CHAPTER VII

CONCLUSION

7.1 Dissertation Summary

In this work, we consider the problem of regrasp planning on an object that is described by a polygon, polyhedron or a set of discrete contact points. Given an object, our algorithm constructs a graph structure that stores sets of force-closure grasps and captures abilities of changing grasping configurations among these grasp sets using basic operations which are finger switching and finger aligning.

For a polygon, our algorithm computes a switching graph to store sets of force-closure grasps. A node in the graph contains a set of 2-finger grasps, concurrent grasps or parallel grasps for couple or triple of polygonal edges. In the same node, a finger aligning can be performed without losing contacts on the grasped edges. A finger switching is performed to change grasping configuration between two different sets of grasped edges. This operation directly involves with an edge of the switching graph. We apply a necessary and sufficient condition for 2-finger force-closure grasp to compute a 2-finger grasp node. However, in the case of 3-finger grasps, a necessary and sufficient condition is non-linear. We simplifies the condition into two grasping types : concurrent grasps and parallel grasps of which constraints are linear. Further, representations of all grasping types are in 2D and 3D spaces, we can apply linear algebra and computational geometry theory to compute the complete switching graph.

For a polygon consisting of a large number of edges, we propose an algorithm to solve the problem of finger switching by three fingers. A node in a switching graph contain a connected set of 2-finger grasps. This allows finger aligning across edges of a polygon and also reduces computational cost of a switching graph construction. By applying the principal of L_∞ Voronoi diagram, we can locally optimize finger switching based on independent contact region criterion.

For the 3D case, for each four faces of a polyhedron, we consider only concurrent grasps which can be represented by a set of points in spatial. Out algorithm applies the same principal of the polygon case. A node of the switching graph contains a set of concurrent grasps for four grasped faces. An edge linking two nodes when there exist two grasps from the distinct nodes that change to each other using a finger switching. However, computing a complete switching graph may take much running time. We propose a random approach to compute partial solution of a switching graph. The obtained switching graph is constructed in lazy fashion, i.e., actual force-closure grasp sets are not computed when the switching graph is being constructed. The results show that the random approach drastically decreases running time but it can almost capture the topology of the complete switching graph.

For the discrete contact point set case, we propose a heuristic approach to solve the regrasp planning problem. Since the input is discrete, only the finger switching is considered. Our algorithm exploits similarities among contact points to group them into disjoint clusters. This principal is induced from the finger switching. If we want to change one contact point in a grasping configuration, contact points that produce similar wrenches are appropriate for switching. Therefore, contact points producing similar wrenches are grouped into the same cluster. A representative contact point is chosen for each cluster. A graph structure called representative-level roadmap is construted by considering 4-finger force-closure grasps whose configurations consist of representative contact points to decrease search space for regrasp planning. Clearly, this roadmap does not cover all contact points. Given arbitrary initial and target grasping configurations, a local planner is also proposed to find paths from these grasping configurations to the representative-level roadmap. In our experiments, the results show that our approach can mostly find a regrasp sequence between two arbitrary grasping configurations in a few seconds whereas constructing the complete roadmap and planning a regrasp sequence over it seem to be not possible using an ordinary PC.

7.2 Further Improvement and Extension

In this section we list some future improvement and extension that could be done to this work.

1. **Condition improvement:** All force-closure conditions applied for regrasp planning of a polygon and a polyhedron are sufficient conditions. To plan in the complete search space, necessary and sufficient conditions could be taken place. A new planner is needed to handle with non-linear constraints. Appropriate grasping representations are also required to describe a set of force-closure grasps. However, it is quite complex to compute the exact geometry of a grasp set. A node of a switch-

ing graph may contain a set of constraints instead. An edge may contain a set of constraints for finger switchings. We can apply non-linear optimization to prove the existence of a solution of non-linear constraints. we are also interested in addition of the other two types of 4-finger force closure grasps (i.e., pencil and regulus grasps) to our regrasp planning.

2. **Optimized regrasp sequence:** A regrasp sequence obtained from our algorithm is guaranteed for force-closure but it is not considered for its quality or qualities of grasps in the sequence. Quality measure metrics for a grasp can be exploited such as independent contact region, Q-distance, etc. There are many ways to determine a quality of a regrasp sequence such as integrating qualities of all grasps in the sequence or optimizing bound of qualities of all grasps in the sequence.

3. **Random approach improvement and application:** The random approach in this work uses the ordinary random function in C++ programming language. There are many probabilistic approaches in motion planning such as PRM and RRT that could be improve convergence of the switching graph construction. We can also apply the random approach to plan a regrasp sequence over pre-computed sets of force-closure grasps and finger switching in a switching graph. For example, in the case of a polyhedron, sample points in a focus cell for finger aligning and sample points in the intersection of two focus cell that have one distinct grasped face for finger switching operations.

4. **Local planning improvement:** For the problem of regrap planning for discrete contact points, we can speed up the local planner by exploiting the properties of the spectral clustering algorithm. In the clustering procedure, the measurement of a contact point is converted into Euclidean space and $L-2$ distance is used to cluster contact points. Since $L-2$ distance is metric distance function, we can apply the existence nearest neighbor search algorithms to improve the determination of sets S_i.

5. **Including hand constraints:** With pre-computed sets of force-closure grasp at hand, we can plan a regrasp sequence in these sets including kinematic and dynamic constraints of a hand without verifying for force-closure anymore. Recently, probabilistic approaches are reasonable when these constraints are included.

7.3 Discussion

An autonomous robot that accomplishes a required task with minimum supervision is a goal yearned by most researchers. A similar goal is also set for the dexterous manipulation problem. It is the uttermost goal of this dissertation to, at least, provide a stepping stone to that problem.

Recently, robot hands are widely applied to many tasks instead of human because they work with more decision and endurance. As we can see in many industries, robot hands are programmed to assembly cars or tiny circuit boards. However, the ability of the robot hands are much less comparing with a human hand. To control a robot hand, a planner has to consider many constraints : task, grasping stability, kinematic constraints and dynamic of the hand. Kinematic focuses on a robot hands' geometry, an object's geometry, configurations and limitations that allow us to derive relations among joints and fingertips' positions and also relations between the hand and the object. Many works in kinematics often assume that a robot hand is perfectly controlled neglecting hand dynamic. Actually, forces at fingertips are exerted via movements or rotations of joints in a robot hand which requires analysis of hand dynamic. The remaining procedure is to control forces and torques of joints for precision of fingertip positioning and forces exerted at the fingertips. Although hand kinematic and dynamic are necessary for analysis of the dexterous manipulation, it also requires higher level planner that provides a manipulation sequence satisfying grasping constraints. Recently, there are a few works that attack the problem of planning a sequence of finger repositioning which our work focuses on. Our planner provides a sequence of finger repositioning that all grasps in the sequence satisfy force-closure. For a given object, our approach constructs a graph structure that contains a set of force-closure grasps in a node and an edge is associated with the finger switching operation. We apply this graph structure as a framework for the regrasp planning problem. Since the graph contains sets of force-closure grasps, a planner is allowed to include other constraints such as kinematic or dynamic of an arbitrary hand for a regrasp sequence that all grasps satisfying these additional constraints also maintain force-closure.

The main advantage of the switching graph is that it *explicitly* contains sets of force-closure and sets of finger switchings. Note that the traditional necessary and sufficient conditions for computing a set of force-closure grasp on given edges are non-linear. Therefore, the set of force-closure grasps is *implicitly* represented by non-linear constraints which are complex to transform them into geometries. The advantage of our approach is strongly based on the simplifications of force-closure conditions. In 2D, we classify grasps into three types which are the 2-finger grasp, the concurrent grasp and the parallel grasp. For given grasped edges, the conditions of all grasping types can be formulated into linear constraints. A set of 2-finger grasps and a set of concurrent grasps are represented by a set of points in the plane. In contrast, a set of parallel grasps consists of polytopes in the 3D parameter space. Finger switchings between grasps in distinct two sets are computed using existing boolean operation of polygons in the plane. Although our approach simplifies the force-closure conditions into sufficient conditions, but we can solve the problem efficiently using linear algebra and computational geometry in 2D. The results evidences that the proposed approach covers a large number of force-closure grasp sets which adequate for the regrasp planning of a polygon.

For a polyhedron, we focus on concurrent grasps which are natural for 3D grasping, i.e., exerted forces intersect at a point. A set of points in spatial is used to represent a concurrent grasp set. Although the condition of concurrent grasps is just a sufficient condition, but it reduces the dimension of the representation from 8D (2 parameters for a contact point) into 3D. This condition allows us to apply the existing geometric computation library which is ACIS library to our implementation. Moreover, based on the representation of concurrent grasps in 3D, the regrasp planning problem can be efficiently solved using a probabilistic approach in low dimensions.

Our last problem is the regrasp planning for discrete contact points. Discrete contact points suit more to the data acquisition sensors, such as a laser range scanner or a stereoscopic camera which are widely available. Discrete contact point model also calls forth the need to handle input of a large number of contacts. Though it is possible to approximate the scanned data with one polynomial, this approach suffers from the high cost of curve fitting and the accuracy problem from Runge phenomenal. Spline fitting, arguably, reduces the effect of both problems but the result is still a large number of polynomials. In fact, when the resolution of the scan is large enough, spline fitting results in similar representation of discrete contact points. We realize that the use of the discrete contact point model is necessary for complete automation. Evidently, this problem is included as one objective of this dissertation.

Using discrete contact points result in an enormous number of contact points of which all force closure grasps and finger switchings must be computed. The number of the solutions can be as high as $O(N^4)$ and $O(N^5)$. It is precisely this problem that our work tries to cope with. Instead of planning in the whole search space, we apply a two-level scheme approach to plan in much smaller search space. We show that, at least, the pre-computed representative-level roadmap contains partial solutions; it is possible to solve a regrasp planning problem using our proposed local planner in much lesser time than complete approach and there are many possible improvement that could be done.

Another advantage of our framework is generality of the structure which does not specifically depend on a task or a robot hand. The switching graph can be considered as a middle level in manipulation planning. Given an initial grasp and a goal grasp from a task planner, the switching graph provides sets of force-closure grasps and finger switchings that involve changing of grasps between the two grasps. These sets and their relations are then transferred to lower levels to compute feasible trajectories of a hand constrained on the grasp sets and the finger switching sets. More practically, the switching graph can be applied to other planner. Computed grasp sets serve explicit wrench closure sets for the approach in (Jr et al., 2004). Also, finger switching sets can be applied to search for transitions of contacts. For the recent approach in (Saut et al., 2007), the switching graph provides the explicit grasp subspaces from which a PRM planner can sample grasp sequences without verifying all generated grasps for the force-closure condition. Another advantage is globalization of the switching graph. Once we compute a switching graph that contains all force-closure grasps for an object, the switching graph then allows a planner to globally search for sets of force-closure grasps and finger switchings.

The author strongly believe that, with the proposed algorithms and the proposed approaches, we could see many interesting, or the ultimate, solution to the dexterous manipulation problem in the near future.