Chapter 1

Introduction

The use of robots in industry entails an increase in the productivity and in the quality of the products, while allowing the performance of a vast range of tasks due to their flexibility. Yet, the use of robots is not widespread and is mainly restricted to tasks performed in a structured environment, and that do not require much accuracy, like welding or painting, where the robot is limited to repeat a fixed sequence of preprogrammed motions.

The use of robots to automate other tasks has been mainly restrained by the difficulty of programming them. These tasks, like for instance the assembly tasks, may require the use of sensors and of motion planning strategies in order to cope with different types of uncertainties and with changing environments. Therefore, the programming of these tasks is difficult, and the use of a system able to automatically program them is desirable, i.e. a system able to program the robot motions from a high level description of the task.

Since assembly tasks are an important part of the manufacturing processes, the automatic programming of robotic assembly tasks is an important challenge, and one of the main topics in robotics research.

1.1 Framework

The manufacturing costs may be reduced if robots are used to automate assembly tasks, basically due to:

- An increase in the productivity and in the quality of the products thanks to the reliability and repeatability of the robots,
- The ability to reconfigure the assembly cells to a broad range of tasks thanks to the flexibility introduced by the robots.

The second reason is an advantage with respect to the rigidness of hard automation. Nevertheless, the automatic programming of the assembly tasks is necessary, since the time to reprogram the system plays an important role. The automatic programming faces several problems, covering the fields of artificial intelligence and control engineering, as for example:

- *The uncertainties and the manufacturing tolerances:* The uncertainty in the robot control, in the sensory information, and in the positioning of the parts to be assembled, together with their manufacturing tolerances, make it difficult to successfully perform the task from a preprogrammed robot trajectory.

- *The use of sensors:* Sensors are needed to adapt the robot trajectories to the perceived environment, which may be different from the nominal one due to uncertainties, or may be a changing environment. Therefore, the right sensors to be used, the processing and fusion of the sensory information, the planning of sensory strategies, and the real-time constraints of the sensing-action cycles, are problems to be solved.

- *Contact motions:* During the assembly tasks the manipulated object may be in contact with the objects in the environment, giving rise to the need of contact motion control.

- *Task analysis:* The specification of the assembly sequence, the specification of the sequence of motions to assemble two parts, the determination of error detection and recovery strategies, and resources planning are problems related to the analysis of the assembly task.

The research areas that tackle these problems are *Assembly Planning* and *Task Planning*. A thorough taxonomy of these fields has been developed by the IEEE Technical Committee on Assembly and Task Planning [44]. A survey and categorization of the requirements of automated assembly planners can be found in [57]. *Assembly planning* focuses on the analysis of the assembly task and copes with:

- *Assembly representations*: Study of the best representation of the assembly parts and operations in order to facilitate the planning activities.

- *Workcell planning*: The planning of the required resources to perform an assembly task, or the planning of the use of the available resources in the workcell.

- *Sequence planning*: The planning of a feasible and optimal sequence of operations to perform the assembly task.

- *Determination of mating pose*: The automatic determination of the transformation describing the pose of an object from a symbolic description of its relative pose with respect to other objects.

- *Design process*: The use of the constraints imposed by the assembly operations in the design process of the parts to be assembled.

Task planning focuses on the synthesis of a plan to carry out the assembly task, i.e. a plan to determine which actions may be executed by the robot to perform an assembly operation. Since the robot actions may include sensing operations, gross motions, fine motions or grasping operations, the task planner may invoke low level planners, like motion, sensor or grasp planners, to detail these specific operations. Therefore, *Task planning* must cope with:

- *Analysis of uncertainties and manufacturing tolerances*: Analysis of the uncertainties that affect an assembly task, how to model them, how to take them into account when planning a motion; study of the tolerances, their representation and their propagation in order to analyze the feasibility of an assembly.
- *Planning of sensory operations*: Study of the necessary sensory information, its processing and fusion, and the planning of sensory strategies.
- *Gross-motion planning*: Determination of collision-free trajectories to be followed by the robot when not performing matting-part operations (uncertainties are ignored, since they are small relative to the clearances between the objects in the workcell).
- *Fine-motion planning*: Determination of the trajectories to be followed by the robot when the manipulated object is in contact with the environment, or when it may be in contact due to the uncertainties being not small enough relative to the clearances between the manipulated object and those of the environment.
- *Grasp planning*: Determination of strategies to grasp the objects to be manipulated, which may include the need of regrasping and uncertainty reduction strategies.
- *Force control*: Analysis of the different force control schemes to move the manipulated object in contact with the objects in the environment maintaining a constant bounded force.
- *Task execution and monitoring*: Determination of error detection and recovery strategies to be carried out, if necessary, when an assembly task is executed.

Within this framework, this thesis focuses on fine-motion planning, which involves other issues of task planning, in particular the analysis of uncertainties and manufacturing tolerances, force control and task execution and monitoring.

1.2 Objectives

The performance of robot trajectories obtained from the nominal description of the task may fail if the uncertainties are not small enough relative to the clearances between the objects to be matted. Nevertheless, by using sensory information, the robot motions are able to adapt to the deviations due to uncertainties. These motions, known as *compliant motions*, specify how to modify a trajectory from sensory information when the objects to be matted are in contact. Therefore, a trajectory defined as a sequence of compliant-motions may be able to successfully perform the execution of an assembly task.

The aim of this thesis is to develop a system able to automatically plan and execute a sequence of compliant motions to perform a robotic assembly task.

The system takes into account:

- Modelling and sensing uncertainties.
- The effect of friction.
- The availability of configuration and force sensory information.

The following constraints are assumed:

- Planar assembly tasks (two degrees of freedom of translation and one of rotation).
- Polygonal and rigid objects.

Section 1.3 presents the related works coping with the automation of robotic assembly tasks, and Section 1.4 presents an overview of the approach of this thesis, including the contents of each chapter.

1.3 Related work

1.3.1 Compliance

Several reasons make it difficult to perform an assembly task, like the manufacturing tolerances, the sensing and control uncertainties, and the uncertainties in the positioning of the objects to be assembled. The use of compliance, either passive or active, allows the performance of constrained motions in the presence of uncertainty, by mapping reaction forces to corrective motions.

Passive compliance uses a flexible mechanical device mounted at the wrist of the robot, that corrects the position of the manipulated object when it is submitted to reaction forces. The RCC (Remote Center of Compliance) is the best known passive compliance device [104]. The RCC defines a point in the space - the accommodation center - in such a way that the applied forces produce displacements and the applied torques produce rotations about this point, being the elasticity of the device a fixed parameter. A new analysis of the properties of the RCC devices are presented in [24]. An enhanced version of an RCC device, the Spatial Remote Center of Compliance SRCC [92], has been proposed which corrects spatial misalignments of prismatic parts of general cross section.

Active compliance uses an active device, usually the robot itself, to modify the position of the manipulated object as a response to sensed reaction forces. Active compliance allows a programmed compliance, which requires the robot to be force controlled besides being position controlled. Some of the control schemes used to achieve active compliance are the generalized damping control [103], the stiffness control [85], the impedance control [53], the hybrid position-force control [81], and the parallel force-position control [22]. A detailed analysis of active compliant motions can be found in the works of Mason [71], Kazerooni [59], and De Schutter and Van Brussel [29, 30, 15].

Two research lines use active compliance to perform assembly tasks. The first one is based on fine-motion planning, which relies on geometrical path planning. A fixed predefined accommodation matrix is assumed (usually lineal and diagonal), and a sequence of motions is determined with the maximum probability of success, given the geometry of the task and the uncertainties affecting it. The second one is based on the reactive control approach. It is devoted to synthesize an accommodation matrix for each assembly task (that usually will not be neither lineal nor diagonal), that transforms the sensed reaction forces to corrective motions in order to succeed in the performance of the task despite the deviations due to the uncertainties.

1.3.2 Fine-motion planning

The approach of fine-motion planning to the automatic performance of assembly tasks with robots is devoted to automatically synthesize a sequence of compliant motions, from the task geometry and taking explicitly into account the uncertainties affecting it, that permits the successful performance of the tasks.

LMT approach

One of the most significant fine-motion planning approaches is due to Lozano-Perez, Mason and Taylor and it is known as the LMT approach [70]. This is a formal approach to the automatic synthesis of compliant-motion strategies from geometric descriptions of assembly operations and explicit estimates of error in sensing and control. It provides criteria for the correctness of the obtained compliant-motion strategies. The approach is based on the concept of *pre-images*. A pre-image for a given specified velocity is the set of positions that can reach the goal by a single motion along this velocity. From any point in the pre-image it is guaranteed that the goal can be reached and that it will be recognizable. If no pre-image of the goal contains the initial position of the manipulated object then the pre-image computation is recursively applied, using the existing pre-images as a possible goal. Therefore, the LMT approach is based on the backward chaining of pre-images from the goal position to the initial position.

The LMT approach considers the uncertainty in the sensing and control but not in the model, and implements the compliant motions using the generalized damping model [103]. It is an approach correct and complete [72] that presents an algorithm to be used as a formal framework for the synthesis of compliant-motion strategies. Several researchers have followed this approach, being their main contributions summarized below.

Erdmann [37] presents a method to compute a simple class of pre-images, for two degrees of freedom motions, known as backprojections. A backprojection of a goal is the set of positions from where the goal can be reached. Erdmann demonstrates that if the termination predicates only use current sensor values, then the reachability and the recognizability of the goal can be separated, and then pre-images are determined by backprojections.

Buckley [16, 17] implements a planning program that synthesizes compliant-motion strategies for assembly tasks involving three degrees of freedom of translation. The input of the planner is a model of the task geometry and the start and goal regions. Using a best first search, compliant motions are synthesized from the backprojections introduced by Erdmann until a strategy is found from the start state to the goal state.

Donald [32, 33] present a formal approach to compute compliant-motion strategies that guarantee that the goal is reached despite sensing, control and model uncertainties. A generalized configuration space is introduced, where model uncertainties are represented by position uncertainties. Therefore the fine-motion planning problem for assembly tasks involving n degrees of freedom of the manipulated object and k degrees of freedom in the model error, is translated to a problem of planning in a nk dimensional generalized configuration space. In this work *error detection and recovery* (EDR) strategies are introduced. A region H, recognizable and disjoint form de goal region G, is defined in such a way that an erroneous motion is detected when H is reached instead of G. EDR strategies are further developed in [11]. Donald summarizes in [34] the LMT approach and these later contributions.

Latombe et al. [63, 87] introduce more powerful termination predicates that may allow the synthesis of faster plans able to solve more complex problems. Brost and Christiansen [12, 13] introduce the concept of probabilistic backprojection, which describes the probability of reaching the goal from a set of initial positions, given an applied velocity. Therefore, a compliant-motion strategy with great probability of success may be synthesized when a guaranteed strategy is not possible due to the uncertainties affecting the task. Following this line, LaValle and Hutchinson [66] present an evaluation of motion strategies by developing formalisms for nondeterministic forward projections, and Su and Lee [93] propose a method to automatically generate goal regions from the geometric model of the task, considering the uncertainty to establish a probability of success. Finally, Fox and Hutchinson [39, 40] extend the LMT synthesis to visual compliant motions.

The LMT approach is the more formal and accurate approach to the synthesis of compliant-motion strategies. Nevertheless, the double exponential complexity of this method [18], has reduced its impact. The main problems to implement a fine-motion planner based on the LMT approach are the following:

- The difficulty to compute pre-images when there are degrees of freedom of rotation.
- The difficulty to include the model uncertainty (although Donald [32] solves this problem with the generalized configuration space, this solution is complex due to the high number of degrees of freedom of the generalized configuration space).
- The difficulty to fulfill the rigorous requirement to find a guaranteed compliant-motion strategy (this may be solved by the probabilistic backprojection introduced by Brost and Christiansen [12]).

For these reasons more research is needed in order to be able to implement compliant-motion strategies based on the LMT approach.

Two-phase approach

The two-phase approaches, also known as approaches based on replanning, divide the problem in two parts. Initially, a collision-free nominal plan is synthesized assuming no uncertainties. In a second phase uncertainties are considered and the plan is modified in the steps of the plan prune to errors.

Following this approach Xiao and Volz [105, 106] propose a replanning based on the contacts between the objects to be assembled. They introduce the concept of *contact formation* to classify the possible contacts. When the manipulated object collides with an obstacle, a patch plan is generated from the current contact formation and from the sensory information, in order to bring the manipulated object back to the nominal plan. Nevertheless, the patch plan is not guaranteed to be contact-free and therefore several patch plans may be followed before the nominal plan is resumed. A geometric simulator is presented in [110] to test this replanning approach. In [113] Xiao reviews the contact formation representation of the contact situations, and introduces the *goal-contact relaxation graphs* to represent and organize neighboring contact formations of a goal contact formation in order to ease the contact motion planning.

Gottschlich and Kak [41, 42, 43] present a planner which converts the geometric descriptions of assembly parts into potential field representations. Part matting operations are described using this new representations, which permits to easily isolate the regions of the path where compliant-motions are needed to cope with possible collisions. In the replanning phase the uncertainties are considered in augmenting the potential field representations. The initial pose uncertainty, the control uncertainty and the model uncertainty are considered. At the configurations where there is a possible collision, a compliant-motion strategy is selected from a library of strategies. This selection is based on the components of uncertainty that may cause the collision and the surfaces of the objects that may collide.

Dakin and Popplestone [25, 26] start from a nominal trajectory synthesized from the geometric models of the parts to be assembled with zero clearance at the sites of insertion. For every critical configuration a local contact space is represented as a graph and used to plan a traversable sequence of contact states.

McCarragher [74, 75, 76, 3] presents an approach that models the assembly tasks as a discrete event dynamic system using Petri Nets. A discrete event controller is developed which finds a desired trajectory to the desired end state. If an error occurs during the execution of the task, the system determines a new path through the Petri Net. A similar approach is presented in [23].

The main drawback of the approaches based on replanning is that the set of compliant-motions strategies that can be generated, may be not too broad due to the fact that they rely on plans synthesized in a first phase without considering uncertainty. On the other hand, the plans generated by the replanning phase are local solutions to problematic configurations of a nominal path, and hence they do not guarantee the successful execution of the task. Nevertheless, these approaches are easier to implement, since they separate the generation of a collision-free path from the consideration of uncertainty to generate compliant motions along this path. This is the reason why most of the implemented fine-motion planners are based on the two-phase approach.

Contact space approach

Contact space approaches consider the uncertainty in the planning phase, like the LMT approach. The task is divided into states according to the contacts or sets of contacts that can occur during the execution of the task. The search of a compliant-motion strategy is based on these states.

Laugier [64] describes a method for planning compliant-motion strategies by reasoning on an explicit representation of the contact space. The different ways in which an assembly can be dismantled are analyzed in contact space, leading to a construction of a state graph representing the set of potential solutions. This graph is searched in order to find a good reverse path defining the compliant-motion strategy. The method reduces the complexity of the problem by heuristically guiding the geometric reasoning.

Suárez and Basañez [6, 94, 95, 97] propose a fine-motion planner that takes explicitly into account friction forces and several uncertainty sources. The planner is developed for planar assemblies with polygonal objects, using a damping control mode. A graph of nominal task states is defined and a solution from the initial to the goal state is searched. For each task state the set of configurations where the state can occur and the set of possible reaction force arising at it, respectively known as configuration and force realization domains, are computed and used to determine a transition operator to change to the next state in the solution sequence. Taking into account the uncertainty in the robot control, the sequence is augmented until the goal state is the only possible final state. The sets of configurations and forces that can be measured when a state occurs, respectively known as configuration and force observation domains, are also computed and used during the execution of the plan to iteratively identify the current task state and apply the appropriate transition operator until the goal is reached.

De la Rosa, Laugier and Nájera [28] present an approach to plan motion strategies in the plane constrained by uncertainty in the position, orientation and control. The approach is based on a progressive exploration of the contact space that combines a contact-based attraction function which generates compliant motions to reduce position/orientation uncertainty, and an exploration function which generates subgoals within the contact space to progress towards the goal when local minima are found.

One of the main problems of the contact state approaches is the computational complexity of taking explicitly into account the uncertainty in the planning phase, as in the LMT approach.

1.3.3 Reactive Control

The reactive control approach to the automation of assembly tasks is based on the synthesis of an accommodation matrix able to transform the sensed reaction forces into corrective motions, in such a way that the task can be successfully performed despite the uncertainties affecting it. In fact, several reactive control approaches can be framed in the second phase of a two-phase approach. The difference is that in the reactive control approaches the nominal trajectory is not substituted by a fine-motion strategy, but the uncertainty is implicitly taken into account in the definition of an error-corrective accommodation matrix.

Passive compliance devices describe the accommodation center in such a way that the reaction forces lead to corrective motions. Nevertheless, the accommodation center may not exist for some tasks. These are tasks where the accommodation matrix cannot be diagonalized in any point in the space. There are two types of reactive control approaches. Those that try to analytically synthesize the accommodation matrix, and those that try to learn the mapping from reaction forces to corrective motions.

Accomodation matrix synthesis

Schimmels and Peshkin [80, 89, 90] present an analytical method to synthesize the accommodation matrix of a given task from a nominal trajectory and a set of qualitatively distinct contact configurations. For each of these configurations the method predicts the reaction forces that characterize the contact. The accommodation matrix must satisfy at each of these contacts that the forces are bounded and that the motion is error-corrective. By applying these conditions to all the configurations of the set the accommodation matrix is found by least-squares optimization.

Hirai and Iwata [51] develop an analytical method to synthesize the admittance[1] matrix in damping control from the geometric model of the objects. First the task is modelled as a set of transitions between contact states. Second, the theory of polyhedral convex cones is used to formulate for each contact the set of velocities satisfying the geometric constraints, and the set of possible reaction forces. Third, error-reduction conditions are applied to find the set of error-reduction velocities, and the admittance matrix is derived from the requirement that the corrective velocities be obtained from the reaction forces. This is done by solving a set of linear inequalities using the theory of polyhedral convex cones.

Vougioukas and Gottschlich [101, 102] present a method to derive the admittance matrix by identifying the possible erroneous configurations by simulating the robot motion under the given uncertainties in a discretized configuration space, and computing a set of possible resulting contact forces. Then, a motion is found for each configuration which is error-corrective for all the forces of the set, and which maximizes a measure of progress towards the goal. Finally the admittance matrix is obtained by a linear interpolation from the set

[1] the accommodation matrix is also known as admittance matrix

of force-velocity pairs.

Matsuo and Iwaki [73] assume that a set of possible erroneous configurations is given, and focus on the design of an accommodation matrix which satisfies the conditions of stability, feasibility, velocity dependency and error correctivity. By formulating these conditions as a set of linear inequalities, they reduce the accommodation matrix design to a linear programming problem, with this set of inequalities as constraints.

A different approach is that of Kang et al. [58] that presents a method which dynamically updates the center of compliance to the contact point, which is computed from the force/torque sensor readings using a contact localization algorithm, thus minimizing the chance of jamming and unwanted collisions.

Learning

The learning approaches may be used to learn admittance mappings, i.e. from reaction forces to corrective motions, but can also be used to learn the mapping to corrective motions from reaction forces, contact configurations and possibly other informations of the state. These mappings are learned from successive executions of the assembly task or from simulations. In the former case, the knowledge of the uncertainty models affecting the task is not a requirement, which make the learning approaches qualitatively different from all the previous ones.

Most of the learning approaches are connectionist approaches based on neural networks. A summary of neural network methods applied to robot control can be found in [99][86].

One of the first learning approaches is that of Asada [1, 2] which focus on the learning of compliance. These works specify the neural network structure needed to satisfy the non-lineal requirements of the compliance. It is illustrated using backpropagation with a two d.o.f. peg in a hole assembly task. The approach of Nuttin et al. [77] synthesizes a fuzzy controller composed of a four-layer neural network, which is used to learn the compliance mapping from examples manually generated or extracted from an already existing controller.

Reinforcement learning can be used if a training set is not available to learn from, since the appropriate actions to be performed in various situations can be learned through search guided by evaluative performance feedback. Gullapalli et al. [45, 46, 47, 48] use this learning technique to learn active compliant control for peg-in-hole insertions.

Learning and planning are combined in the approach of Cervera and Pobil [20, 21]. This approach proposes a framework to integrate robot programming, sensing and learning in a modular architecture. Focused in peg-in-hole insertions, apriori task knowledge is programmed and then the performance of the system is improved by the learning process. By using reinforcement learning the robot begins randomly exploring the action space and learns the best associated action for each contact state. With only eigth discrete actions, real insertion tasks are successfully performed.

The main drawback of these learning approaches is the need of examples to learn from.

The generation of these examples may require a previous existing controller or the need of the search of the best action to be performed, which may be slow and even dangerous.

1.3.4 Contact identification

This subsection presents the previous work related to contact identification, since the contact identification problem is one of the main problems that the approaches to the automatic performance of assembly tasks with robots must face.

The representation of a contact state between two objects is usually done in terms of the involved topological elements, i.e. faces, edges and vertices. In this sense Lozano-Perez [69] presents the contact states as a set of contact primitives that are defined as point contacts, i.e. vertex-edge in 2-D objects and vertex-face contacts in 3-D objects. Desai and Volz [31] define the contact primitives, called elemental contacts, as a pair of topological elements, and a contact state as a set of elemental contacts called contact formation. Contact analysis is simplified with these primitives, since less primitives are required to describe a contact state. Further on, Xiao [107] introduces principal contacts as those elemental contacts necessary for characterizing motion freedom, and the contact formation as a set of principal contacts.

Besides configuration information, force information is also used for contact identification. Hirai et al. [50, 52] deal with the estimation of contact states from force information by using state classifiers based on geometric models of the objects, and which are formulated with the theory of polyhedral convex cones. Brost and Mason [14] present the dual representation, which is a method for analyzing planar contact problems that represent planar motions and forces by acceleration centers. This graphical method allows the reasoning about sets of feasible contact motions, and the sets of forces consistent with those contact motions. Other approaches use force information to estimate the contact position when the geometry of the manipulated object is assumed to be unknown [60, 49].

Contact identification in the presence of uncertainties is a complex issue, since several contact states may be compatible with the sensed information.

Desai and Volz [31] present an algorithm to verify termination conditions of compliant guarded motions which has an static and an active phase based on an hypothesis and test scheme. In a similar way, Spreng [91] uses test motions for verifying contact hypothesis in terms of motion freedoms.

The determination of all the possible contact states due to the uncertainties is not a trivial problem. Suárez, Basañez and Rosell [97] present a method for planar assembly tasks which computes, for each task state, the set of configurations that can be measured when the state occurs, taking into account all the uncertainties affecting the task geometry. The contact identification algorithm also uses force information. It uses the dual representation of forces and includes the uncertainty of the force measurements besides the geometric uncertainties of the task [96, 7]. Suárez et al. [98] make a comparison of this analytical method with some learning methods to contact identification.

In order to avoid the complexity of finding the contact hypothesis for assembly tasks in the space (i.e. with 6 d.o.f.), Xiao and Zhang [108, 109, 111, 112] introduce a method for growing polyhedral objects by its location uncertainties in physical space, and implement an algorithm for finding all principal contacts possibly established between their features.

Other approaches that model the assembly tasks as discrete event dynamic systems, focus on the recognition of the contact events. McCarragher et al. [76] use a process monitor based on Hidden Markov Models for this purpose, and similarly Eberman [36] presents a statistical, model-based contact-state observer.

1.4 Overview

This thesis presents a fine-motion planning approach that considers modelling and sensing uncertainties and the effect of friction. It has two phases. The first phase plans a nominal path in free-space, i.e. without uncertainty. An exact cell decomposition method decomposes the free and the contact configuration spaces and represents them with two graphs. The nominal solution path in free-space is found by searching the corresponding graph. The second phase considers uncertainty and evaluates the feasibility of all the steps of the nominal path. When ambiguous configurations may arise, a patch plan in contact-space is elaborated. Motions are synthesized using a force-compliant control based on the generalized damping model. The fine-motion planner has been developed for planar assembly tasks with two degrees of freedom of translation and one of rotation.

The thesis is structured as follows:

Chapter 1: *Introduction*
This Chapter presents the motivation and objectives of the thesis and reviews the related works.

Chapter 2: *Basic Motion Planning*
This Chapter makes the analysis of the geometric constraints of planar assembly tasks with polygonal objects, and presents an exact cell decomposition method to plan the motions to move the manipulated object from an initial configuration to a goal configuration. The Chapter also makes an analysis of the possible reaction forces resulting at the contact situations.

Chapter 3: *Contact uncertainty analysis*
This Chapter analyzes the uncertainty sources that affect a planar assembly task and their effect on the contact situations involving one or several basic contacts. The analysis is done in physical and configuration space and includes a contact identification procedure. An analysis of contact reaction forces is also included, as well as a method to reduce uncertainty and to adapt the motion commands during the task execution.

Chapter 4: *Motion Synthesis*
This Chapter presents the synthesis of the fine-motion plan. The plan is a sequence of compliant motions which define a non-ambiguous path from an initial configuration to a goal configuration. The mechanism to find a non-ambiguous path is presented,

which is based on an algorithm that evaluates the arcs of the path. Then, free-space motion commands and contact-space motion commands to traverse the path are synthesized. Finally, task execution and implementation issues are discussed.

Chapter 5: *Conclusions*
This Chapter presents the conclusions of this thesis including its main contributions and future work to extend the presented approach.