

Multifingered Robot Hands: Control for Grasping and Manipulation

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Abstract

Robot hands have been one of the major research topics since the beginning of robotics because grasping and manipulation of a variety of objects by robot hands are fundamental functionalities of various robotic systems. This paper presents a survey on the current state of research on control of grasping and manipulation by multifingered robot hands. After a brief history of the hardware development of multifingered robot hands, representative theoretical research results are presented in the area of grasping and manipulation. Regarding grasping, basic analytical concepts including force/form closures and active/passive closures are explained and various grasp quality measures for grasping position optimization are introduced. Regarding manipulation, the hybrid position/force control method and impedance control method are presented. Some of our recent results on grasping and manipulation by a soft-fingered hand are also presented. Finally, some future research directions are discussed.

Keywords: Multifingered robot hand, Grasping, Manipulation, Impedance control, Hybrid control, Soft-fingered hand

1. Introduction

Grasping and manipulation of various objects by robot hands are fundamental functionalities for many robotic systems, including humanoid robots, industrial robots, and wheel-type mobile robots, to be useful in a variety of environments, such as home, public buildings, city area, factory, space, sea, and so on.

Motor function of humans may be considered as consisting of their two main abilities: walking ability by feet and grasping and manipulation ability by hands. Much research has been done for realizing these abilities by robotic mechanisms. At first, robot hands were more actively studied than robot feet and it was thought that robot hands were more advanced than robot feet. However, after successful development of humanoid walking robots by Honda in 1996 (Hirai, Hirose, & Takenaka, 1998) and by some other research groups after that (for example, Sakagami et al. (2002), Kaneko et al. (2004), Ishida (2004), and Gouaillier et al. (2009)), walking ability of robots has advanced so quickly that I now feel that development of robot hands for performing various skillful grasping and manipulation tasks turned out to be more urgent and critical issue for realizing useful humanoid robots that can really help people.

This paper presents a survey of research on control of grasping and manipulation by multifingered robot hands, giving physical meanings of the achieved results as much as possible. First, a brief history of the hardware development of multifingered robot hands is presented. Then representative theoretical research results are presented in the area of grasping and manipulation. Regarding grasping, several analytical concepts including force/form closures and active/passive closures are explained and various grasp quality measures for grasping

position optimization are introduced. Regarding manipulation, the hybrid position/force control method and impedance control method are presented. Some of our recent results in grasping unknown objects and manipulating various objects by robot hands with soft fingers are also presented. Finally, some future research directions are discussed.

2. Multifingered mechanical hands

Many experimental multifingered mechanical hands have been developed in the last 45 years or so. After several preliminary mechanical hands, robotic hands with multi-articulated fingers with computer control have been developed. Representative examples are three-fingered Okada-Hand (1979) (Okada, 1979), three-fingered Stanford/JPL hand (1981) (Mason & Salisbury, 1985), and three-fingered Utah/MIT hand (1984) (Jacobsen et al., 1986). All of these hands use long tendon cables that connect the hand joints to their drive units placed in a large separate box.

Then around 2000 several new hands were developed: four-fingered DLR hand (2000) (Hirzinger et al., 2000), five-fingered Robonaut Hand (1999) (Lovchik & Diftler, 1999), and five-fingered Gifu Hand (2002) (Kawasaki, Komatsu, & Uchiyama, 2002). All these hands do not use tendon cables but use some mechanical linkages such as lead screws and differential bevel gears. The drive mechanisms are integrated into the hand itself or contained in the forearm. They are equipped with various sensors. The size of these hands is still a little larger than human hands.

More recently, small size hands that could be used for humanoid robots have been developed, such as Universal-Hand

(2005) (Hoshino & Kawabuchi, 2005) and Shadow Dexterous Hand (2007) (SHADOW, 2010). These hands have five fingers and are of human size. They were developed by private companies. One interesting feature is that both of them have 5 degrees-of-freedom thumb showing the designer's view on the importance of the thumb. Another small size five-fingered hand called DLR/HIT Hand II has also been developed (Liu et al., 2008).

The latest development is that two hands have been developed with the purpose of actually mounting them on humanoid robots. One is the hand for HRP3P (2007) (Kaneko, Harada, & Kanehiro, 2007) and the other is the hand of TWENDY-ONE Robot (2009) (Iwata & Sugano, 2009). Both hands have four fingers. An interesting feature of the latter hand is that the whole surface is covered by soft skin.

From these developments, it can be said that the size and mechanical functionality of robotic hands are now coming very close to human hand. Experimental realizations of several specific manipulation tasks by using these hands have also been reported. However, the control algorithms for these tasks seem to be rather task specific. More general framework of planning and control will be necessary for performing wider class of grasping and manipulation tasks.

3. Grasping

Between the two major closely related functionalities of grasping and manipulation of robot hands, grasping is usually a prerequisite for the other function of manipulation. Researches on grasping, with emphasis on grasp analysis and grasp planning, will be surveyed in this section.

3.1. Analysis and synthesis of grasp

Fig.1 shows a basic situation where a hand with n three-jointed fingers is grasping an object in three-dimensional space. Various analytical studies have been done extensively for this or some more general situations. Among basic concepts developed are grasp map (or grasp matrix), hand Jacobian, form and force closure grasps, and active and passive closures.

Consider the case where the fingertips and the object is making a point contact with friction, that is, finger i can exert a fingertip force $f_{Ci} \in R^3$ (three-dimensional vector) on the object, but not moment, within the friction cone at the contact

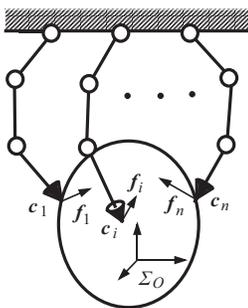


Figure 1: Multifingered hand grasping an object.

point c_i). Then Grasp matrix (Murray, Li, & Sastry, 1994) is the matrix G transforming the contact forces at the fingertips $f_C = [f_{C1}^T \ f_{C2}^T \ \dots \ f_{Cn}^T]^T$ to the resultant force/moment vector $t_B \in R^6$ working on the object (f_{Ci} and t_B are both expressed in the object coordinate frame Σ_O):

$$t_B = G f_C \quad (1)$$

This means, due to the principle of virtual work, that the relation $v_C = G^T v_B$ holds between the contact point velocity v_C and the object velocity v_B . Hand Jacobian (Murray, Li, & Sastry, 1994) is the matrix relating the finger joint velocity $\dot{q} = [\dot{q}_1^T \ \dot{q}_2^T \ \dots \ \dot{q}_n^T]^T \in R^{3n}$ to the fingertip velocities $v_F \in R^{3n}$, that is, $v_F = J \dot{q}$. If there is no slippage or contact break between the fingertips and the object, then $v_C = v_F$. Hence the following relation should hold.

$$J \dot{q} = G^T v_B \quad (2)$$

One of the basic requirements for robot hand is to grasp and manipulate objects firmly without slippage or break of contact. Regarding this, the concepts of force and form closures (Mason & Salisbury, 1985) and passive and active closures (Yoshikawa, 1999a) have been developed. These concepts will be explained below by some examples in the two-dimensional plane. The rectangular object in Fig.2 (a) is completely constrained by the four constraining limbs through four frictionless point contacts (represented by white arrows). Even when a translational force in X or Y direction or a moment around Θ axis is applied to this object, the object does not move just by the structure of the constraining mechanism. This is called a passive form closure. Note that the constraining limbs cannot move the object actively and the force does not play any explicit role. (b) is the case where the object is constrained by two frictional point contacts (represented by black arrows). By applying certain fixed pushing force from the right by the prismatic motored joint, any external force smaller than the pushing force is automatically balanced by a reaction force from the constraining mechanism and the object does not move. This is called a passive force closure because the force plays an essential role in fixing the object. (c) is the case of robot fingers with two rotational motored joints in each finger. By applying appropriate joint torques, arbitrary contact forces, and hence arbitrary resultant force and

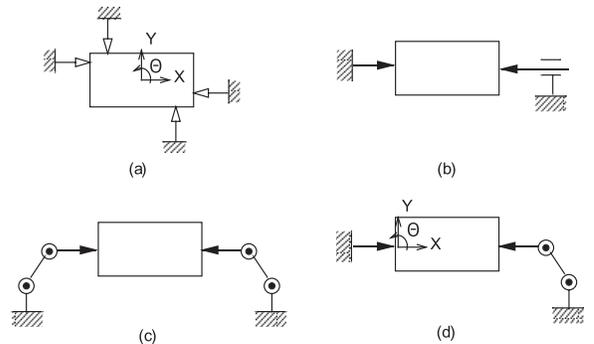


Figure 2: Various closures in case of plane motion. (a) Passive form closure. (b) Passive force closure. (c) Active closure. (d) Hybrid active/passive closure.

moment, can be exerted on the object, meaning that the fingers can move the object in arbitrary direction. This grasp is called an active closure. Finally, (d) is a hybrid active/passive closure where the direction of active closure (around the Θ axis) and those of passive closure (X and Y directions) exist together.

In Xu et al. (2007) the concept of active force closure was applied to the grasping force analysis and optimization of the whole hand grasp. In Liu & Wang (2009) the passive force closure condition was studied to understand the essential characteristics of the passive grasping such as the whole-arm grasping and manufacturing fixture.

Next problem is how to determine the grasp position for a given object by a multifingered robot hand in terms of the quality of grasp. This is a fundamental problem which has not yet been solved satisfactorily. Many grasp quality measures have been proposed for grasp optimization. In Kirkpatrick, Mishra, & Yap (1990) and Ferrari & Canny (1992), two general grasp measures were introduced: they are radii of the largest balls, centered at the origin of the wrench space, contained in the set of all possible wrenches that can be resisted by applying allowable finger forces along the normal of the object surface, denoted as $f_{C_i}^\perp$, under two kinds of magnitude constraints on the fingertip forces; $\max\{\|f_{C_i}^\perp\|\} \leq 1$ and $\sum_{i=1}^n \|f_{C_i}^\perp\| \leq 1$. In Miller & Allen (2000) a simulator for grasp analysis, called GraspIt, was developed and the second grasp measure of Ferrari & Canny (1992) (under the constraint of $\sum_{i=1}^n \|f_{C_i}^\perp\| \leq 1$) and the volume of the set of all resistible wrenches were adopted for evaluation of grasps.

Some quality measures were also proposed that take into account the manipulation task assigned to the hand and the disturbance force that might happen. A task-directed quality measure was proposed in Li & Sastry (1988) based on the concept of task ellipsoid which represents the set of all wrenches needed to perform a given task. A quality measure which takes into account the object shape was proposed in Pollard (1994) based on the object wrench set consisting of wrenches caused by all possible disturbing force distributions on the object surface. Based on a similar idea, Strandberg & Wahlberg (2006) formulated the grasp evaluation problem as a min-max optimization problem and proposed an efficient computation algorithm. In Watanabe & Yoshikawa (2007) a method of grasp optimization using the concept of required external force set was proposed.

Most of the grasp quality measures mentioned above are given in terms of fingertip forces. When some manipulation is expected after grasping, it is desirable to consider other factors such as manipulating ability and workspace. However, researches that consider these factors in an integrated and physically clear manner are rather scarce. In Park & Starr (1992) a heuristic criterion was proposed for grasp of polygonal objects using a three-fingered hand. The criterion is not directly related to the forces, but is given by a weighted sum of five terms: the arrangement of force directions, distribution of grasp points, grasp location with respect to the centroid of polygon, number of convex vertexes, and number of grasp points located near the end of the edge. The weighting factors were selected based on the best grasps selected by human's heuristic intuition for several sample objects.

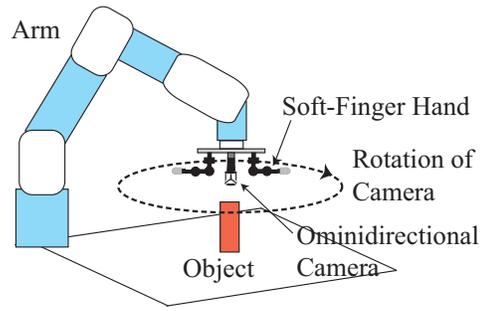


Figure 3: Robotic hand system.

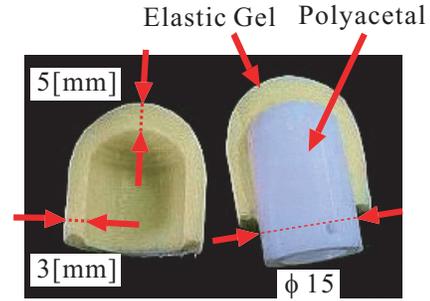


Figure 4: Inner structure of soft fingertip.

3.2. Grasping by soft fingers

Most of the above studies on grasping are for rigid fingers which make point contacts with rigid grasped objects. However, rigid fingers sometimes have stability and versatility problem in practical applications. Partly because of this, hands with deformable soft fingers have also drawn much attention (for example, Akella & Cutkosky (1989), Sinha & Abel (1992), Shimoga & Goldenberg (1996), Xydas & Kao (1999), Arimoto et al. (2000), Murakami & Hasegawa (2003), Biagiotti et al. (2005), Yoshida, Arimoto, & Luo (2008), and Yamazaki, Inoue, & Hirai (2009)). However, analytical studies so far are limited to rather simple cases (mostly to two dimensional motion). One main reason for this will be that, in order to advance analytical studies of soft fingers, we need to take into consideration the deformation of the soft skin, but making a proper model of this deformation is very difficult. In spite of this difficulty, however, it is expected that hands with soft skin or, in more general, robots with its whole body covered by soft skin will be developed in the future, at least for humanoid robots.

We have proposed a method of shape recognition and optimal grasping of unknown planar objects (Yoshikawa, Koeda, & Fujimoto (2008), Sugiyama et al. (2009)) for a robotic hand system consisting of a hand with two soft-fingers, an arm, and an omnidirectional camera attached to the hand (Fig.3). The fingertips are round and covered by soft skin made of elastic gel as shown in Fig.4.

For shape recognition, we move the camera attached to the hand around the object horizontally keeping the height of the camera constant and take images of the object from different directions. Then by applying a two-dimensional version of the

volume intersection method (Laurentini, 1994), we obtain the visual hull in the horizontal plane, which corresponds to the horizontal cross section of the object.

For grasping we propose the following simple grasp quality criterion to obtain the best grasping position.

$$J(\mathbf{c}_1, \mathbf{c}_2) = k_p J_p(\mathbf{c}_1, \mathbf{c}_2) + k_\alpha J_\alpha(\mathbf{c}_1, \mathbf{c}_2) \quad (3)$$

where \mathbf{c}_1 and \mathbf{c}_2 are a pair of candidate contact points on the object surface (see Fig. 5). The first term $J_p(\mathbf{c}_1, \mathbf{c}_2)$ is for evaluating the global location of the contact points. The second term $J_\alpha(\mathbf{c}_1, \mathbf{c}_2)$ is for evaluating the angle α_i between the surface normal of the object and the grasp force direction at the contact point \mathbf{c}_i . k_p and k_α are weighting coefficients.

The first term is given by

$$J_p(\mathbf{c}_1, \mathbf{c}_2) = k_a d_a / d_{amax} + k_b d_b / d_{bmax} \quad (4)$$

This term J_p means that the distance between the contact points, d_a , should be small and the distance between the geometrical center of the object and the grasp line connecting the two contact points, d_b , should also be small, reflecting the intuitive judgement that the manipulating ability and the workspace of the hand is larger when d_a is smaller, and that the weight balance of the object under the gravitational force will be better when d_b is smaller. d_{amax} and d_{bmax} are constants for normalizing these distances.

The second term is given by

$$J_\alpha(\mathbf{c}_1, \mathbf{c}_2) = \max(|\alpha_1|, |\alpha_2|) / \alpha_{max} \quad (5)$$

where α_i is the angle between the surface normal of the object and the grasp force direction at the contact point \mathbf{c}_i . Hence this term means that the grasping force direction should be close to the surface normal so that the slippage will not occur. The angle α_i is obvious in the case of smooth surface but in the case of corners we need a little more consideration about its definition. One merit of soft fingers is that they can grasp an object not only at smooth surfaces but also at corners due to the deformation of the finger surface. Taking this into consideration, we define the angle α_i at corners of the object as follows. We first denote the angle from the normal vector on the right side surface of the corner to the grasp force direction as α_{ir} and that on the left side surface as α_{il} . We then define α_i as the minimum absolute value in the interval $[\alpha_{ir}, \alpha_{il}]$. For instance, the value of α_1 in the case of Fig. 6(a) is 0 and that in the case of Fig. 6(b) is $|\alpha_{il}|$. This corresponds to the fact that the grasp in case (a) is easier than the grasp in case (b).

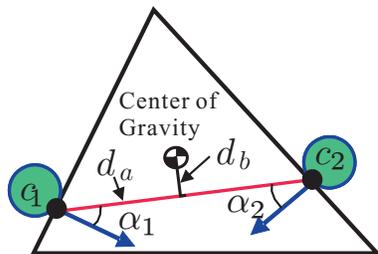


Figure 5: Parameters of grasp quality criterion.

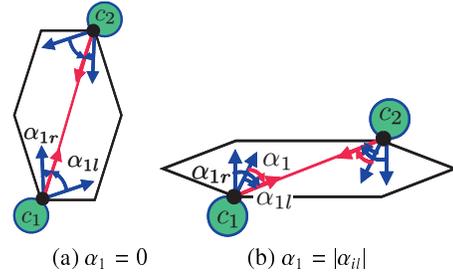


Figure 6: Angle α_i for corners.

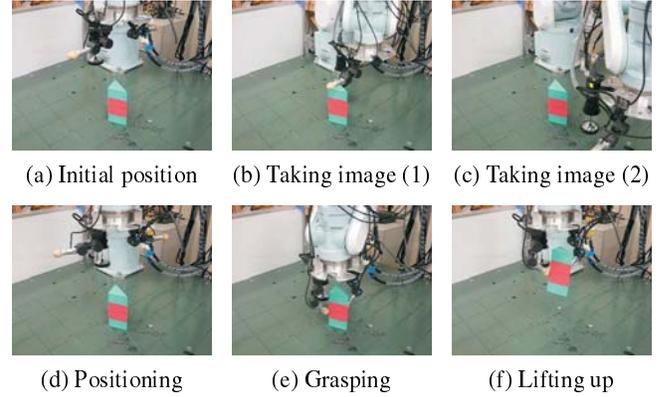


Figure 7: Grasping a triangular prism.

We have performed experiments of grasping prisms with various cross sections. Fig.7 shows the case of a triangular prism. As can be seen from the figure, the prism was grasped successfully at an intuitively proper grasp position including one corner as a contact point.

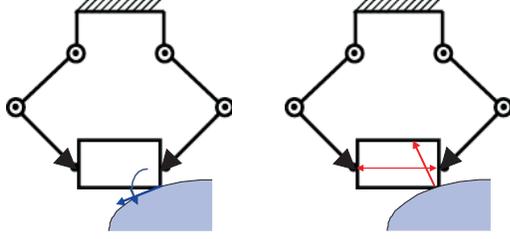
The proposed criterion given by (3), (4), and (5) is still very intuitive. We will need to make clear for which object classes this criterion works well. We are studying the relation between the criterion (3) and the measured grasp positions by human hands (Sugiyama et al., 2009). A criterion with physically clearer meaning and at the same time with not so large computational load for real-time use is desirable.

4. Manipulation

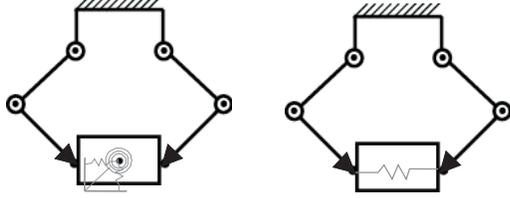
4.1. Control synthesis for manipulation

Various control algorithms for multifingered robot hands for grasping and manipulation with fixed, rolling, and sliding contacts have been proposed. They can roughly be divided into two groups. One is hybrid position/force control (including the so-called computed torque control) (see Li, Hsu, & Sasstry (1989) and Yoshikawa & Zheng (1993)) and the other is impedance control (see Mason & Salisbury (1985), Schneider & Cannon (1992), Liu & Hirzinger (1999), and Wimböck, Otto, & Hirzinger (2008)).

Hybrid control method (Raibert & Craig (1981), Yoshikawa (1987), Yoshikawa, Sugie, & Tanaka (1988)) controls simultaneously the force in some directions and the position in other directions. Fig.8 illustrates the method schematically for the



(a) Position control directions (b) Force control directions
Figure 8: Hybrid control method.



(a) Object impedance (b) Impedance between fingers
Figure 9: Impedance control method.

case of multifingered hand control where the grasped object is in contact with a fixed object in the environment. The arrows in (a) show the position control directions and those in (b) the force control directions.

Impedance control method (Hogan, 1985) controls the force indirectly through specification of the mechanical impedance of the grasped object against external forces. Fig.9(a) illustrates the method schematically for the case of multifingered hand control. The object is attached to a reference frame through virtual translational and rotational springs (impedance elements). Fig.9(b) will be referred to in 4.3. The formulation and control algorithms of these control methods will be described in the following subsections.

First the dynamics equations of the grasped object and the hand will be given. When discussing the control problem it is more convenient to express the orientation of the object by a set of 3 angles, $\phi = [\phi \ \theta \ \psi]^T$ (ϕ , θ , and ψ are roll, pitch, and yaw angles taken in the order of X axis, Y axis and then Z axis) instead of the rotation matrix. Then the position and orientation of the object can be expressed by a 6-dimensional vector $\mathbf{r}_O = [\mathbf{p}_B^T \ \phi^T]^T$ and the velocity of the object by its time derivative $\dot{\mathbf{r}}_O$. The relation between $\dot{\mathbf{r}}_O$ and the original object velocity representation using angular velocity vector $\boldsymbol{\omega}_B$, $\mathbf{v}_B = [\dot{\mathbf{p}}_B^T \ \boldsymbol{\omega}_B^T]^T$, is given by $\mathbf{v}_B = \mathbf{T}(\mathbf{r}_O)\dot{\mathbf{r}}_O$ where $\mathbf{T}(\mathbf{r}_O)$ is given by

$$\mathbf{T}(\mathbf{r}_O) = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0} \\ \mathbf{0} & \mathbf{T}_r \end{bmatrix}, \quad \mathbf{T}_r = \begin{bmatrix} 1 & 0 & \sin \theta \\ 0 & \cos \phi & -\sin \phi \cos \theta \\ 0 & \sin \phi & \cos \phi \cos \theta \end{bmatrix} \quad (6)$$

and \mathbf{I}_3 is the 3-dimensional unit matrix. Furthermore, the generalized force \mathbf{t}_O corresponding to the generalized position \mathbf{r}_O is given by $\mathbf{t}_O = \mathbf{T}^T \mathbf{t}_B$. Note that when $\phi \cong \mathbf{0}$, we have $\mathbf{T}(\mathbf{r}_O) \cong \mathbf{I}_6$, $\mathbf{v}_B \cong \dot{\mathbf{r}}_O$, and $\mathbf{t}_B \cong \mathbf{t}_O$.

Using the notations \mathbf{r}_O and \mathbf{t}_O , we assume that the object

dynamics is given by

$$\mathbf{M}_O \ddot{\mathbf{r}}_O + \mathbf{h}_O(\mathbf{r}_O, \dot{\mathbf{r}}_O) + \mathbf{g}_O(\mathbf{r}_O) = \mathbf{t}_O + \mathbf{t}_E \quad (7)$$

where \mathbf{M}_O is the inertia matrix of the object, \mathbf{h}_O is the centrifugal and Coriolis forces, \mathbf{g}_O is the gravitational force, \mathbf{t}_O is the resultant force applied by the fingers, \mathbf{t}_E is the other possible external force working on the object. We also assume that the dynamics of finger i is given by

$$\mathbf{M}_{Fi}(\mathbf{q}_i) \ddot{\mathbf{q}}_i + \mathbf{h}_{Fi}(\mathbf{q}_i, \dot{\mathbf{q}}_i) + \mathbf{g}_{Fi}(\mathbf{q}_i) = \boldsymbol{\tau}_i - \mathbf{J}_i^T \mathbf{f}_C \quad (8)$$

where $\boldsymbol{\tau}_i$ is the joint driving force. Putting all the fingers together we have

$$\mathbf{M}_F(\mathbf{q}) \ddot{\mathbf{q}} + \mathbf{h}_F(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}_F(\mathbf{q}) = \boldsymbol{\tau} - \mathbf{J}^T \mathbf{f}_C \quad (9)$$

We consider the case where each finger has 3 degrees of freedom and the hand/object system forms an active closure. We also assume that the contact points are fixed, that is, (1) and (2) holds.

From (1), we obtain a general solution

$$\mathbf{f}_C = \mathbf{G}^+ \mathbf{T}^{-T} \mathbf{t}_O + \mathbf{E} \tilde{\mathbf{f}} \quad (10)$$

where \mathbf{G}^+ denotes a pseudo-inverse of \mathbf{G} and \mathbf{E} is an arbitrary matrix of full column rank satisfying $\mathbf{G}\mathbf{E} = \mathbf{0}$. The first term on the right hand side of (10) produces the resultant force \mathbf{t}_O and the second term represents the internal grasping force which does not affect the object motion. Vector $\tilde{\mathbf{f}}$ is the parameter vector representing the magnitudes of internal force components in the direction of column vectors of \mathbf{E} .

4.2. Hybrid position/force control

We will first explain the hybrid position/force control approach (Yoshikawa, 2000) for the simple case of moving the grasped object in free space (that is, there is no constraining object in the environment in Fig.8 and $\mathbf{t}_E = \mathbf{0}$ in (7)). Note that even in this case the hybrid control approach is appropriate because it is necessary to control the grasping force to a desired value such that the friction condition is satisfied besides controlling the position of the object along a desired trajectory.

we can derive a dynamic hybrid position/force control algorithm using the two-stage approach (see Yoshikawa (1987), Yoshikawa, Sugie, & Tanaka (1988), and Yoshikawa (1990)). In the first stage, to linearize the nonlinear characteristics of the system, we consider the following linearizing control law with new control inputs \mathbf{u}_O and \mathbf{u}_I :

$$\boldsymbol{\tau}_d = \mathbf{M}_W \mathbf{T} \mathbf{u}_O + \mathbf{J}^T \mathbf{E} \mathbf{u}_I + \mathbf{Q} \quad (11)$$

where $\mathbf{M}_W = \mathbf{M}_F \mathbf{J}^{-1} \mathbf{G}^T + \mathbf{J}^T \mathbf{G}^+ \mathbf{T}^{-T} \mathbf{M}_O \mathbf{T}^{-1}$, $\mathbf{Q} = \mathbf{h}_F + \mathbf{g}_F + \mathbf{J}^T \mathbf{G}^+ \mathbf{T}^{-1} (\mathbf{h}_O + \mathbf{g}_O) + \mathbf{M}_F \mathbf{J}^{-1} \{ (\dot{\mathbf{G}}^T \mathbf{T} + \mathbf{G}^T \dot{\mathbf{T}}) \dot{\mathbf{r}}_O - \dot{\mathbf{J}} \dot{\mathbf{q}} \}$. By applying the control law (11) to the hand/object system, the closed loop system becomes linearized and decoupled:

$$\ddot{\mathbf{r}}_O = \mathbf{u}_O \quad (12)$$

$$\ddot{\tilde{\mathbf{f}}} = \mathbf{u}_I \quad (13)$$

The second stage is to determine the inputs \mathbf{u}_O and \mathbf{u}_I . This corresponds to designing servoing control laws for position and force feedback loops. Typical servoing control laws are

$$\mathbf{u}_O = \ddot{\mathbf{r}}_{Od} - \mathbf{K}_V(\dot{\mathbf{r}}_O - \dot{\mathbf{r}}_{Od}) - \mathbf{K}_P(\mathbf{r}_O - \mathbf{r}_{Od}) \quad (14)$$

$$\mathbf{u}_I = \tilde{\mathbf{f}}_d - \mathbf{K}_I \int (\tilde{\mathbf{f}} - \tilde{\mathbf{f}}_d) dt' \quad (15)$$

where \mathbf{K}_V , \mathbf{K}_P , and \mathbf{K}_I are constant feedback gain matrices and \mathbf{r}_{Od} and $\tilde{\mathbf{f}}_d$ are the desired position and force trajectories. Then the position and force errors $\mathbf{e}_p = \mathbf{r}_O - \mathbf{r}_{Od}$ and $\mathbf{e}_f = \tilde{\mathbf{f}} - \tilde{\mathbf{f}}_d$ satisfy the following error equations.

$$\ddot{\mathbf{e}}_p + \mathbf{K}_V \dot{\mathbf{e}}_p + \mathbf{K}_P \mathbf{e}_p = \mathbf{0}, \quad \dot{\mathbf{e}}_f + \mathbf{K}_I \mathbf{e}_f = \mathbf{0} \quad (16)$$

Therefore, we can make the position trajectory \mathbf{r}_O and force trajectory $\tilde{\mathbf{f}}$ converge asymptotically to the desired ones by selecting appropriate feedback gains \mathbf{K}_V , \mathbf{K}_P , and \mathbf{K}_I .

It can be shown that the joint control input $\boldsymbol{\tau}_d$ of (11) can be calculated by the following three steps.

- (i) Calculate the resultant force \mathbf{t}_O that asymptotically realizes the desired object motion \mathbf{r}_{Od} , using (14) and $\mathbf{t}_O = \mathbf{M}_O \mathbf{u}_O + \mathbf{h}_O + \mathbf{g}_O$.
- (ii) Determine the contact force \mathbf{f}_C that produces \mathbf{t}_O obtained in (i) and satisfies the friction condition at the contact points, using (10), (13), (15) and by adjusting the desired internal force parameter $\tilde{\mathbf{f}}_d$.
- (iii) Calculate the finger command torque $\boldsymbol{\tau}_d$ that produces \mathbf{f}_C obtained in (ii), using (9) and

$$\ddot{\mathbf{q}} = \mathbf{J}^{-1}[\mathbf{G}^T \mathbf{T} \mathbf{u}_O + (\mathbf{G}^T \dot{\mathbf{T}} + \dot{\mathbf{G}}^T \mathbf{T}) \dot{\mathbf{r}}_O - \mathbf{J} \dot{\mathbf{q}}]$$

which is derived from (2).

Note that the calculation in step (i) is for the object, that in step (ii) is for the contact points, and that in step (iii) is for the fingers. Furthermore, the calculation in step (iii) can be decomposed into that for each finger. Hence the calculation procedure is physically very clear.

Note also that when the object is in contact with some other object in the environment, the contact force between them can also be controlled in a similar way by the hybrid control approach (Yoshikawa & Zheng, 1993) by assuming that the constraint imposed by this contact can be described by a set of m hypersurfaces $p_i(\mathbf{r}_O) = 0, i = 1, 2, \dots, m$.

4.3. Impedance control

Next we will explain a typical impedance control approach that aims at realizing the following desired object impedance property.

$$\mathbf{M}_D \ddot{\mathbf{r}}_O + \mathbf{D}_D(\dot{\mathbf{r}}_O - \dot{\mathbf{r}}_{Or}) + \mathbf{K}_D(\mathbf{r}_O - \mathbf{r}_{Or}) = \mathbf{t}_E \quad (17)$$

where \mathbf{M}_D , \mathbf{D}_D , and \mathbf{K}_D are, respectively, the desired inertia, damping-coefficient, and stiffness matrix, all of which are symmetric and positive definite. \mathbf{r}_{Or} is the position of the reference

frame to which the desired impedance is attached to. A simple way of choosing \mathbf{M}_D , \mathbf{D}_D , and \mathbf{K}_D is to make them diagonal and to determine the diagonal elements in such a way that the impedance is made small in the force control directions so that the object can comply with constraints and can adjust the contact force properly, and it is made large in the position control direction so that the position error is corrected with high feedback gain.

Substituting (17) into (7), the resultant force \mathbf{t}_O needed to realize the desired object impedance property is given by

$$\mathbf{t}_O = (\mathbf{M}_O - \mathbf{M}_D) \ddot{\mathbf{r}}_O - \mathbf{D}_D(\dot{\mathbf{r}}_O - \dot{\mathbf{r}}_{Or}) - \mathbf{K}_D(\mathbf{r}_O - \mathbf{r}_{Or}) + \mathbf{h}_O + \mathbf{g}_O \quad (18)$$

The impedance control algorithm can be given by the three step procedure for hybrid control with the first step replaced by:

- (i') Calculate the resultant force \mathbf{t}_O that realizes the desired object impedance (17), using (18).

Note that we need to know the value of current acceleration $\ddot{\mathbf{r}}_O$ (or external force \mathbf{t}_E) to perform steps (i') and (iii). If we take the desired inertia \mathbf{M}_D to be the same as the real inertia of the object \mathbf{M}_O , then (18) reduces to

$$\mathbf{t}_O = -\mathbf{D}_D(\dot{\mathbf{r}}_O - \dot{\mathbf{r}}_{Or}) - \mathbf{K}_D(\mathbf{r}_O - \mathbf{r}_{Or}) + \mathbf{h}_O + \mathbf{g}_O \quad (19)$$

Hence we do not need the value of $\ddot{\mathbf{r}}_O$ in steps (i') and (ii), but we still need it in step (iii). There are several methods to overcome this difficulty in step (iii). A simplest way is to estimate the value $\ddot{\mathbf{r}}_O$ by assuming that $\mathbf{t}_E = \mathbf{0}$. Then the desired object impedance (17) is realized for the nominal case of zero external force. Another possibility is to measure \mathbf{f}_C by the fingertip force sensor and control it to the value obtained in step (ii) by adding a force control loop to the finger controller.

Extensions of the above object impedance control method in the direction of including virtual coupling springs (and dampers) between the object and the fingertips, or among the fingertips (see Fig.9(b)), have been proposed by Wimböck, Otto, & Hirzinger (2008).

4.4. Determination of internal force

To execute the control algorithms in the previous subsections, we need to find some $\tilde{\mathbf{f}}$ for which the contact force \mathbf{f}_C satisfies the friction condition in step (ii). Some discussion on this will be given in this subsection (Yoshikawa, 2000).

The friction condition in terms of $\tilde{\mathbf{f}}$ will first be derived. Under the assumption of Coulomb friction, the static friction condition is given by

$$\mathbf{n}_i^T \mathbf{f}_{Ci} \geq \eta_i \|\mathbf{f}_{Ci}\|, \quad i = 1, 2, \dots, n \quad (20)$$

where \mathbf{n}_i is the contact normal (directing into the object), $\eta_i = 1/\sqrt{1 + \mu_i^2}$, and μ_i is the static friction coefficient at c_i . The set of all \mathbf{f}_{Ci} satisfying (20) forms the friction cone. Note that (20) is equivalent to the following two conditions

$$\mathbf{n}_i^T \mathbf{f}_{Ci} \geq 0, \quad \mathbf{f}_{Ci}^T (\mathbf{n}_i \mathbf{n}_i^T - \eta_i \mathbf{I}_3) \mathbf{f}_{Ci} \geq 0 \quad (21)$$

Substituting (10) into (21), we obtain the friction condition in terms of $\tilde{\mathbf{f}}$ as follows.

$$\mathbf{n}_i^T (\mathbf{f}_{Ci} + \mathbf{E}_i \tilde{\mathbf{f}}) \geq 0 \quad (22)$$

$$(\mathbf{f}_{CPi} + \mathbf{E}_i \tilde{\mathbf{f}})^T (\mathbf{n}_i \mathbf{n}_i^T - \eta_i \mathbf{I}) (\mathbf{f}_{CPi} + \mathbf{E}_i \tilde{\mathbf{f}}) \geq 0 \quad (23)$$

We can determine a solution $\tilde{\mathbf{f}}$ that is optimal in some sense under the friction condition (22) and (23). For example, Nakamura, Nagai, & Yoshikawa (1989) gave an algorithm for minimizing the norm of the internal force by applying a nonlinear programming method. This solution can be used for determining the desired force $\tilde{\mathbf{f}}_d$ in (15). In Buss, Hashimoto, & Moore (1996) it was observed that friction force limit constraints and force balancing constraints are equivalent to the positive definiteness of a certain matrix subject to linear constraints. Based on this observation, the grasping force optimization was formulated as an optimization problem on the smooth manifold of linearly constrained positive definite matrices for which there are known globally exponentially convergent solutions via gradient flows.

In order to facilitate the analysis and synthesis of the internal force, some simple physical models have been proposed: The virtual linkage model was proposed in Williams & Khatib (1993) for multiple hand grasps. This model consists of linearly actuated members and spherically actuated joints. The virtual truss model was proposed in Yoshikawa (1999b) for multiple finger grasps. This model consists of skeletal line members connecting every pair of contact points, and each member is joined at its ends to other members by means of frictionless ball-and-socket joints. An application of this model for hand control was shown in Yoshikawa (2000).

4.5. Comparison of control methods

Comparing the two control methods, the hybrid control is generally better than impedance control in controlling the position and force precisely. However, the hybrid control needs to switch the control mode between the position and force control whenever the contact state changes between contact and non-contact with other objects in the environment. A small delay in changing the control mode may cause a large overshoot in positional response. The impedance control does not have this difficulty and stability is usually guaranteed. Also, the impedance control is better in that the stiffness and damping properties against external forces can be specified which may be advantageous for some sophisticated tasks such as deburring and peg-insertion. However, in order to control the object position or the force between the object and the environment, it needs to specify the desired equilibrium position of the impedance carefully.

As for the computational load, both control methods require a lot of computation if we wish to implement the method rigorously. This is because we need to know the dynamics and other detailed information on the hand and object precisely and we essentially need to cancel out the dynamics of the hand and object to realize the desired dynamic property. Partly because of this, these control methods seem to have not been used widely. However, they will be useful at least as the theoretical baselines for developing more practical control algorithms.

To cope with the situation where the kinematics and/or dynamics of the hand and/or object are not known, some other control methods were also proposed. For example, Ueki, Kawasaki, & Mouri (2009) proposed an adaptive coordinated

control method in which the dynamic parameters of both the object and hand are estimated adaptively. Zhao & Cheah (2009) proposed a neural network controller for hands with uncertainties in kinematics, Jacobian matrices, and dynamics.

4.6. Manipulation by soft-fingered hand

In the case of hands with soft-fingers, especially when the soft skin of the fingers is fairly thick, it is difficult to apply the sophisticated control methods described in the previous subsections mainly because of the deformation of soft skin. In fact, the stiffness varies nonlinearly and considerably depending on the magnitude of the applied force, the shape of the object surface and fingertip surface, and the thickness of the soft skin around the contact area. On the other hand, it is expected that the impedance property provided by the soft skin will be very useful for firm and stable manipulation.

Taking these points into consideration, we have done an experimental study of dexterous manipulation of various objects by a robot hand with two soft fingers (Yoshikawa, Koeda, & Fukuchi, 2007). This hand is basically controlled by a position-based PID control algorithm. However, by taking advantage of the soft skin and utilizing the fingertip force sensor measurement, the hand can regulate the grasping force and can comply with the constraints given by the manipulation task and excessive external forces. The control scheme and the experimental results will be explained below in some detail.

4.6.1. Basic Position-Based Control Scheme

The joint torque vector $\boldsymbol{\tau}_i \in \mathcal{R}^3$ for finger i ($i = 1, 2$) is given by the following simple PID control scheme:

$$\boldsymbol{\tau}_i(t) = k_P \mathbf{q}_{ei}(t) + k_I \int \mathbf{q}_{ei}(t) dt + k_D \dot{\mathbf{q}}_{ei}(t) \quad (24)$$

$$\mathbf{q}_{ei}(t) = \mathbf{q}_{di}(t) - \mathbf{q}_i(t) \quad (25)$$

where k_P , k_I , and k_D are proportional, integral, and derivative gains, and $\mathbf{q}_{ei}(t)$ the error of the joint angle between the desired joint angle $\mathbf{q}_{di}(t)$ and the current joint angle $\mathbf{q}_i(t)$.

When the fingers are not in touch with objects or environment, the desired joint angle $\mathbf{q}_{di}(t)$ is calculated from the desired finger motion. However, if the fingers are in touch with them, this $\mathbf{q}_{di}(t)$ is modified to regulate the fingertip force to a desired value using the measured contact force information as described in the following.

4.6.2. Force Regulation

In order to realize a given desired force to some extent without having unstable behaviour of the conventional force control approaches, we have adopted the following position-based force regulation scheme. In Fig.10, \mathbf{O} is the origin of a hand coordinate system, \mathbf{p}_i is the tip-position of finger i ($i = 1, 2$), $\mathbf{p}_c = (\mathbf{p}_1 + \mathbf{p}_2)/2$ is the center of the two fingertip positions, and $r = |\mathbf{p}_1 - \mathbf{p}_c| = |\mathbf{p}_2 - \mathbf{p}_c|$ is the distance from the center of the fingertips.

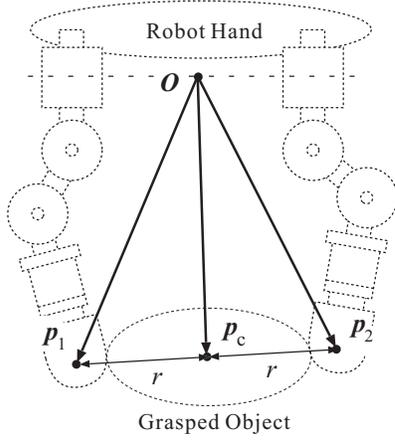


Figure 10: Fingertip positions p_1 and p_2 and finger distance r .

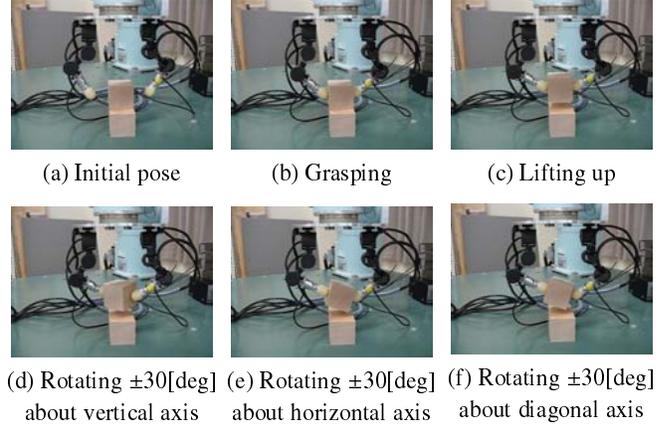


Figure 11: Manipulation of wooden cube.

A. Grasping Force Regulation

To regulate the grasping force between the two fingers grasping a common object, the thickness of the soft material is modified by changing the distance r according to the error between the desired contact force and the current contact force measured by the force sensors. To reduce the noise of force sensors the following filter is used to obtain the estimated fingertip force $f_i(t)$:

$$\dot{f}_i(t) = (\gamma/\Delta t)(f_{mi}(t) - f_i(t)) \quad (26)$$

where $f_{mi}(t)$ is the measured force signal of $f_i(t)$, Δt is the sampling period, and γ is a parameter of the filter which corresponds to the inverse of the time constant.¹ The value of γ is taken to be small so that the stability of the system may not be affected very much. In our experimental system, $\Delta t = 1[\text{ms}]$ and γ is empirically selected as $\gamma = 0.1$.

The magnitude of the grasping force $f_g(t)$ is defined to be the minimum value of the magnitudes of two fingertip force components along the line of grasp (Yoshikawa & Nagai, 1991), that is,

$$f_g(t) = \min \left\{ \mathbf{u}_{12}^T(t) \mathbf{f}_1(t), \mathbf{u}_{21}^T(t) \mathbf{f}_2(t) \right\} \quad (27)$$

where \mathbf{u}_{ij} is the unit vector directing from p_i to p_j . Hence the error of grasping force can be evaluated by

$$e_g(t) = f_{gd}(t)/f_g(t) - 1 \quad (28)$$

where $f_{gd}(t)$ is the desired magnitude of the grasping force. Using this $e_g(t)$, the desired distance $r_d(t)$ is modified by the following equation:

$$\dot{r}_d = \begin{cases} a_g e_g / \delta_g, & \text{if } |e_g(t)| \leq \delta_g \\ a_g \text{sgn}(e_g), & \text{otherwise} \end{cases} \quad (29)$$

¹Note that a discrete-time version of (26) is given by

$$f_i(t) = \gamma f_{mi}(t) + (1 - \gamma) f_i(t - \Delta t).$$

where a_g is a parameter that specifies the maximum speed of the fingertip and δ_g is a parameter that determines the saturation region of e_g . In the experiment the values $a_g = -5[\text{mm/sec}]$ and $\delta_g = 0.1$ are used. The desired joint angles $\mathbf{q}_{di}(t)$ are calculated from $r_d(t)$ by solving the inverse kinematics problem.

B. Complying with Unknown Constraints

When the motion of the grasped object is constrained in some way to the environment or some large external force is applied to the object, it is desirable to comply with this excessive force. In our system this is achieved in the following way. When the total external force $\mathbf{f}_{ex} = \mathbf{f}_1 + \mathbf{f}_2$ is larger than certain threshold, the position p_c is translated in the direction of \mathbf{f}_{ex} so that the external force may become smaller. In a similar way, when the total external moment $\mathbf{n}_{ex} = (\mathbf{p}_1 - \mathbf{p}_c) \times \mathbf{f}_1 + (\mathbf{p}_2 - \mathbf{p}_c) \times \mathbf{f}_2$ expressed with respect to p_c , is larger than certain threshold, the fingertip positions p_i are rotated around the same axis as \mathbf{n}_{ex} so that the external moment may become smaller. Note that this function of complying with external constraints can also be achieved by the position control of the arm to which the hand is attached.

4.6.3. Experimental Results

We have shown experimentally that, by using the above control algorithm, the hand can stably and firmly manipulate a wooden cube in free space, open and close a bottle cap, and turn a crank. The result of manipulation of a wooden cube is shown in Fig.11. Starting from the initial pose, the hand grasps the cube, lifts it up, and then rotates it about a vertical axis, then about a vertical axis, and finally about a diagonal axis, while keeping the grasping force to the desired value of 3[N]. Fig.12 shows the trajectory of the fingertip forces and the fingertip distance. From the figure it can be seen that the grasping force is tracking well the desired value 3[N] by adjusting the fingertip distance.

Snapshots during the tasks of opening and closing of a bottle cap and turning a crank are shown in Fig.13. The grasping force was regulated fairly well to the desired value and the constraints imposed by the bottle cap and the cranks were complied without

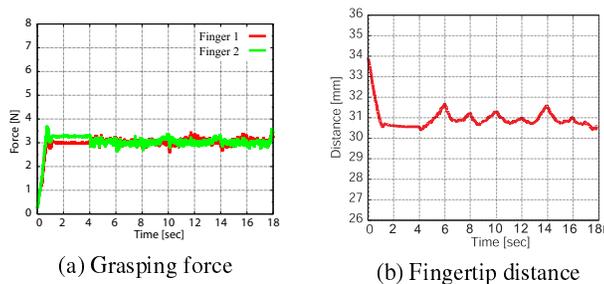


Figure 12: Grasping force and fingertip distance for the case of target force 3[N].

difficulty. Refer to (Yoshikawa, Koeda, & Fukuchi, 2007) for more details.

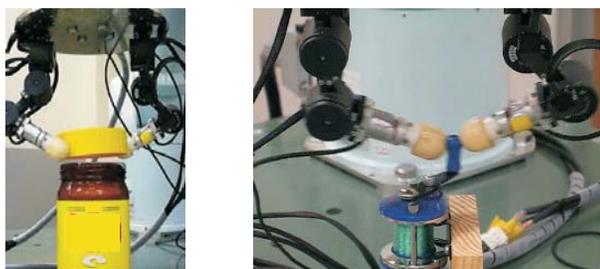
5. Concluding remarks

This paper has presented a survey on the current state of art of the researches on multifingered robot hands. First, a brief history of the past development of the hardware of multifingered robot hands was described. Then representative research results were introduced in the area of grasping and manipulation that are the two main functionalities of hands, with special focus on grasping position optimization, hybrid position/force control and impedance control for manipulation.

Several future research directions I believe important are listed below.

(a) Human Size Robot Hand with Enough Functionality: An ultimate goal of robot hand research is to develop hands for humanoid robots. More powerful and compact actuators are needed to develop them. Tactile and force sensors should be densely integrated into the design. Robotic hands totally covered by soft skin have large potential for realizing firm grasping and stable manipulation.

(b) Planning and Skill of Grasping and Manipulation: One of the most difficult problems in utilizing robot hands at the moment is to make a detailed motion plan for a given grasp and manipulation task. For a skillful manipulation, feedback of various information on the object and environment will be needed. Only preliminary studies have been done so far. Coordination between hand and other part of the body, especially the arm to which the hand is attached, will also be needed.



(a) Opening bottle cap (b) Turning crank

Figure 13: Two manipulation tasks with constraints.

(c) Selection of Best Grasp Position: In handling various unknown objects, it is desirable to be able to select a good grasp position that is suitable not only for resisting external forces but also for performing a given manipulation task. Further research will be necessary for developing a procedure selecting a best grasp position taking account of the factors of workspace, manipulating ability, and resisting ability against predicted external force will be necessary.

(d) Versatile vs. Customized Hands: Multifingered hands discussed in this article are mostly those aiming at versatile hands. However, if we consider just a particular task or a class of tasks, customized hands will work more efficiently. Of course these customized hands may be quite different from human's hands (Bicchi, 2000). Both approaches will be needed depending on the situation.

The tremendous skill and versatility of human hands will continue to be a great challenge and source of encouragement for researchers of robot hands.

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