_{t1} + l_{t2} \sin(q_{t1} + q_{t2}).
\]

(3)

(4)

where, \(l_{t1}, l_{t2}\) are lengths of thumb finger and \(q_{t1}\) and \(q_{t2}\) are angles of corresponding joints.

Based on above equation the Jacobian matrix for index finger is as:

\[
J_i = \begin{bmatrix}
\frac{\partial x}{\partial q_{i1}} & \frac{\partial x}{\partial q_{i2}} & \frac{\partial x}{\partial q_{i3}} \\
\frac{\partial y}{\partial q_{i1}} & \frac{\partial y}{\partial q_{i2}} & \frac{\partial y}{\partial q_{i3}} \\
\frac{\partial \theta}{\partial q_{i1}} & \frac{\partial \theta}{\partial q_{i2}} & \frac{\partial \theta}{\partial q_{i3}}
\end{bmatrix},
\]

(5)

and Jacobian for thumb finger is as:

\[
J_t = \begin{bmatrix}
\frac{\partial x}{\partial q_{t1}} & \frac{\partial x}{\partial q_{t2}} \\
\frac{\partial y}{\partial q_{t1}} & \frac{\partial y}{\partial q_{t2}} \\
\frac{\partial \theta}{\partial q_{t1}} & \frac{\partial \theta}{\partial q_{t2}}
\end{bmatrix}.
\]

(6)

III. VIRTUAL SPRING DAMPER METHOD

Virtual model control was first proposed by J. Pratt et al [12] for biped walking robot. This method is a motion control scheme that uses simulations of virtual components to generate desired joint torques [12]. These joints produce the same effect that the virtual elements placed on robot would have created; hence they create the illusion that these virtual elements are connected to the real robot. Virtual elements can be any kind of real physical elements such as springs, dampers, gravity fields, nonlinear fields or any other components. In a study by Arimoto [11] on robotic hand arm system, it is shown that using a virtual spring damper between robot end effector and desired point, and virtual dampers at each joint, human like movement can be achieved.

For precision grasping by a prosthetic hand, one of the best options is the use of Virtual Spring-Damper (VSD) hypothesis. Some benefits of VSD control scheme are that it has a simple structure and requires relatively less computation. Besides, it doesn’t need inverse dynamics to precisely define the robot movement. Thus, we use spring set points instead of commanded movement and robot automatically adapts its shape. Since finger joints at prosthetic hand work as virtual dampers, which is sensitive to velocity and not to position, they don’t have a forced shape, instead just finger tip follow a defined path as will be discussed more in control strategy section.

The joint torques to virtual forces is given by:

\[
\tau = J^T F,
\]

(7)

where \(\tau\) is the torque, and \(F\) is the force due to virtual spring damper given as

\[
F = -(\xi \sqrt{k} \ddot{x} + k \Delta x),
\]

(8)

and

\[
\tau_{spring-damper} = -J^T (\xi \sqrt{k} \ddot{x} + k \Delta x),
\]

(9)

where \(k\) represents the stiffness of the virtual spring, \(\Delta x\) is distance between finger tip and desired point, and \(\xi\) is the damping ratio. The damping force is defined at each joint as
\[ \tau_{\text{joints damping}} = -C \dot{q}, \quad (10) \]

where, \( C \) denotes a diagonal positive definite matrix as follows:

\[ C = \xi_0 \, \text{diag}(c_1, \ldots, c_n). \quad (11) \]

Hence control signal would be sum of these two terms:

\[ u = -C \dot{q} - f^T(q)(\xi \sqrt{k} \Delta x + k \Delta x). \quad (12) \]

IV. CONTROL STRATEGY

Virtual spring-damper hypothesis is suitable for point to point control. In precision grasping two approaches can be considered. 1) Defining a virtual spring damper between fingers tip and geometrical center of the object, which requires information about the object position and shape, and this information is not available in case of a prosthetic hand for the controller which is used in [13] 2) Defining a virtual spring damper between tips of two fingers, then fingers attract together and grasp the object in between, without exact knowledge of object position and shape. In this case the amputee should place the hand close to the object and in appropriate position. Besides, a virtual damper force is considered at each finger joint. The latter method is used and physical counterpart of virtual forces are depicted at Fig. 2.

Higher values of \( k \) (virtual spring stiffness) results in faster movement of fingers as well as, higher grasping force. Thus by defining \( k \) proportional to EMG signal, amputee have control over speed of movement and grasping force. The damping coefficient of finger joints, can change the final shape of fingers. The joints with lower damping tends to move more, while higher damped joints move more. The appropriate values of damping are evaluated based on trial and error to reach positions close to normal hand and they are held constant for further simulations.

V. NUMERICAL SIMULATION

In order to show the effectiveness of the proposed control strategy, numerical simulations were conducted to grasp two different objects, based on the physical parameters of a hand system and objects summarized in Table I.

The Adams software which is multi-body dynamic simulation software is used for numerical analysis. The software is capable to conduct information between Matlab/Simulink software environment, hence the plant is modeled by Adams and controller is implemented in Matlab/Simulink.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>index finger link 1 length</td>
<td>5 cm</td>
</tr>
<tr>
<td>index finger link 2 length</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>index finger link 3 length</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>thumb finger link 1 length</td>
<td>4 cm</td>
</tr>
<tr>
<td>thumb finger link 2 length</td>
<td>3 cm</td>
</tr>
<tr>
<td>distance between thumb and index</td>
<td>6 cm</td>
</tr>
<tr>
<td>damping at joints</td>
<td>0.01 kg/s</td>
</tr>
<tr>
<td>virtual damping ratio</td>
<td>1</td>
</tr>
<tr>
<td>virtual spring stiffness</td>
<td>50 N/m</td>
</tr>
<tr>
<td>rectangular object width</td>
<td>2 cm</td>
</tr>
<tr>
<td>circular object radius</td>
<td>2 cm</td>
</tr>
</tbody>
</table>

The Adams software which is multi-body dynamic simulation software is used for numerical analysis. The software is capable to conduct information between Matlab/Simulink software environment, hence the plant is modeled by Adams and controller is implemented in Matlab/Simulink.

For first simulation, two fingers are modeled without any object in between. As shown in Fig. 3, two fingers come together, and final position is close to normal hand coordination.

For the second simulation, a rectangular object is chosen to be grasped. The object is free to move in 2 dimensional plane, and contact and friction force are simulated between finger tip and the object. The object is placed at arbitrary final position of previous experiment. The finger movement at 0.25 sec time intervals and finger tip angles relative to palm are shown respectively in Figs. 4 and 5.
VI. CONCLUSION

Based on virtual spring damper hypothesis, a control strategy for precision grasping of a prosthetic hand was proposed. The controller doesn’t require extensive computation of inverse kinematic or inverse dynamics to describe finger movement and hence the method is appropriate for real-time applications. The control strategy is independent of object shape or force and contact sensor. By numerical simulation, the capability and effectiveness of control strategy are shown. The same strategy was used for two different objects and grasping was successful.

The future work will focus on precision grasping by gravity cancelation and analysis in three-dimensional space and experimental implementation with EMG signals.

REFERENCES