Chapter 5

Conclusions

This Chapter is divided in two Sections. Section one presents the conclusions of this work, detailing its main contributions. Section two suggests possible improvements and explores the future extensions of the fine-motion planner proposed in this thesis.

5.1 Contributions

This thesis proposes a fine-motion planner for assembly tasks in the plane considering two degrees of freedom of translation and one of rotation, taking into account modelling and sensing uncertainties and the effect of friction.

A thorough study of the fine-motion planning problem for three degrees of freedom planar assembly tasks in the presence of uncertainties allows a detailed analysis of the role of the different types of uncertainties and the treatment of the rotational degree of freedom. This analysis is a necessary step to deal with the planning of assembly tasks in six degrees of freedom.

The proposed planner is based on a two-phase approach. First, uncertainty is not considered and a nominal solution path is searched in a graph representing the free-space, which has been obtained with an exact cell decomposition method. Then, uncertainty is considered and the arcs of the solution path are evaluated in order that the possible contacts occurring during the traversing of the arc do not provoke a failure of the task execution. When this is not possible, the planner finds a patch plan in contact-space in an analogous way as the nominal solution path in free-space. Motions are synthesized using a force-compliant control based on the generalized damping model. Task execution includes uncertainty reduction routines in order to adapt the robot commands to the actual geometry of the task.

The main contributions of this thesis are the following:

- *Use of the parametrized translational configuration space*:

Motion planning algorithms often make use of the configuration space, where motion constraints are explicitly represented by reducing the manipulated object to a point, and modifying the obstacles accordingly. Nevertheless, the dimension of this space (three for tasks in the plane and six for tasks in the space) makes it difficult the understanding of motions and thus the development of the algorithms.

In this thesis, the parametrized translational configuration space has been introduced, which is an embedding of the rotational degree of freedom into the translational configuration space, and has been used for the analysis of the geometric constraints of planar assembly tasks.

The use of the parametrized translational configuration space allows an intuitive graphical representation, which gives an insight into the motion of a mobile object in contact with static objects. It has also been used in Chapter 3 for contact identification in the presence of uncertainty.

- *Thorough uncertainty analysis*:

  A thorough analysis of the sources of uncertainty that affect an assembly task has been developed in this thesis. Modelling and sensing uncertainties have been considered. Although modelling uncertainty is an important source of uncertainty that affects assembly tasks, it has usually been overlooked by most of the researchers. In this work, this source of uncertainty has been meticulously studied, by analyzing the effects of both positioning uncertainty and manufacturing tolerances. Both modelling and sensing uncertainties have been assumed with an uniform distribution of the parameter values within the specified limits, since the planner is intended to cope with all possible real cases, e.g. all the objects within tolerances are accepted and should be assemblable.

  The approach has also carefully considered the dependence between sources of uncertainty, since one one hand they constrain the possible contact configurations of a given contact situation when they are dependent, and on the other hand they allow the occurrence of complementary contact situations, i.e. non-nominal, when they are independent.

  All the uncertainties affecting a contact situation have been fused in a Contact Configuration Domain, which is associated to the measured configuration and to a given contact situation. This allows the use of the nominal parametrized translational configuration space for contact identification purposes.

  Uncertainty reduction is an important aspect that has been considered in this thesis, since the performance of an assembly task can be improved if the knowledge acquired during an execution is used for both constraining the uncertainty regions used for the termination conditions, and for updating the estimation of parameters needed for the generation of the robot commands.

  Force analysis has been done using the dual representation of forces, which allows to consider in an easy way both the geometric uncertainties that affect the possible raction forces arising at the contact situations, as well as the sensor uncertainties. Friction has been considered and modelled with the generalized friction cone. The suitability of this model for this kind of tasks has been validated from the experiments.

- *Motion synthesis*:

  Algorithms have been provided to determine if the possible occurrence of a new contact during the traversing of an arc of the nominal solution path, taking into account all the sources of uncertainty affecting the assembly task, may produce the failure of the task execution.

  These algorithms are used for the motion synthesis by evaluating the arcs of a nominal solution path and providing nominal patch paths in contact space in case no motion in free space can guarantee the success of the task. As a result, a solution path is found which is composed of compliant and guarded arcs. Compliant arcs can be followed by complying at the occurrence of any new contact, and the goal node is guaranteed to be reached (i.e. although the occurrence of new contacts is possible due to a tight clearance, the force control loop makes it possible to comply at them without the need of identifying each new contact situation). Guarded arcs can be followed by issuing a recovery plan to be executed in case any new contact occurs, since in this case the goal is not guaranteed to be reached (i.e. in this case the contact identification procedure must supervise the possible occurrence of any new contact).

  All the modules of the planner have been implemented and tested, and task execution has been verified by real experiments.

5.2 Future work

Several proposals can be made as future work, following the results obtained by the fine-motion planning approach presented in this thesis. First, some improvements are suggested in order to enhance the performance of the planner. Then, two different research lines are put forward as possible continuations of this work.

5.2.1 Improvements

Some suggestions to improve the proposed planner are the following:

- The solution paths obtained by the proposed planner depend on the partition of the contact-space and the free-space used to determine the graphs where the solution path is searched. These partitions can be improved with the aim to obtain the shortest paths which are composed of the less possible number of arcs.
- Regarding sensory information and with the aim to simplify on-line computations the following should be considered:

  - Study other representations of force in order to simplify the classification of force measurements.
  - Determine which assumptions can be done in order to simplify the classification of the measured configurations.
- Consider probabilities in the specification of the sources of uncertainty, as well as in the contact identification procedures.

5.2.2 Extension to 6 d.o.f.

One of the possible research lines to continue the proposed planner is its extension to assembly tasks in the space, i.e. considering six degrees of freedom.

Some of the steps to be done are the following:

- Determination of the translational configuration space.
- Study of the possible assumptions to be done in order to simplify the uncertainty analysis, based on the experience obtained with planar assembly tasks.
- Use of another force representation able to represent generalized forces in 6 d.o.f.
- Study the possibility to reduce the degrees of freedom of the assembly tasks either by making use of symmetries, or by dividing the assembly in a sequence of sets of motions involving less degrees of freedom each.
- Search the possibility of using approximate cell decomposition methods to partition the free-space.

5.2.3 Application to mobile robots

Another of the possible research lines to continue the proposed planner is its adaptation to solve motion planning problems for mobile robots.

Some of the steps to be done in this direction are the following:

- Extend compliant motions to be used with other sensory information provided either by cameras, ultrasonic sensors or infrared sensors.
- Consider the case when there is only a partial knowledge of the environment.
- Include control uncertainty.