

Robot Hands: Past, Present, and Future

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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 various objects by robot hands are fundamental functionalities of various robotic systems. A brief survey of the history and current state of research on multifingered robot hands both from hardware and software aspects is presented. Some of our recent results in grasping unknown objects optimally and performing various manipulation tasks by robot hands with soft fingers are also presented. Some future research directions are discussed.

I. INTRODUCTION

Grasping and manipulation of various known and unknown objects by robot hands are fundamental functionalities for robotic systems, including humanoid robots, industrial robots, and wheel-type mobile robots, to be useful in various 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 and by some other research groups after that, 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 robot that can really help people.

In this article, a brief survey of the history and current state of research on grasping and manipulation by multifingered robotic hands both from hardware and software aspects will be presented. Some of our recent results in grasping unknown objects and manipulating various objects optimally by robot hands with two soft fingers will also be introduced. Finally some future research directions and issues will be discussed.

II. HARDWARE

Various 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 for computer control have been developed. Representative examples are three-fingered Okada-Hand (1979) [1], three-fingered Stanford/JPL hand (1981) [2], and three-fingered Utah/MIT hand (1984) [3]. These hands have several things in common. They use tendon cables and have large separate drive units.

Then around 2000 several new hands were developed: four-fingered DLR hand (2000)[4], five-fingered Robonaut Hand (1999)[5], and five-fingered Gifu Hand (2002)[6]. 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 hand itself or contained in the forearm. They are equipped with various sensors. The size of these hands is still a little larger than our hands. Another interesting hand is the Three-fingered High-Speed Hand (2003) [7] which can move so fast that it can even catch a falling ball.

More recently, small size hands that could be used for humanoid robots have been developed, such as Universal-Hand (2005) [8] and Shadow Dexterous Hand (2007) [9]. 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 5dof thumb showing the designer's view on the importance of the thumb. Another interesting hand is five-fingered lightweight 328 g Anthropomorphic Hand (2009) [10] with maximum fingertip force more than 20 N.

The latest development is that two hands have been developed with the purpose of actually mounting on humanoid robots. One is the hand for HRP3P (2007) [11] and the other is the hand of TWENDY-ONE Robot [12]. Both hands have four fingers and have smaller number of motors than most of the hands mentioned above. An interesting feature of the latter hand is that the whole surface is covered by soft skin and the fingers have nails.

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 are rather task specific. Establishing more general framework of planning and control for wider class of manipulation tasks will be an important future research topic.

III. GRASPING

A. Analysis and Synthesis of Grasp

Various analytical studies of grasping by multifingered hands have been done extensively. Among basic concepts developed are grasp map (or grasp matrix) [13], hand Jacobian [13], form and force closure grasps [14], and active and passive force closures [15], and manipulability [16].

Determining the grasp position for any given object by a multifingered robot hand is a fundamental problem which has not yet been solved satisfactorily. Many grasp quality measures have been proposed [17]-[26] for grasp optimization. See [17] for a very thorough survey of literatures until about 1992. A good short summary on the topic is also given in [18].

In [19] and [20], two general grasp measures were introduced: they are radii of the largest balls, centered in 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, f_i^\perp , under two kinds of magnitude constraints $\max\{f_i^\perp\} \leq 1$ and $\sum_{i=1}^n f_i^\perp \leq 1$ where n is the number of fingers. In [21] a simulator for grasp analysis, called GraspIt, was developed and the second grasp measure of [20] and the volume of the set of all resistible wrenches were adopted for evaluation of grasps. A task-directed quality measure were proposed in [22] based on the concept of task ellipsoid which represents the set of all wrenches needed to perform the task. A quality measure which takes into account the object shape was proposed in [23] based on the object wrench set consisting of wrenches caused by all possible disturbing force distributions on the object surface. In [24], a method of grasp optimization using the concept of required external force set was proposed.

Grasp quality measures mentioned above are all given in terms of fingertip forces and external wrenches. In [25] 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 vertices, and number of grasp points located near the end of the edge. The weighting factors were selected by using human intuition for

several sample objects. Our grasp measure introduced below is also very heuristic.

Most of these studies are for rigid fingers which make point contacts with 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 [27]-[32].

B. Grasping by Two Soft Fingers

We have proposed a method of shape recognition and optimal grasping of unknown planar objects [33] for a robotic hand system consisting of an arm, a hand with 2 soft-fingers, and an omnidirectional camera attached to the hand (Fig. 1). The fingertips are round and covered by thin and soft skin made of elastic gel as shown in Fig. 2.

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 viewpoints. Then by applying a two-dimensional version of the volume intersection method [34], we obtain the visual hull in the horizontal plane, which corresponds to a polygon circumscribing the horizontal cross section of the object.

For grasping we propose a simple grasp quality criterion to obtain the best grasping position for the two soft fingers based on a visual hull in a horizontal grasp plane. 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 account, the grasp quality

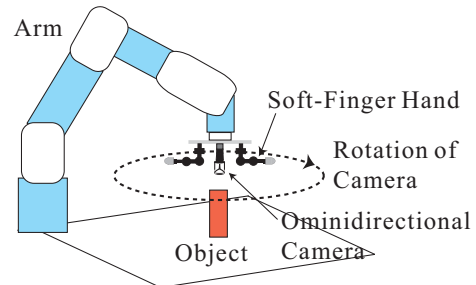


Figure 1. System Structure

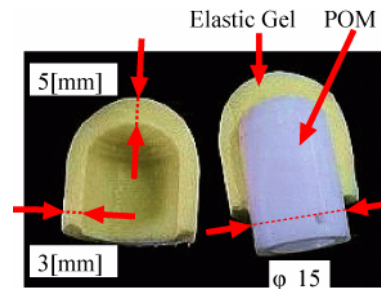


Figure 2. Inner Structure of Soft Fingertip

criterion [33] is given by

$$J(c_1, c_2) = k_p J_p(c_1, c_2) + k_\alpha J_\alpha(c_1, c_2) \quad (1)$$

where c_1 and c_2 are a pair of candidate contact points on the object surface. $J_p(c_1, c_2)$ is the term evaluating the global location of the contact points and is a function of distances d_a and d_b (see Fig.3). $J_\alpha(c_1, c_2)$ is the term evaluating the angle α_i between the surface normal of the object and the grasp force direction at the contact points.

When the contact point i is at a corner of the object, we define the angle α_i as the minimum absolute value in the interval $[\alpha_{ir}, \alpha_{il}]$ where α_{ir} (α_{il}) is the angle from the normal vector on the right (left) side surface of the corner to the grasp force direction. For instance, $\alpha_i = 0$ in the case of Fig. 4 (a), and $\alpha_i = |\alpha_{il}|$ in the case of Fig. 4 (b).

We have performed experiments of grasping prisms with various cross sections. Fig.5 shows the case of a rectangular prism. As can be seen from the figure, the prism was grasped successfully at an intuitively proper grasp position. We are also studying the relation between the criterion (1) and the measured grasp positions by human hands [35]

IV. MANIPULATION

A. Control Synthesis for Manipulation

Various control algorithms for multifingered robot hands for grasping and manipulation with fixed, rolling, and sliding contacts have been proposed [14] [36]-[41] (see [40] for a brief survey on control algorithm for manipulation by multifingered hands). They can roughly be divided into two groups. One is impedance control and the other is hybrid position and force control (see Fig.6). Impedance control method controls the force indirectly through specification of the mechanical impedance of the grasped object against external forces. Hybrid control method controls simultaneously the force in some directions and the position in other directions. Although these control methods seem to have not been used widely, they will be useful as the theoretical baseline for developing more practical control

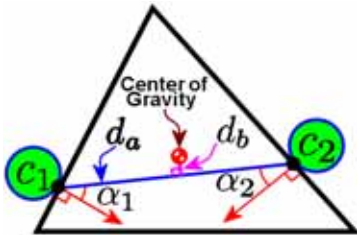


Figure 3. Parameters of the Criterion

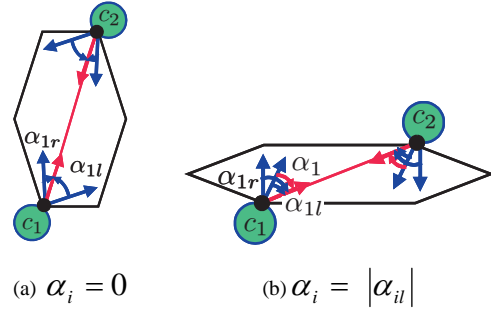


Figure 4. Angle α_i for Corners

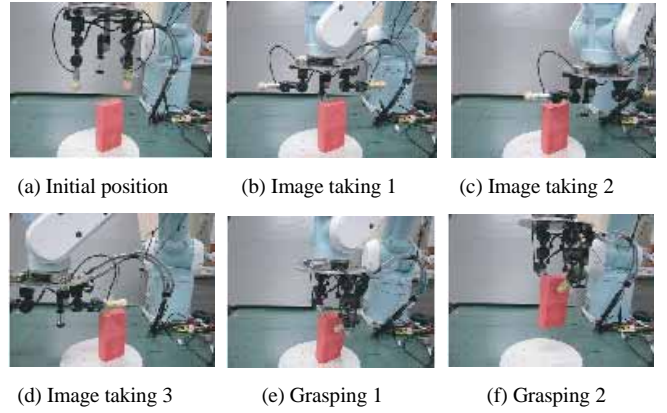


Figure 5. Experiment of Grasping a Rectangular Prism

algorithms.

B. Manipulation by Soft-Fingered Robot Hands

Our result on dexterous manipulation of various objects by a robot hand with two soft fingers [42] will be introduced. This hand is basically controlled by a position-based PID control algorithm. However, by utilizing the fingertip force sensor measurement and taking advantage of the soft skin, it tries to regulate the grasping force and to comply with the constraints given by the manipulation task and excessive external forces in the following way.

To control the grasping force between the two fingers, the fingertip distance is changed according to the grasping

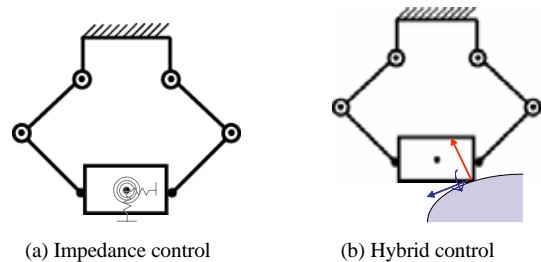


Figure 6. Control Methods of Multifingered Hands

force information obtained from the fingertip force sensors. A first-order filter with a rather large time-constant is used to smooth out the fingertip force measurement.

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 is larger than certain threshold, the fingertip positions are translated in the direction of external force so that the external force becomes smaller. In a similar way, when the total external moment is larger than certain threshold, the fingertip positions are rotated in the direction of total external moment.

We have shown experimentally that, by using the above control algorithm, the hand can perform various manipulation tasks stably and firmly, such as manipulation of a wooden cube in free space, opening and closing of a bottle cap, and turning a crank. The result of manipulation of a wooden cube is shown below. The size of cube was 50[mm] on a side and the weight was 77[g]. To grasp the cube, the distance between the two fingertips was made smaller by using position control until the grasping force became a target value. When the grasping force reached the target value, the cube was lifted upward by 30[mm]. Then, while keeping the grasping force to the desired force, each fingertip was moved following some circular paths in a horizontal plane, a vertical plane, and a diagonal plane. The sequential images of this experiment are shown in Fig.7 for the case of grasp target force of 3[N]. Fig.8 shows the change of the distance between the two fingers and the grasping force. From the figure it can be seen that the

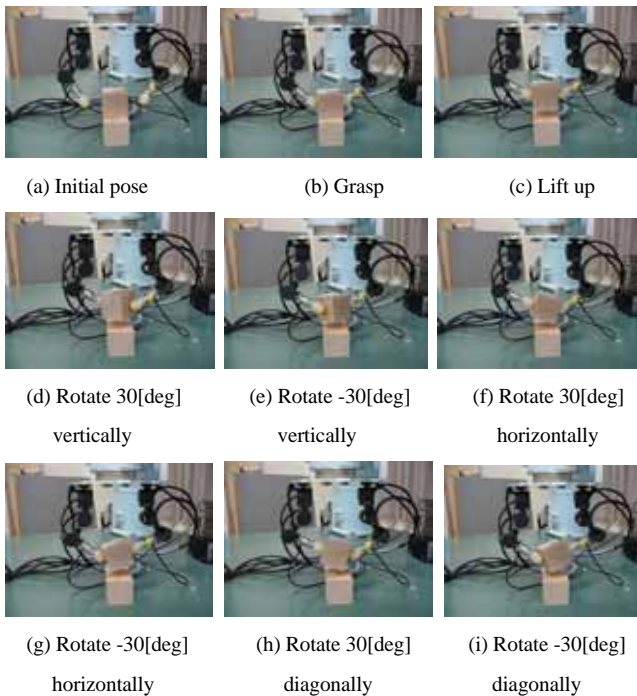


Figure 7. Manipulation of Cube

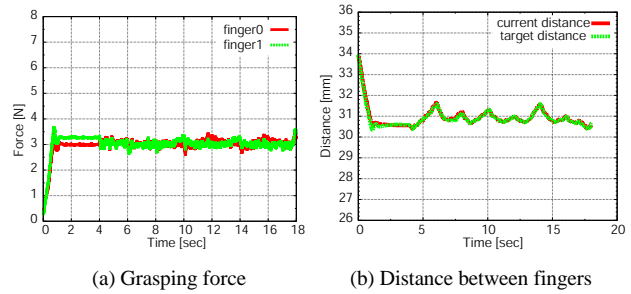


Figure 8. Grasping Force and Finger Distance for Target Force 3[N]

grasping force is tracking well the desired value by adjusting the fingertip distance. The servo control period was 1[ms].

V. FUTURE DIRECTIONS AND ISSUES

Several future research directions and issues are listed below.

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.

Hand Covered by Soft Skin: Robotic hands totally covered by soft skin have large potential for realizing firm grasping and stable manipulation.

Planning and Skill of Grasping and Manipulation: One of the most difficult problems 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 of hand and other part of the body will also be needed.

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. An optimality criterion taking into consideration the factors of workspace, manipulating ability, and resisting ability against predicted external force will be necessary. This problem has not been solved yet satisfactorily.

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. Both approaches will be needed depending on the situation.

REFERENCES

[1] T. Okada, "Object-Handling System for Manual Industry," IEEE Transactions on Systems, Man, and Cybernetics, vol. SMC-9, no. 2, 1979.

- [2] M. T. Mason and J. K. Salisbury, Jr., *Robot Hands and the Mechanics of Manipulation*, MIT Press, Cambridge, MA, 1986.
- [3] S. C. Jacobsen, E.K. Iversen, D. F. Knutti, R. T. Johnson, and K. B. Biggers, "Design of the Utah/M.I.T. Dexterous Hand," *Proc. of IEEE Int. Conference on Robotics and Automation*, pp.1520-1532, 1986.
- [4] G. Hirzinger et al., "A Mechatronics Approach to the design of light-weight arms and multifingered hands," *Proc. of IEEE Int. Conference on Robotics and Automation*, pp.46-54, 2000.
- [5] C. S. Lovchik, M. A. Diftler, "The Robonaut Hand: A Dexterous Robot Hand for Space," *Proc. of IEEE Int. Conference on Robotics and Automation*, pp.907-912, 1999.
- [6] H. Kawasaki, T. Komatsu, and K. Uchiyama, "Dexterous Anthropomorphic Robot Hand with Distributed Tactile Sensor: Gifu Hand II," *IEEE/ASME Transactions on Mechatronics*, vol.7, no.3, pp. 296-303, 2002.
- [7] A. Namiki, Y. Imai, M. Ishikawa, and M. Kaneko, "Development of a High-Speed Multifingered Hand System and Its Application to Catching," *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp.2666-2671, 2003.
- [8] K. Hoshino and I. Kawabuchi, "Pinching at Finger tips for Humanoid Robot Hand," *Journal of Robotics and Mechatronics*, vol. 17, no. 6, pp.655-663, 2005.
- [9] <http://www.shadowrobot.com/>
- [10] T. Takaki and T. Omata, "High Performance Anthropomorphic Robot Hand with Grasp Force Magnification Mechanism," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.1697-1703, 2009.
- [11] K. Kaneko, K. Harada, and F. Kanehiro, "Development of Multifingered Hand for Life-size Humanoid Robots," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 913-920, 2007.
- [12] H. Iwata and S. Sugano, "Design of Human Symbiotic Robot TWENDY-ONE," *Proc. of IEEE Int. Conf. on Robotics and Automation*, 2009.
- [13] R. M. Murray, Z. Li, and S. S. Sastry, *A Mathematical Introduction to Robotic Manipulation*, CRC Press, 1994.
- [14] M. T. Mason and J. K. Salisbury, Jr., *Robot Hands and the Mechanics of Manipulation*, MIT Press, Cambridge, Mass., 1985.
- [15] T. Yoshikawa, "Passive and Active Closures by Constraining Mechanisms," *Transactions of the ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 121, pp. 418-424, 1999.
- [16] T. Yoshikawa, *Foundations of Robotics*, MIT Press, Cambridge, MA, 1990.
- [17] K. B. Shimoga, "Robot Grasp Synthesis Algorithms: A Survey," *International Journal of Robotics Research*, vol. 15, no. 3, pp. 230-266, 1996.
- [18] M. Strandberg and B. Wahlberg, "A Method for Grasp Evaluation Based on Disturbance Force Rejection," *IEEE Transactions on Robotics*, pp. 461-469, 2006.
- [19] D. G. Kirkpatrick, B. Mishra, and C. K. Yap, "Quantitative Steinitz's Theorems with Application to Multifingered Grasping," *Proc. 20th ACM Symp.on Theory of Computing*, pp.341-351, 1990.
- [20] C. Ferrari and J. Canny, "Planning Optimal Grasps," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 2290-2295, 1992.
- [21] A. T. Miller and P. K. Allen, "GraspIt!: A Versatile Simulator for Grasp Analysis," *Proc. of ASME International Mechanical Engineering Congress & Exposition*, pp. 1251-1258, November 2000.
- [22] Z. Li and S. Sastry, "Task-oriented optimal grasping by multifingered robot hands," *IEEE J. Robot. Autom.*, vol. 4, no. 1, pp. 32-44, 1988.
- [23] N. S. Pollard, "Parallel methods for synthesizing whole-hand grasps from generalized prototypes," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., MIT, Cambridge, MA, 1994.
- [24] T. Watanabe and T. Yoshikawa, "Grasping Optimization Using a Required External Force Set," *IEEE Trans. on Automation Science and Engineering*, vol. 4, no. 1, pp. 52-66, 2007.
- [25] Y. C. Park and G. P. Starr, "Grasp Synthesis of Polygonal Objects Using a Three-Fingered Robot Hand," *Int. J. Robotics Res.*, vol. 11, no. 3, pp. 163--184, 1992.
- [26] B. Mirtich and J. Canny, "Easily computable optimum grasps in 2-D and 3-D," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.739-747, 1994.
- [27] P. Akella and M. Cutkosky, "Manipulating with Soft Fingers," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 764-769, 1989.
- [28] S. Arimoto, P. A. Nguyen, H.-Y. Han, and Z. Doulgeri, "Dynamics and control of a set of dual fingers with soft tips," *Robotica*, vol. 18, pp.71-80, 2000.
- [29] Z. Doulgeri and J. Fasoulas, "Grasping Control of Rolling Manipulation with Deformable Fingertips," *IEEE/ASME Trans. on Mechatronics*, vol. 8, no. 2, pp. 283-286, 2003.
- [30] M. Yoshida, S. Arimoto, and Z. W. Luo, "Three- Dimensional Object Manipulation by Two Robot Fingers with Soft Tips and Minimum D.O.F.," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 1615-1616, 2008.
- [31] N. Xydias and I. Kao, "Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results," *International Journal of Robotics Research*, vol. 18, no. 8, pp. 941-950, 1999.
- [32] T. Inoue and S. Hirai, "Study on hemispherical soft-fingered handling for fine manipulation by minimum d.o.f. robotic hand," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 2454-2459, 2006.
- [33] T. Yoshikawa, M. Koeda and H. Fujimoto, "Shape Recognition and Grasping by Robotic Hands with Soft Fingers and Omnidirectional Camera," *Proc. of IEEE Int. Conf. on Robotics and Automation*, paper WeA8.6, 2008.
- [34] A. Laurentini, "The Visual Hull Concept for Silhouette-Based Image Understanding," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 16, no. 2, pp. 150-162, 1994.
- [35] S. Sugiyama, M. Koeda, H. Fujimoto and T. Yoshikawa, "Measurement of Grasping Position by Human Hands and Grasp Criterion for Two Soft-fingered Robot Hands," *Proc. of IEEE Int. Conf. on Robotics and Automation*, paper FrC5.2, 2009.
- [36] Z. Li, P. Hsu, and S. Sastry, "Grasping and Coordinated Manipulation by a Multifingered Robot Hand," *Int. J. Robotics Res.*, vol. 8, no. 4, pp. 33-50, 1989.
- [37] Y. Nakamura, K. Nagai, and T. Yoshikawa, "Dynamics and Stability in Coordination of Multiple Robotic Mechanisms," *Int. J. Robotics Res.*, vol. 8, no. 1, pp. 44-61, 1989.
- [38] T. Yoshikawa and X.-Z. Zheng, "Coordinated Dynamic Hybrid Position/Force Control for Multiple Robot Manipulators Handling One Common Object," *Int. J. Robotics Res.*, vol. 12, no. 3, pp. 219-230, 1993.
- [39] T. Yoshikawa, "Virtual Truss Model for Characterization of Internal Forces for Multiple Finger Grasps," *IEEE Transaction on Robotics and Automation*, vol. 15, no. 5, pp. 941-947, 1999.
- [40] T. Yoshikawa, "Control Algorithm for Grasping and Manipulation by Multifingered Robot Hands Using Virtual Truss Model Representation of Internal Force," *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp. 369-376, 2000.
- [41] H. Liu and G. Hirzinger, "Cartesian Impedance Control for the DLR Hand," *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 106-112, 1999.
- [42] T. Yoshikawa, M. Koeda, and H. Fukuchi, "Grasping and Manipulation by Soft-Fingered Robot Hands," *Proc. of IEEE Int. Conf. on Advanced Robotics*, paper F3D.3, 2007.