Dextrous Manipulation by Rolling and Finger Gaiting

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Abstract

Many practical dextrous manipulation tasks involve large-scale motion of the grasped object while maintaining a stable grasp. To plan such tasks, one must control both the motion of the object and the contact locations, while also adhering to the workspace constraints typical of multi-fingered hands. In this paper, we integrate the relevant theories of contact kinematics, nonholonomic motion planning, coordinated object manipulation, grasp stability and finger gaits to develop a general framework for dextrous manipulation planing. To illustrate our approach, the framework is applied to the problem of manipulating a sphere with three hemi-spherical fingertips. The simulation results are presented.

1 Introduction

A dextrous manipulation system is composed of a multifingered robotic hand and an object that will be grasped and manipulated by the hand. There are three types of manipulation tasks for multifingered hand systems: (1) *Object Manipulation*:achieve the desired object configuration without regard for contact configurations;(2) *Grasp Adjustment*: obtain the desired contact configurations without regard for object configuration; (3) *Dextrous Manipulation*: achieve the goal configuration for the object *and* contacts.

Given that most robot fingers have severe workspace limits, large-scale object manipulation and grasp adjustment can be very difficult to achieve. For example, suppose that a trajectory for large-scale object manipulation is specified, and that one will attempt to execute this trajectory incrementally by solving the well known velocity kinematic relationships of Salisbury [18] and Montana [13]. In general, at least one finger will reach the boundary of its workspace or the grasp will become unstable, before the trajectory is completed. This is true for any of the three tasks listed above. Therefore, some strategy must be developed to generate manipulation plans that avoid these problems. This is the heart of dextrous manipulation problem addressed here.

Object manipulation, usually with fixed points of contacts, has been extensively studied and many good algorithms as well as results[11, 5] have been presented. As for the grasp adjustment, some algorithms have been proposed to improve the grasp quality locally[19, 6] or to adjust the contact points to accommodate object movement [4]. To gain a new grasp when some finger reaches its limit, Hong et al. [8] proposed using *finger gaiting*, i.e. a periodic movements of fingers, to form a new grasp consisted of fingers lying within their workspace limits. The authors proved the existence of some 'good' grasps on smooth objects and repeatedly used finger gaiting to achieve those grasps. The change of a grasp from three fingers to two fingers, i.e. finger gaiting, was referred as a "hyperspace" jump by Montana[14], since the number of degrees of freedom increased as contact is lost. Montana discussed a path of twirling a baton using coordinated object manipulation and finger gaiting, but didn't discuss how to automatically generate plans utilizing finger gaits. A planner that uses whole-arm manipulation to reorientate polyhedral, which also has the effect of contact adjustments, was presented by Bicchi et al.[1]. However, the general problem of grasp adjustment for curved and polyhedral objects with fingertips remains open.

Grasp adjustment is characterized by the change of contacts and some fingers need to be relocated to form a new grasp. If all fingers need to be used to

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form a grasp during the adjustment procedure, then only rolling or sliding can be used for finger relocation. Generating a rolling or a sliding path usually involves detailed computation of the geometry of the object and fingers, and the requirement of maintaining force closure complicates the problem. It is more convenient to use finger gaiting when possible, but this requires the grasps that have force closure(FC) do not use all fingers of a robot hand. If the initial grasp uses all fingers, rolling or sliding need to be used to generate a new FC grasp that at least 1 finger is not used in the grasp. Currently sliding is preferred not to be used since control of sliding is very tricky. However the fact that sliding can usually simplify the contact motion planning suggests it may be worth putting more effort to the study of sliding.

Our framework to plan general manipulation tasks is as the following: if the initial grasp uses all fingers, then use rolling to obtain a FC grasp that leaves at least one finger not used in the grasp. If the task is to manipulate the object, first move the object until some finger reaches its limit. Then use finger gaiting to form a new FC grasp composed of fingers all lying in their interior workspaces and move the object again with the new grasp. Repeat the above procedure if it is needed. For the task of grasp adjustment, if the goal contact points are initially not within the workspaces of the fingers, first do an object manipulation to bring them to the workspaces. Then use finger gaiting and rolling to reach the goal grasp. If the task involves moving the object and adjusting the grasp, then it can be done by (a) reaching the goal object configuration first, then adjusting the grasp; or (b) achieving the goal grasp first and then using coordinated manipulation to reach the goal object configuration; or(c)moving the object and adjusting the contacts simultaneously. The relevant theory of contact kinematics[13, 14], nonholonomic motion planning[10, 15], grasp stability [16, 17],coordinated object manipulation [11] and finger gaiting [8] are naturally incorporated in this framework. The general methodology is applied to the problem of dextrous manipulation of a sphere with 3 hemi-spherical fingertips and the simulation results are presented.

2 Finger Gaits

We make the following assumptions:each body in the hand-object system is rigid; the geometry of each body is known; only the fingertips can contact the object and contacts are point contacts; each finger has six degrees of freedom and its workspace is known. The workspace mentioned here is the dextrous workspace of the fingers, i.e. any point within the workspace can be reached by the fingertip with any orientation.

A workspace of a robot finger is determined by its link structure and joint limits, arising from mechanical and electrical constraints of the parts used to build the joints. The cross product of all finger workspaces is the workspace of the hand. When there exist obstacles in the hand workspace, a hand at certain configuration may be separate from/ contact/collide with the obstacles. The set of all configurations of the hand that are separate from/contact/collide with the obstacles forms the free/contact/collision space of the robot hand. Clearly, only the free space and contact space may be used to generate valid hand trajectory. Note that for a given hand, the partition of its configuration space into free/contact/collision space is determined by the obstacle geometries and configurations.

Besides workspace limits of the fingers, there also exist limits for the maximum rotation of fingertips. Recall that the first step of our manipulation strategy is to roll the fingers to form a new FC grasp with at least 1 finger free. While only the contact space is useful for the rolling movement, it is not straight forward to find a path connecting two points in the contact space with fingers of limited rotation capability, which also makes finger gaiting more appealing in terms of easy planning and implementation.

2.1 Notations

Denote the object and the fingers by O and $f^i, i \in I$ respectively, where I is the set of indices of all fingers . The surface of object is ∂O. $p(u,v)$ is a point on the object surface with local coordinate (u,v). $g_O \in SE(3)$ and $g_{f^i} \in SE(3)$ are configurations of the object and fingers, respectively. Denote the workspace of f^i as WS^i.Here we assume the palm is fixed, so WS^i is fixed, otherwise it will be a function of the palm configuration. Denote the contactable region of f^i on the object at configuration g_O as $CWS^i(g_O) = WS^i \cap \partial O(g_O)$, which is the function of the object configuration. To simplify the notation,subscript (g_O) will be dropped in the following discussion. For the purpose of FC grasps, only the contact points on the object are concerned as long as the contact points lie in the workspace of fingers. So we will discuss the grasp in terms of CWS^i without concerning the contact points on the fingertips. A grasp is denoted by the set of contact points on the object: $\{p^i \in CWS^i, i \in I\}$, where p^i is the (possibly null) contact point between object and finger f^i.

For each CWS^i, denote its (possibly empty)force closure region on the object surface by FC^i, which is defined as

$$FC^i = \{x \in \partial O \mid \exists y \in CWS^i, x \text{ and } y \text{ are antipodal}\}$$

Under this notation, two fingers can form a FC grasp if and only if $CWS^j \cap FC^i \neq \emptyset$, or equivalently, $CWS^i \cap FC^j \neq \emptyset$. These two conditions are equivalent because of the symmetric property of two-finger FC grasp.

Denote CWS^i_j as the contactable workspace of finger f^i which can form a FC grasp with f^j,i.e. $CWS^i_j = CWS^i \cap FC^j$. $CWS^i_{j,k} = CWS^i \cap FC^j \cap FC^k$ indicates the contactable workspace of finger f^i which can form a FC grasp with both fingers f^j and f^k. Such a region is called *double FC region.*

2.2 Three-Finger Gaits

Considering the fact that several research robotic hands are composed of three fingers, we will study three-finger gaitings in more detail. In the following, the fingers used in a grasp will be called as *grasping fingers*, and the others as *free fingers*. The contact model for three-finger grasp is *hard-finger* contact and the model for two-finger grasp is *soft-finger* contact[15].

To implement finger gaiting with three fingers, two fingers need to form a FC grasp. Then a necessary condition for using gaiting with three fingers is that at least one of the grasping fingers can form a force closure grasp with other two fingers of the hand.

Theory 1 *Suppose two fingers, f^i and f^j, form a FC grasp. A necessary condition for using a finger gaiting to form a new grasp is that at least one of the fingers, f^i and f^j, can form a FC grasp with f^k, i.e. $f^i \in CWS^i_{j,k}$ or $f^j \in CWS^j_{i,k}$, where (i,j,k) is a permutation of $\{1,2,3\}$.*

Clearly if neither of the grasping fingers can form a FC grasp with the third finger, then none of them can be lifted and rolling must be used to relocate the finger(s).

Assuming the above necessary condition is satisfied, we identify two finger gaiting primitives: finger rewind and finger substitution.

The three-finger gaiting proposed in paper [8] relocates the limiting fingers back to their workspace limits. The scenario is as the following: suppose fingers f^1 and f^2 form a grasp but reach their limits. Suppose f^3 can form a grasp with f^1, then f^2 will be relocated back to a new position within its workspace which also forms a FC grasp with f^1; after that f^3 will be relocated to form a FC grasp with f^2 and finally f^1 can be relocated back to its workspace to form a FC grasp with f_2. Then fingers f_1 and f_2 form a new valid FC grasp and the object will be moved again. We call such a finger gaiting as *finger rewind* since the basic procedure is to rewind the limiting fingers back to their workspace.

Another useful finger gaiting primitive is *finger substitution*, which works as the following:

Assume f^1 and f^2 form a FC grasp. Suppose only f^1 reaches its limit and f^2 is in a position that can also form a FC grasp with f^3. Then use f^3 to form a FC grasp with f^2. If the new location of f^3 is not at the boundary of its workspace, then the grasp of f^2 and f^3 can be used to further move the object and the limiting finger f^1 can be lifted up and becomes free finger. In this case, f^1 is substituted by f^3 and there will be no need to rewind f^1 back to form a grasp with f^2.

Finger substitution is an easy way to remove the limiting finger(s) from the grasp. Also note that the new substituting finger is placed to form a FC grasp with another one which is FC of the substituted one. This essentially suggests that only one pair of FC regions on the object may be enough for using finger substitution to move the object for arbitrary amount. This observation is important since paper [8] proved the existence of opposite positions on smooth objects, which means there exists at least 1 pair of FC regions on all smooth objects. If the workspace of the three fingers allow them to be substituted periodically as discussed above, then the object can be moved arbitrarily without using any other FC regions.

For a general object reorientation problem, a sequence of finger gaiting need to be planned to achieve a new grasp, which usually involves detailed analysis of the workspace of the fingers and the geometry of the object as well as the fingers to determine the existence of grasps and the connectivity between the grasps. As an example, the results of a sphere manipulated by three spherical fingertips will be given in next section.

3 Dextrous Manipulation of a Sphere

Our general strategy for planning dextrous manipulation is applied to the problem of manipulating a sphere with three hemi-spherical fingertips: first use rolling to change an initially three-finger FC grasp to two-finger FC grasp; then use finger gaits to achieve large-scale motion of the sphere. Several results related to the force closure grasps of a sphere and primitive planing algorithms are given in this section. Due

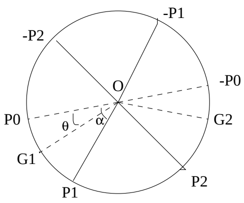

Figure 1: Shortest Path for 2 points to form a FC grasp

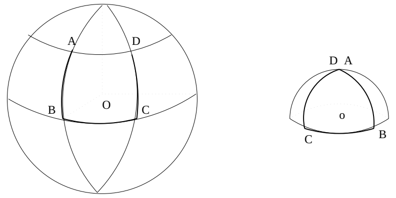

Figure 2: Rolling Path

to the limited paper space, we will not give proofs here and interested readers please refer to our technical report [7]. The simulation results will be given in next section.

Assume the radius of a sphere is r and the coefficient of friction between the sphere and fingers are $\mu = \tan(\theta)$. The we have following results on FC grasps of a sphere:

1. The maximum independent region of FC grasps on the sphere are the intersections of the sphere with two opposite cones of half angle θ, originated at the sphere center.
2. Two soft-finger contacts, p_1 and p_2, on a sphere form a force-closure grasp if and only if their straight line distance $d(p_1, p_2) \geq 2rcos(\theta)$.
3. A sufficient condition for three hard-finger contacts on a sphere to form a force-closure grasp is that the triangles formed by the three contact points on the sphere is acute and the distance from the center of the sphere to the triangle is less than $r\sin(\theta)$.

Note that a result of differential geometry[2] indicates that the great circles are the only geodesics of a sphere and realize the distance between any two points lying on the same semi-circle. Refer to figure(1), suppose two points P_1 and P_2 don't form a FC grasp . Then the shortest path for them to form a FC grasp is to move along the great circle $GC(P_1, P_2)$ toward each other's opposite points with angle $\alpha - \theta$, i.e. move P_1 and P_2 to G_1 and G_2, where α is the half angle between vectors (o, P_1) and $(o, -P_2)$, which is also the the half angle between vectors $(o, -P_1)$ and (o, P_2). Also note that moving P_1 and P_2 with angle α will make them reach opposite points, p_0 and $-p_0$.

Due to the rotation limit of the fingertips, it may not be possible for a fingertip to roll to any contact point on the object in a straight forward manner and a fine planning algorithm to roll a fingertip to a point beyond its rotation limit is needed. First notice the following result about rolling between two spheres:

Theory 2 *For two spheres rolling on each other, the trajectory of contact points of one sphere is a great circle if and only if the contact trajectory of the other sphere is a great circle.*

It was proven in paper[9] that the rolling constraints between two spheres with different radius are completely nonholonomic. Based on the theory [2] and motivated by the geometric algorithm of rolling a sphere on a plane[9], we propose an algorithm to roll a sphere on a sphere by using 'longitudes' and 'equator', which is shown in figure[2] and briefly explained below.

Figure(2) shows a path for rolling a small sphere, with radius r and rotation limit γ, on a big sphere with radius R, to change contact point on the big sphere from A to D with the small sphere having 'north pole' as contacting points in both ends. The corresponding contact points on both spheres are labeled with same alphabets. The path consists of rolling from A to B, B to C and then C to D. The arc lengths of AB and CD are $r\pi/2$, and the arc length of BC is $r\gamma$.

After the small sphere(fingertip) reaches point D, it can re-rotate itself back to its operating region and use the above path again to further roll on the big sphere. Note the 'longitude' and 'equator' here are not restricted for one specific coordinate system of the sphere. Any two great circles that are perpendicular to each other can be made into a longitude and an equator, through some coordinate transformation[7].

If the initial grasp is only 3-finger FC but not 2-finger FC, the rolling path need to be used to adjust the contact points to get a 2-finger FC grasp. Theoretically, a 3-finger FC grasp may be changed to 2-finger FC grasp by choosing the pair of contacts with largest straight line distance, moving them along the great circle toward each other and moving the 3rd finger 'accordingly' to maintain the grasp to be FC. However, it requires detailed computation to maintain the 3 fingers to form a FC grasp before the two reach antipodal positions. Borrow the concept [12] of task-oriented optimal grasp, the initial grasps which are or close to 2-finger FC grasp are preferred for dextrous manipulation tasks with three fingers.

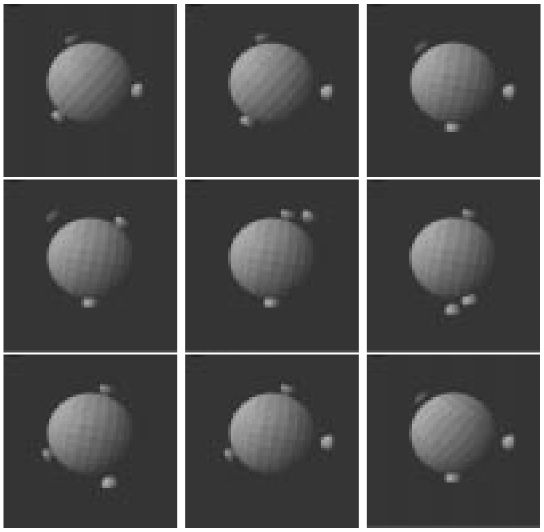

Figure 3: Manipulation with finger rewind

As for applying the finger gaitings for sphere manipulation, note that sphere is homogeneous with respect to rotation movements. We can get a sufficient condition for the existence of finger rewinds in sphere rotation:

Theory 3 *Suppose a sphere of radius* r *is grasped by fingers* f^i *and* f^j*. If* $CWS^i_{j,k}$ *and* $CWS^j_{i,k}$ *are not empty, and* $\exists x \in CWS^i_{j,k}, \exists y \in CWS^j_{i,k}$ *such that* $dist(x, y) > 2r\cos(\theta)$*, then fingers* f^i *and* f^j *can form a FC grasp with* x *and* y *as the contact points on the sphere. If the fingers* f^i *and* f^j *remain in their double FC regions during the rotation of the sphere, then fingers* f^i *and* f^j *can always be rewinded back to their workspaces to from a new force closure grasp.*

4 Simulation Results

This section presents three simulation results shown by three sets of figures. In each figure set, the figures are going across instead of down and the indices start from one. Fingers f^1,f^2 and f^3 are in clockwise order with finger 1 as the bottom left one in the first frame of figure (3) and (5). Note that the fingers never change their relative (clockwise) positions.

Figures (3) and (4) show the simulation results of a sphere rotated about the axis pointing out of the paper by there hemi-spherical finger tips with finger rewinds and finger substitutions, respectively. At the initial step (frame 1 of figure3), three fingers form a force-closure grasp but no pair of the fingers forms a 2-finger force closure grasp. Then use rolling to make f^1 and f^2 form a FC grasp in frame 2 of figure(3) and thus f^3 can be lifted. After this step, finger rewind or substitution can be used repeatedly for finger gaiting as shown in figure(3) and (4) respectively. Note that in this case finger substitution is easier than finger rewind.

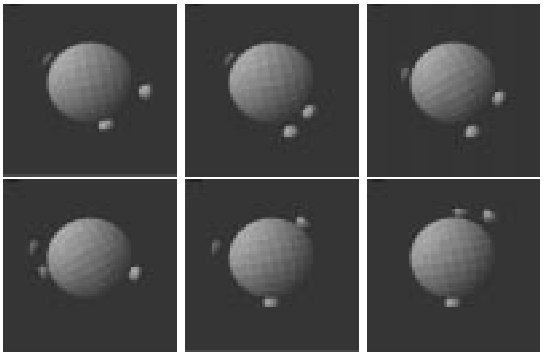

Figure 4: Manipulation with finger substitution

Figure 5: Dextrous Manipulation

The second task studied(figure 5) was to adjust the contact points and change the object configuration. Three different radii are used to distinguish the fingertips. The goal contact point of each fingertip is shown by a hemi-sphere with same radius in dark color. The initial configuration is shown in the upperleft corner of the figure set. First we use roll/pitch/yaw rotations to get the first finger reach its goal contact point and to get the other two fingers close to their goals(frame 4). Finger gaiting and rolling are then used to bring them to their goal contact points at frame 5. In the end, coordinated object manipulation will move the sphere to its goal configuration, which completes the task.

5 Conclusion

In this paper, we presented a general framework of dextrous manipulation planning by incorporating the relevant theories of contact kinematics, nonholonomic motion planning, coordinated object manipulation, grasp stability, and finger gaits. The general framework was applied to the problem of dextrous manipulation of a sphere with 3 hemi-spherical fingertips. The simulation results showed that large-scale motion were achieved by incorporating rolling movements and finger gaiting. We are currently working on generalizing this work to dextrous manipulation of general objects and incorporate the finger chains into the problem setting. More issues like contact force optimization[3], uncertainty and dynamic constraints will also be incorporated into the framework.

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