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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.

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, and sea.

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, Haikawa, & Takenaka, 1998) and by some other research groups after that (for example, Sakagami et al., 2002; Kaneko et al., 2004; Ishida, 2004; 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, Iversen, Knutti, Johnson, & Biggers, 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

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(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 $\boldsymbol{f}_{Ci} \in R^3$ (three-dimensional vector) on the object, but not moment, within the friction cone at the contact point $\boldsymbol{c}_i$). Then Grasp matrix (Murray, Li, & Sastry, 1994) is the matrix $\boldsymbol{G}$ transforming the contact forces at the fingertips $\boldsymbol{f}_C = [\boldsymbol{f}_{C1}^T \boldsymbol{f}_{C2}^T \cdots \boldsymbol{f}_{Cn}^T]^T$ to the resultant force/moment vector $\boldsymbol{t}_B \in R^6$ working on the object ($\boldsymbol{f}_{Ci}$ and $\boldsymbol{t}_B$ are both expressed in the object coordinate frame Σ_O):

$$\boldsymbol{t}_B = \boldsymbol{G}\boldsymbol{f}_C \tag{1}$$

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

$$\boldsymbol{J}\dot{\boldsymbol{q}} = \boldsymbol{G}^T\boldsymbol{v}_B \tag{2}$$

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 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, Wang, Wang, and Li (2007) the concept of active force closure was applied to the grasping force analysis and optimization of the whole hand grasp. In Liu and 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

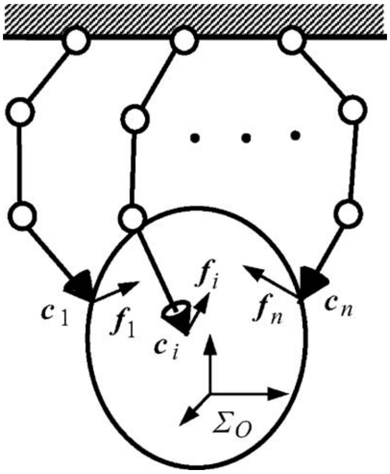

Fig. 1. Multifingered hand grasping an object.

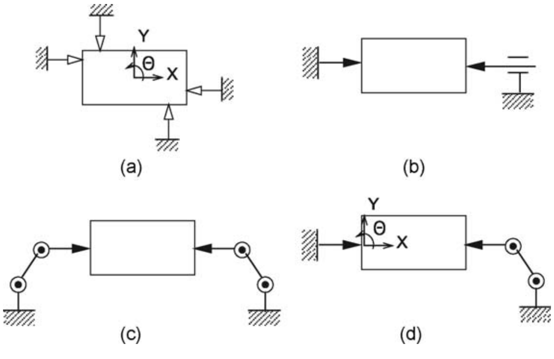

Fig. 2. Various closures in case of plane motion. (a) Passive form closure. (b) Passive force closure. (c) Active closure. (d) Hybrid active/passive closure.