

# CHAPTER I

## INTRODUCTION

The ability to manipulate objects is one of the fundamental tasks which we need a robot to interact with its surroundings. Grasping and regrasping are operations which a human performs to change the environment by grabbing an object, lifting and placing it to another position or another posture. This seems to be a natural and simple ability for a human but not for a robot. The robot does not have its own instinct to perform any task. It has to be controlled restrictively on a task, the geometry of an object, the constraints of itself and the environment. This challenges robotic researchers to analyze and transfer these manipulation skills to a robot in the recent decades.

The central idea of manipulation is to move an object to a desired configuration while the object being restrained in stable states. One approach of object manipulation is grasping an object in a fixed stable grasping configuration and then moving the object from place to place. However, the pick and place operation is performed by a motion sequence of an arm which requires a large workspace to change the grasping configuration even for manipulating a small object. Further, it requires a stable placement for the object when the robot changes a grasping configuration. To avoid these limitations, an in-hand manipulation is taken place to bring the object through several actions by changing grasping configurations without releasing the grasped object. The operation of changing a grasping configuration is usually called *regrasping*. To achieve a manipulation task, the fingers have to be moved several times to reach the target posture. This arises the *in-hand manipulation planning problem*, given an initial grasp and a target grasp, the goal is to compute the sequence of the fingers' movements which changes the grasp to the target position while still maintaining stability. For manipulation involving grasping, to verify stability of a grasp, the *force-closure property* is usually considered in several literatures dealing with the grasp synthesis problem.

In a manipulation, we have to consider all constraints arising from a task and a robot hand. Despite planning a manipulation sequence considering all these constraints could accomplish a task, there are some kinds of arising restrictions and drawbacks. All complexities are gathered in the manipulation planning that might use non-reasonable time to compute a simple manipulation sequence. Further, combining mechanical constraints of a robot hand in planning confines the result manipulation sequences to the specific robot

hand platform. Therefore, the manipulation sequences may be not feasible for another hand platform.

The problem is that, currently, we have so many tasks, so many objects and so many robot hands. There is no algorithm that works best on all settings. This is mainly because tasks, objects and robot hands are varying. The problem of task/object/hand dependency is the inspiration of this work. We propose to decompose the manipulation problem into layers. We split the problem into three main levels, each of which considers task constraints, object constraints and hand constraints separately. It allows a hardware practitioner to concentrate on creating a hand. At the same time, we can imagine any use of robot in manipulation. The advantage of the decomposition is that robot visionaries can abstract their manipulation algorithms away from constraints and limitations of the recent robot hand developments.

We aim to derive a framework that shall be applicable to any task, any object or any robot hand. The key concept is simple; a task and a hand impose on manipulation planning many constraints, which we simply decide to neglect them. Without any assumption on a task or a hand, solutions from the algorithm will be dependent only on the object being manipulated, not with any predefined hand or task. After solutions are identified, when knowledge of a hand and a task is provided, we then find solutions that satisfy the arising constraints.

Given an object to be manipulated, a condition that can be verified without considering constraints of a task and a robot hand is the force-closure condition because we can consider only contact positions of the end effectors which are applicable only for force-closure verification. This reduces our consideration into the problem of planning a sequence of the end effectors from an initial grasp to a target grasp while all grasps in the sequence maintain force-closure. We call a sequence of changing the end effectors' positions *regrasp sequence*. The problem of determining such sequence is referred to as *regrasp planning problem*.

This work studies the problem of regrasp planning which computes a sequence of finger repositioning from initial grasping configuration to a desired configuration for polyhedral-modelled object and a set of discrete points based on the following assumptions. The polyhedral model is chosen because most objects in the real world can be represented by linear surfaces. An object is described by linear segments in 2D and flat surfaces in 3D. Further, since the representation of an object is linear, we can efficiently

solve the regrasp planning problem using existing linear algebra and computational geometry algorithms. For a complex object, we describe it by a set of discrete points on its surface. Approaches to handle this problem setting in both 2D and 3D workspace are also proposed.

The hands are assumed to be equipped with three or four in 2D workspace and five fingers in 3D workspace. 2- and 3-finger grasp are sufficient to grasp a 2D object and 4-finger grasp is sufficient to grasp a 3D object. The other one finger is used to switch grasping position. Our planner aims to construct general solution satisfying grasping constraints regardless task constraints, kinematic constraints, dynamic constraints, etc. The most advantage of general solution is independency. It is applicable to any task or hand in the real world. A finger is therefore assumed to be a free-flying point contact. To maintain stability, grasping constraint considered in this work is associated with force closure property. Every grasping configuration in the obtained sequence of finger repositioning has to satisfy force closure property to ensure stability during the entire repositioning process.

## 1.1 Related Works

Regrasp problem consists of various problems in many subfields on robotics. Firstly, we have to define what we want the robot to do. This is according to task constraints. Based on the classification of grasp by Cutkosky (1989), two main grasping types are concerned, fingertip grasp and power grasp. Fingertip grasps achieve dexterity by holding the objects by the tips of the fingers. Power grasps are distinguished by large areas of contact between the object and the fingers and palm which do not allow the motion of the grasped object. The grasps perform with low dexterity. For regrasping, the fingertip grasps are preferred since the problem required dexterity of grasps.

Regrasp planning is the main theme of this work. The method reports a sequence of fingers' position from initial grasp to desired grasp given by task planner. The obtained grasping positions not only associate with task requirement but also satisfy stability constraint. The force closure property is applied to satisfy the stability constraint. This means that every grasping position in a sequence calculated by the method has to achieve force closure grasp.

In practice, a robot finger is not a point. A grasp has to satisfy kinematic constraints and dynamic constraints as well. Motions of fingers when a regrasp process is performed, also introduce to a manipulation planning problem which mainly mentions accessibility

and collision avoidance of a path from an initial configuration to a desired one.

### 1.1.1 Robot Hands

Dexterous manipulation or regrasp problem require a manipulator which is able to change a grasped object's configuration with respect to the hand without releasing it. The robot hand is one suitable manipulator for this task. It may be designed to be an approximation of the human hand or specified for particular tasks. A well-known 3-finger robot hand is Barret Hand(Townsend, 2000) commercially made by Barrett Technology Inc. Two fingers can be spread synchronously by  $180^\circ$  around the palm. The Utah/MIT hand (Jacobsen et al., 1986) is the first anthropomorphic hand with four fingers. Each finger has four degrees of freedom. The whole hand system is very large including the out-hand actuators. The Robonaut hand (Lovchik and Diftler, 1999) designed for space based operations has five fingers. The hand combined with wrist and forearm has fourteen degrees of freedom. Another anthropomorphic hand is the DLR-Hand (Butterfaß et al., 2001). The hand consists of four fingers with the actuators embedded inside.

### 1.1.2 Contact Kinematics, Dynamic and Control of Manipulation

When the object has been grasped, the hand is possible to perform in-hand manipulation. To gain more dexterity, the hand is not required to maintain a rigid grasp. It may therefore roll, slide or release and place fingers to change the grasp configuration. The accurate control of the force applied to the object, which associates with the contact constraints is required to achieve the operations.

One approach that the dexterous hand manipulates an object, is exploiting a rolling contact. Rolling is the operation that the fingertip rolls without slipping on the object's surface. It is defined by the constraints that the fingertip and object velocities are equal at contact point. The kinematic constraints and transformations between task-space and local coordinates are presented in (Kerr and Roth, 1986) and (Montana, 1988). The rolling constraints are formulated in different ways. Kerr and Rott (1986) derived the force analysis for the systems using a set of differential equations to describe the motion of the object with pure rolling contact. Montana (1988) proposed a method for relating relative rigid body motion to the rates of change of contact coordinates using a matrix formulation of the motion of a point of contact over the rolling surfaces. Sarkar *et al.* (1997) introduced local contact coordinates which allow them to formulate the dynamics and control of manipulation via rolling contacts in explicit equations relating the velocities and ac-

celerations of the contact points. The formulation admits motion of the contacts during the manipulation process. Li *et al.* (2000) developed a unified formulation describing the relationship between the object motion and the joint motion.

Dexterous manipulation sometimes exploits slippage between the fingers and the object to change grasping configuration. Sliding a finger along the surface of an object requires a good model of the contact friction which is mostly assumed Coulomb friction model. A finger exerts a force inward to the object's surface when it slides along the surface. According to Coulomb friction model, when the finger is sliding, the contact force must lie on the edge of the friction cone. Brock (1988) derived a kinematic relation between the object motion, the motion constraints and the grasp forces. Cole *et al.* (1989) presented a coordinated control law for sliding contacts between an object and fingertip including a problem of choosing contact positions for collision avoidance. In (Cole *et al.*, 1992), the sliding motion of the fingertips along the object's surface is dynamically controlled simultaneously with controlling the position and orientation of the held object. Zheng *et al.* (2000) formulated a dynamic control of a 3-finger robot hand manipulating an object in 3D. One finger is allowed to slide on the object's surface. Motion equations of the whole system are derived. They also proposed a dynamic control law for linearizing the system dynamics and realizing the desired object motion, the desired finger sliding and desired grasping force.

Combinations of rolling and sliding are in consideration as well. Cai and Roth (1987), (1988) studied spatial motions combining rolling and sliding between rigid bodies for point contact and line contact, respectively. Chong (1993) proposed an algorithm generating finite motion of object by considering sliding contacts as well as rolling contacts between the fingertips and the object. The minimum contact forces and minimum joint velocities are solved for the relative velocity at the contact point.

Forces applied to the object by the fingers are controlled for the desired manipulation. Kerr and Roth (1986) developed a hand Jacobian which calculates the joint torques from the desired contact forces. Yoshikawa and Nagai (1988) decomposed forces into two components. Manipulating or external forces produce a net force and torque on the object. The other forces are grasping or internal forces which produce no net force nor torque on the object. These forces are used to maintain a secure grasp. The same authors gave a physically reasonable definition of manipulating force and grasping force for 2-, 3- and 4-finger hands in (1991). They also presented an algorithm for decomposing a given fingertip force into manipulating and grasping forces. Using the concept of the manip-

ulating and grasping forces, they proposed a dynamic manipulation/grasping controller of multifingered robot hands based on the dynamic control and the hybrid position/force control. The controller consists of a compensator which linearizes the whole grasping system and a servo controller for the linearized system. Nakamura *et al.* (1989) discussed the dynamical coordination of a multifingered robot hand. The coordination problem is solved in two phases. Firstly, determine the resultant force used for maintaining dynamic equilibrium and for generating the restoring force. Secondly, determine the internal force used to satisfy the static frictional constraints and is related to contact stability. Li *et al.* (1998) studied a formulation of dynamic stability of grasping using Lapunov stability theory for measurement purpose.

The systems discussed above are formed by complex constraints. A system that a manipulation is achieved by low velocity motions is called quasi-static. Quasi-static analysis results are therefore much simpler and practical. Fearing (1986) considered slip from a quasi-static viewpoint to achieve grasp stability. Yoshikawa *et al.* (1993) used controlled slip in quasi-static system to modify the grasp and increase manipulation range for a 3-finger robot hand.

### 1.1.3 Grasp Definition

Secure holding an object in a robot hand is required in grasping. The concept of a firm grasp is formalized in various ways. Equilibrium, force closure and form closure property are usually applied to ensure the stability of a grasp. Equilibrium grasp is a grasp that the resultant of forces and torques exerted to the grasped object are zero. According to the definition, an equilibrium grasp cannot resist any disturbance. This property is therefore not sufficient to ensure the stability of a grasp. Force closure grasp is a grasp that can exert a resisting force and torque balancing any external disturbance on the object. A closely related property to force closure is form closure firstly investigated by Reuleaux (1963). The distinction between form closure and force closure is that form closure considers the immobility of an object in presence of fixed contact points whereas force closure considers how contact points can exert force and torque on an object. Another difference between form and force closure is the presence of friction. Friction effect is considered in force closure while it is neglected in form closure analysis. Markenscoff *et al.* (1990) provided an upper bound to the number of contacts necessary to achieve form closure grasps. They showed that four contact points are sufficient for the form-closure grasp of any planar object and seven contact points are sufficient in spatial case. Bicchi (1995) considered form closure as a purely geometric property of a set of contact

constraints. Rimon and Burdick (1996) gave precise definitions for first and second order form closure for frictionless grasps based on mobility theory. They also showed that a frictionless grasp is force closure if and only if it is form closure for both first order and second order.

#### 1.1.4 Force Closure

To ensure that the object is grasped securely, the classical force closure condition is employed. A grasp of an object achieves force closure when it can resist any external wrench exerted on the grasped object. The well-known qualitative test for a force closure grasp is to check whether the contact wrenches of the grasp positively span the whole wrench space (Salisbury, 1982). This is equivalent to checking whether the convex hull of the primitive contact wrenches contains the origin (Mishra et al., 1987b). Various approaches for testing whether the origin is inside the convex hull are proposed. Yun-Hui Liu (1998) proposed a recursive reduction technique which allows the problem of testing convex hull containing the origin in high dimensions to be solved in the lowest dimension. The same authors transformed this problem to ray-shooting which can be solved by linear programming (Liu, 1999). Zhu and Wang (2003a) developed the force closure test based on the concept of  $Q$  distance which uses a convex hull containing the origin as a metric to test whether the origin lies in the interior of the convex hull of the primitive wrenches. Recently, Zhu *et al.* (2004) discussed that the problem can be transformed into the problem of calculation of distance between convex objects. They proposed the use of pseudodistance function to solve the problem.

Other approaches of qualitative test for a force closure grasp by considering the workspace, not the wrench space, were also investigated. Nguyen (1988b) proposed a geometric method for testing 2-finger force closure grasps on polygonal objects. The synthesis of stable grasps was proven by constructing virtual springs at the contact points, such that a desired stiffness matrix about its stable equilibrium can be acquired. Ponce *et al.* proposed the concept of non-marginal equilibrium which implies the force closure property. Based on this concept, the qualitative tests of 3-finger grasps for polygonal objects (Ponce and Faverjon, 1995a) and 4-finger grasps for polyhedral objects (Ponce et al., 1997) were proposed.

For regrasping, a set of force closure grasps has to be calculated. In (Ponce and Faverjon, 1995a) and (Ponce et al., 1997), a grasp is represented by parameters related to positions on the grasped faces. To calculate all possible grasps, two(three) additional

parameters are required to construct linear constraints for 2D(3D) case. The additional parameters have to be eliminated to acquire a set of force closure grasping positions on given grasped faces. Sudsang and Ponce (1995) proposed another representation of grasps avoiding the use of additional parameters. A point in workspace is used to represent a set of force closure grasps.

Quantitative tests of force closure grasps are also considered to define the quality of grasps. Kirkpatrick *et al.* (1990) considered the most general stability measurement which does not know a priori knowledge of disturbance. An external wrench is assumed to be uniformly distributed in every direction. The minimum magnitude of a particular external wrench that breaks force closure property is measured. This is equivalent to the radius of the maximal ball that can fit inside the convex hull of primitive contact wrenches. Ferrari and Canny (1992) applied this criterion to plan the optimal grasp. The radius of maximal ball is used in many works, such as (Mirtich and Canny, 1993; Borst *et al.*, 2003; Jia, 1995).

Recently, the best performance in resisting external wrenches as the optimality criterion is still studied. Yun-Hui Lui (1999) addressed the problem of minimizing the  $L_1$  norm of the grasp forces in balancing an external wrench, which can be transformed to ray-shooting problem. Zhu and Wang (2003a) addressed the problem of planning optimal grasps that minimize the  $Q$  distance and expresses the best performance in firmly holding an object while resisting external wrench loads. Zhu *et al.* (2004) solved the same problem by optimizing the pseudodistance function.

Methods mentioned above are used to determine grasps that require precision of fingertip on the objects. To allow some positioning errors, the notion of *independent contact regions* was introduced by Nguyen (1988b). In short, an independent contact region is a parallel-axis rectangular region in fingers' configuration space which represents areas on object's boundary where fingers can be placed independently to compose a force closure grasp. In (Nguyen, 1988b), Nguyen also showed how to geometrically determine independent contact regions for 2-finger grasps of a polygon. Tung and Kak (1996) attacked the completeness of the previous work and proposed an algorithm which is correct and complete. Recently, Cornella and Suarez investigated an algorithm of determining independent grasp regions on 2D discrete objects (Cornella and Suarez, 2005a). A four frictionless grasp is considered. The algorithm determines the independent regions of two fingers when the locations of the other two fingers are given.

In order to find the *best* independent contact region, one needs to define what *best* means. There have been many different definitions of the best independent contact region due to different purposes and constraints of grasping devices. The two popular criteria are: (1) the largest n-cube, and (2) the largest rectangular region (product of lengths on every axis). Using the first criterion, the optimization can be done by linear programming as discussed in (Ponce and Faverjon, 1995a) and (Ponce et al., 1997). Faverjon and Ponce (1991) tackled the problem of 2-finger grasping on curved objects using the second criterion. In their work, a numerical optimization algorithm was presented, but they could not guarantee the algorithm's completeness. Cornella and Suarez (2005b) presented an approach to determine independent contact regions on polygonal objects considering arbitrary number of friction or frictionless contacts on given edges. Their approach subdivides configuration space so that the graspable region in each subdivision is convex, then computes the independent contact region in each subdivision.

### 1.1.5 Regrasp Planning

Regrasp or dexterous manipulation is required when a grasp is not appropriate for a specific task. A planner calculating a sequence of feasible configuration of robot hand and object transforming to the desired one is applied to solve the problem. The obtained results from a planner have to satisfy constraints considered in the system. The distinction between various planners are constraints discussed above, kinematics, dynamic, stability constraints, etc. In this work, force closure constraint is satisfied only for more general results. Some different planners are discussed here.

Hong *et al.* (1990) proved the existence of two and three finger grasps for 2D and 3D objects assuming isolated hard point contacts with friction. The manipulated objects are assumed to be smooth. This paper also proposed a fine motion of an object by repositioning the grasping fingers while maintaining a grasp during entire process. A subclass of fine motion problem focused in this paper is gait problem. Finger gaits with three and four fingers on the plane are proven for the existence. For the prove of three finger gait, a two finger force closure condition is taken into consideration. In the case of four finger gait, two different gaits can behave which are using two pairs separately or using a three finger grasp and replacing one finger with the remaining finger to form a new grasp.

Regrasp planning for reorientation of a prism was addressed by Omata and Nagata (1994). The 4-finger hand and frictional contact point are assumed. The planner plans

a sequence of repositioning of fingers for horizontal rotation of an object for a desired angle. The calculation of finger repositioning are classified into three problems. Problem  $A(c)$  tests whether the finger  $c$  can be removed from the initial grasp. This problem can be solved by linear programming method. Problem  $B(c, n)$  is solved for calculating feasible region of finger  $c$  to form equilibrium grasp without finger  $n$ . The last one is problem  $C(c, n, d)$  which calculates the feasible region of finger  $c$  when finger  $c$  and  $n$  form a grasp without finger  $d$ . These two problem can be solved by non-linear programming. Problem  $C$  is harder and takes more calculation time than  $B$ . Sequences of finger repositioning are attained by a search tree. Each node represents a removed finger. The search algorithm begins with solving problem  $A(c)$  then solves  $B(c, n)$  to remove finger  $n$  and bring finger  $c$  to form a grasp. Problem  $C$  will be solved when the problem  $B$  cannot produce feasible solution. Child nodes are expanded according to a heuristic function. The function is based on a angle which a grasp can rotate the object, the depth of a node and the penalty when problem  $C$  has to be solved.

Omata and Farooqi (1996) studied object reorientation by using regrasp primitive. Two primitives are carried out for reorientation task. The *rotation* presented in (Omata and Nagata, 1994) is a primitive that the fingers grasp on the side faces of the object and rotate it. The *pivoting* primitive uses the two fingertips to form an axis of pivoting and the third finger exerts the force on the side facts to rotate the object about the axis. The algorithm of this primitive is explained in this paper. Based on the following assumptions, four fingered hand and a prism object, sequential executions of these primitives can achieve reorientation. The search tree is applied to solve the problem. Each branch represents a primitive and each node contains the current orientation. The search procedure uses quaternion concept to solve resultant rotation about a unique axis.

An approach to solve the problem of dexterous manipulation using geometrical reasoning techniques was proposed by Munoz *et al.* (1995). Kinematic constraints are respected by checking non-penetration between the fingertips and the object. Some accessibility limitations due to the kinematic constraints of the hand are also considered. Three manipulation modes, which are fixed-point, rolling and sliding, are applied in the planning algorithm. A combination of manipulations in these three modes can form a nominal trajectory of a task that the object is being grasped by a dexterous hand. A manipulation task is represented by a homogeneous transformation that brings the object from its initial configuration to its final configuration. The planner decomposes the transformation into a sequence of infinitesimal motions by exploring the space of potential solutions for the

problem of changing the orientation of the grasped object. Each infinitesimal motion is solved for every manipulation mode. The equilibrium constraints are considered in this procedure. A solution is represented in the form of joint motion. The minimum joint motion is selected by the planner for the particular infinitesimal motion.

Leveroni (1997) addressed finger gait problem for a planar convex object. One method to determine whether local motions will suffice to reorient the object is the grasp map, a graphical representation of all stable grasps. Workspace map is constructed to determine workspaces of three fingers. A sequence of finger gaits can be extracted from the combination of the grasp map and the workspace map. In planning, a new grasp cannot always be found if the object is moved locally until a finger reaches a workspace limit; often a grasp gait must occur before the limit is reached.

In (Cherif and Gupta, 1997), The system of Cherif and Gupta assumed that the manipulation system processes at low velocities. Planning feasible quasi-static trajectories for the fingertips to move object to a desired configuration is available. Two motions which are rolling and sliding the fingertips on the surface of the object are considered. The planner is a 2-level planning scheme. The global planning level applies an  $A^*$  search algorithm to find connectivity between sub-goals in the configuration space of the object. The nominal path generated by this planner ignores any manipulation constraints. The second level is the local manipulation planner. The local planner is based on solving an *inverse finger motion problem* to plan for feasible quasi-static motions of the hand-object system between sub-goals. The instantaneous solution satisfies collision-free, reachability, friction and equilibrium constraints.

Han and Trinkle (1998b) proposed a Framework for dextrous manipulation by rolling fingers on the surface of an object and finger gaits. Three taxonomies of manipulation tasks for multifingered hand systems are stated: *Object Manipulation*, *Grasp Adjustment* and *Dextrous Manipulation*. The contribution of this paper is to propose a general methodology to implement large-scale object manipulation tasks when the capability of the fingers are limited by their workspace. Two strategies, *finger rewind* and *finger substitution*, are applied to accomplish a task. Dextrous manipulation of a sphere is exemplified. The condition of two soft-finger and three hard-finger force closure grasp are derived for spherical object. The trajectory of the finger on the object is restricted to be a great circle which simplifies contact constraint.

Regrasp planning for discrete contact points using independent regions is proposed

in (Roa and Suarez, 2009). The regrasp operation that is allowed in the work is only motion of a finger without contact breaking. The main restriction of applying only regrasp operation is that the approach fails to find a path between two grasps in distinct connected grasp sets.

### 1.1.6 Dexterous Manipulation Planning

Since an object cannot move by itself. The robot hand has to grasp and move it from one stable position to another. The objective of the planner is to calculate a path of robot hand and object's configuration from an initial configuration to a desired configuration while avoiding collision with obstacles, other objects and self-collision.

Modelling the problem with as fully dynamic and using control-based planning is costly expensive. Thus, Alami *et al.* (1989) developed another approach using two distinct paths which are transfer paths and transit paths. The former are defined as motions of the system while the robot hand grasps the object. Transit paths are defined as motions of the robot when it moves alone while the object is in a stable position. Regrasping operation is also calculated by the planner. Based on this concept, Koga and Latombe (1994) solved the manipulation problem for robots with many degrees of freedom. The planner compute a series of transfer and transit paths for the robot that make the robot grasp and move the object from an initial configuration to a goal configuration. Recently, probabilistic algorithms are applied for manipulation planner under continuous grasps and placements in (Siméon *et al.*, 2002), (Sahbani *et al.*, 2002).

Nielsen and Kavraki (2000) developed a manipulation planner which extends the probabilistic roadmap (PRM) frameworks. The planner consists of two levels. The first level builds a manipulation graph. Nodes represent stable placements of the object. Edges represent transfer and transit actions. The actual motion planning for the transfer and transit paths is done by PRM planners at the second level. The fuzzy roadmap was introduced to apply in both levels. The computations is efficient by verifying that the edges are collision-free only if they are part of the final path. Instead, the local planner assigns a probability to the edge that expresses its belief that the edge is collision-free.

Sahbani *et al.* (2002) proposed a probabilistic algorithm for manipulation planning under continuous grasps and continuous object placements. Instead of classifying the regrasping operation as another subproblem, their approach transforms a regrasping operation into a finite sequence of transfer and transit paths. Therefore, a particular planner

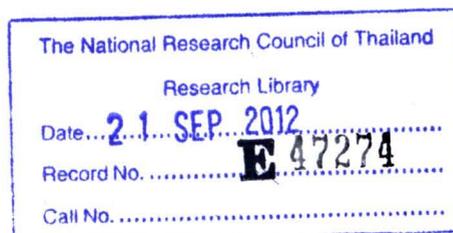
for the regrasping operation is not needed.

Saut *et al.* (2007) attacked in-hand manipulation planning problem by using PRM. Two fundamental paths are applied which are transfer path and regrasp path. The object is immobile and some fingers move to change the grasp during a regrasp path. Based on PRM, a manipulation graph is constructed to plan a path between initial and goal configurations. Instead of sampling a hand's configurations in configuration space, grasping configurations are sampled over grasp subspaces and then verified chain closures at contact positions by considering the kinematics of the robot hand.

Xu and Li (2008) solved finger gait problem for a smooth surface object by evolution of hybrid automaton. The finger gaits is analyzed into discrete and continuous characteristics. The discrete variables describe two actions of all fingers in either manipulation mode or substitution mode. The continuous variables represent the controls of the fingertips in continuous time. In (Xu et al., 2007), the hybrid automaton is used for finger gait planning by improving the RRT approach such that the discrete metric and continuous metric are defined on the state space.

Huber and Grupen (2002) presented finger gaits as finite state control strategies in a discrete event dynamic system framework. A small set of control laws are used as basis controllers to solve a manipulation task in a bottom-up fashion. However, actual contact locations and object motions are computed based on local contact information. Therefore, this framework suits for local manipulation planning. Platt *et al.* (2004) presented a control basis capable to generate a variety of force-based interaction focusing on the grasp and contact artificial potentials. Finger gaits are formulated into states and actions modeled in a Markov Decision Process (MDP) which is defined over the space of wrench closure conditions. However, this space is not explicitly computed. A state in the MDP is not a geometrical assertion but a report about the membership of grasps in the state.

Finger repositioning can be casted into a stratified system. Goodwine and Burdick (2002) proposed a nonlinear motion planning algorithm in a stratified configuration space. The configuration space of finger reposition consists of several smooth strata corresponding to the conditions of fingers used in manipulation. Harmati *et al.* (2002) developed a fitted stratified manipulation planning algorithm which works on a space that a fingertip position is described more directly to its representation in the real physical system. A semi-stratified was also proposed by assuming that a finger can be moved freely in the space to provide a greater degree of freedom for finger repositions in manipulation plan-



ning and to allow more constraints taken into account. However, most works about the stratified system study relations between a manipulated object and joint configurations or fingertip positions while force-closure condition is mostly assumed. Therefore, result trajectories obtained from these frameworks have to be verified for the force-closure condition for a practical use. Trajectories that do not achieve force-closure are not applicable in a real manipulation.

## 1.2 Problem Statement

Given an object (a polygon or a polyhedron or a set of contact points), an initial grasp and a goal grasp, we wish to identify a regrasp sequence from the initial grasp to the goal grasp.

### 1.2.1 Contribution

The contribution of this work is to proposed a framework for regrasp planning problem. Our planner reports a general set of feasible finger repositioning satisfying force closure property for task and constraint independence. An approach using a structure called *Switching Graph* has been introduced. Connectivity in a graph presents ability to change a grasping configuration to another. This allows the regrasp planning to be transformed to graph search. A node in switching grasp represents a connected set of force closure grasps for given surfaces. Any grasps of which representations are in the same node can be transformed to one another using finger sliding along the continuous surfaces. An edge connecting two nodes indicates the ability of switching one finger to another different surface. Based on this structure, the obtained results are not a single solution, they are a set of feasible solutions. An advantage of a set of solutions is that it allows any planner to find a sequence of grasping positions which optimized according to some considered criteria or to add more constraints for practical uses.

## 1.3 Dissertation Outline

In the next chapter, we provide a theoretical preliminaries on grasping which is used subsequently in the remaining of the dissertation. The remaining chapters describe algorithms to solve the problem in each setting which are regrasp planning for a polygon, a polygon with a large number of edges, a polyhedron and a discrete contact point set.

Finally, Chapter 7 concludes our work and describes future extension of our work.