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UNIFYING FEEDBACK CONTROL AND PLANNING FOR A ROBOTIC MANIPULATOR

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ABSTRACT

This chapter giving an overview of motion generation and control strategies in the context of robotic manipulation tasks. Automatic control ranging from the abstract, high-level task specification down to fine-grained feedback at the task interface are considered. Some of the important issues include modeling of the interfaces between the robot and the environment at the different time scales of motion and incorporating sensing and feedback. Manipulation planning is introduced as an extension to the basic motion planning problem, which can be modeled as a hybrid system of continuous configuration spaces arising from the act of grasping and moving parts in the environment.

UNIFYING FEEDBACK CONTROL AND PLANNING

In previous sections we discussed task-level control methods and planning algorithms. Both task-level control and planning methods are able to address specific constraints imposed on robot motion in the context of manipulation tasks. However, neither of these categories of methods is able to address all constraints completely. Control remains susceptible to local minima and thus cannot guarantee that a particular motion will lead to the desired result. Planning methods, on the other hand, overcome the problem of local minima by projecting possible motions into the future to predict if a sequence of motion will lead to success. Given certain assumptions, the resulting plan can be guaranteed to succeed. However, the computations associated with this process are generally too computationally complex to satisfy the feedback requirements of manipulation tasks. Unfortunately, this means that control and motion planning by themselves are unable to address the problem of moving robots for general manipulations tasks.

In this final section of this chapter, we will review efforts to combine the advantages of control methods and planning methods into a single approach to determine the motion of a robot. These efforts aim to create methods that avoid the susceptibility to local minima while satisfying the feedback requirements. Early attempts of integrating planning and control occurred in the early 1990s. Not all of these efforts are specifically directed at manipulation but many contain insights relevant to the topic. In this section, we will review these efforts and also discuss some of the more recent research efforts aimed at unifying motion planning and feedback control. Motion planning and motion control have traditionally been regarded as two distinct areas of research. However, these areas have many features in common.

Both areas are concerned with the motion of robotic mechanism and more importantly planning and control methods both determine a representation that maps robot state to robot motion. In the case of feedback control, this representation is a potential function defined for a given region of the state space. The gradient of the potential function at a specific state encodes the motion command. In contrast, motion planning determines motion plans. These motion plans also encode motions for a set of states. Motion planning and feedback control also differ in certain aspects. A motion planner generally makes stronger assumptions than a controller about the environment, the ability to assess its state, and the changes that can occur in the environment.

Motion planning also requires the ability to project the robot’s state into the future, given its current state and a particular action. By using this ability together with global information about the environment, motion planners can determine motions that are not susceptible to local minima. This positive characteristic of motion planners, however, results in significantly increased computational cost. The large discrepancy in computational requirements for planning and control and the resulting divergence of computational techniques may explain the current separation of the two fields. Researchers are beginning to attempt to reverse this separation by devising a unified theory of planning and control.

FEEDBACK MOTION PLANNING

Feedback motion planning combines planning and feedback into a single motion strategy. A planner considers global information to compute a feedback motion plan free of local minima. Such a feedback motion plan can be interpreted as a potential function or vector field whose gradient will lead the robot to the goal state from any reachable part of the state space. Local minima-free potential functions are also called navigation functions. Given the current state of the robot and the global navigation function, feedback control is used to determine the robot’s motion. The consideration of feedback about the robot’s state in the context of a global navigation function reduces the susceptibility to sensing and actuation uncertainty. Feedback motion planning, in principle, can address the entire spectrum of motion constraints and their feedback requirements. Given a global navigation function that considers all motion constraints, the feedback requirements can easily be satisfied, since the feedback motion plan already specifies the desired motion command for the entire state space.

Obviously, the major challenge in feedback motion planning is the computation of such a navigation function or feedback motion plan. The problem becomes particularly difficult in the context of a manipulation task, since the state space (or configuration space) changes each time the robot grasps or releases an object in the environment. This change makes it necessary to recompute the feedback motion plan. Frequent recomputation is also necessary in dynamic environments, where the motion of obstacles can repeatedly invalidate a previously computed feedback motion plan. In the remainder of this section, we will review a variety of methods for computing navigation functions. In general, the problem of efficiently computing feedback motion plans for manipulation tasks remains unsolved. We therefore also present methods that do not explicitly consider manipulation. These methods can be divided into three categories:

a. Exact methods,
b. Approximate methods based on dynamic programming,
c. Approximate methods based on composing and sequencing simpler potential functions.

The earliest exact methods for the computation of navigation functions are applicable to simple environments with obstacles of specific shapes. Approximate methods based on discretized spaces (grids) overcome this limitation but possess an exponential computational complexity in the number of dimensions of the state space. These approximate navigation functions are called numerical navigation functions.

These navigation functions are often used for applications in mobile robotics. Due to the low-dimensional configuration space associated with mobile robots, they can generally solve motion planning problems robustly and efficiently. Some physical processes, such as heat transfer or fluid flow, can be described by a specific type of differential equation, called harmonic functions. These functions possess properties that make them suitable as navigation functions.

Navigation functions based on harmonic functions are most commonly computed in an approximate, iterative fashion. The requirement for iterative computation increases the computational cost relative to the simpler numerical navigation functions. More recent methods for the computation of numerical navigation functions consider differential motion constraints at a significantly reduced computational cost. These methods rely on classical numerical dynamic programming techniques and numerical optimal control. However, in spite of their reduced computational complexity, these methods remain too computationally costly to be applied to manipulation tasks with many degrees of freedom in dynamic environments. Navigation functions can also be computed by composing local potential functions based on global information. The goal is to compute a navigation function for the entire configuration space C. This is accomplished by sequencing overlapping funnels. Each of the funnels represents a simple, local potential function. By following the gradient of this potential function, motion commands can be determined for a subset of the configuration space. If the funnels are sequenced correctly, the composition of local funnels can yield a global feedback plan. This feedback plan can be viewed as a hybrid system in which the sequencing of funnels represents a discrete transition structure, whereas the individual controllers operate in a continuous domain.

The composition of funnels is considered planning. The consideration of global information during the planning permits to determine a funnel composition that avoids local minima. One of the earliest methods based on the global composition of local funnels was proposed by *Choi* et al. In this method, the state space of the robot is decomposed into convex regions. The connectivity of these regions is analyzed to determine global information about the state space. This information can be used to combine simple, local potential functions, one for each convex regions of state space, into a local minima free potential function. More rigorous approaches based on this idea have been developed. These approaches can consider the dynamics of the robot and nonholonomic motion constraints. These methods have only been applied to low-dimensional state spaces and cannot easily be applied to manipulation tasks. The random neighborhood graph is a sampling-based method of computing a decomposition of the overall state space. As before, a navigation function can be computed by analyzing the global connectivity of the decomposition and imposing adequate local potential functions for each subdivision. A specialized method following the same principle for planar robots in polygonal environments has also been proposed.

The idea of composing local potential functions has also been applied successfully to a complex robot control task. Finally, in a general and efficient method of computing a smooth feedback plan over a cylindrical algebraic decomposition of configuration space has been proposed. The computation of a navigation function over the entire configuration space quickly becomes intractable as the dimensionality of the space increases. To overcome this challenge, in particular in the context of autonomous mobile manipulation, workspace heuristics have been employed to determine a navigation function efficiently. This navigation function does not cover the entire configuration space but only those regions heuristically determined to be relevant to the motion problem.

AUGMENTING GLOBAL PLANS WITH FEEDBACK

The manipulation planning techniques are not susceptible to local minima, as they consider global state space information. Due to the computational complexity associated with the consideration of global information, these planning techniques are not able to satisfy the feedback requirements of manipulation tasks.

However, the required frequency of feedback about global motion are relatively low: the global connectivity of the configuration space changes relatively infrequently. It would therefore be possible to consider feedback for global motion at the slow rates the planner can accommodate, while considering feedback for other motion constraints at higher frequencies. To achieve this, global motion plans have to be augmented with reactive components that incrementally modify the global plan in response to feedback from the environment. As long as the global connectivity information captured by the plan remains valid, the incremental modifications can ensure that all other motion constraints, ranging from task requirements to reactive obstacles avoidance, are satisfied. The elastic-band framework augments global plans with reactive obstacle avoidance. A global configuration space path, determined by a planner, is covered with local potential functions, each of which is derived from the local distribution of obstacles around the path.

These local potentials cause the path to deform so as to maintain a minimum distance from obstacles. Visually, the path behaves as an elastic band that is deformed by the motion of obstacles. The local potential functions, together with the global path, can be viewed as a navigation function for a local region of the configuration space. Integrated with a global planner and replanner, the elastic-band framework permits real-time obstacle avoidance that is not susceptible to local minima. However, the feedback frequency for global motion remains limited by the global motion planner. Specific task constraints have not been integrated into the elastic-band framework; consequently, its application to manipulation tasks is limited. In its original formulation, the elastic-band framework assumed that all degrees of freedom of the robot are holonomic. An extended formulation augments motion paths for nonholonomic platforms with reactive components. The elastic-strip framework also augments global motion plans with reactive obstacle avoidance.

In addition to reactive obstacle avoidance, however, the elastic-strip framework can accommodate task constraints. Similarly to an elastic band, an elastic strip covers a global path with local potential functions. In contrast to the elastic-band framework, these potential functions are based on task-level controllers and therefore allow the task-consistent modification of the global path. The elastic-strip framework is therefore well suited for the execution of manipulation plans in dynamic environments. An elastic strip will be incrementally modified to represent a constraint-consistent trajectory, as long as the global information captured by the underlying plan remains valid. The elastic-strip framework has been applied to a variety of manipulation tasks on a mobile manipulation platform. Extending the elastic-band and elastic-strips frameworks, the elastic-roadmap framework combines reactive task-level control with efficient global motion planning. The elastic roadmap represents a hybrid system of task-level controllers that are composed into a navigation function, thereby satisfying the motion constraints and their respective feedback requirements.

CONCLUSION

In this chapter, an overview of motion generation and control strategies in the context of robotic manipulation tasks has been provided. Issues related to modeling the interfaces between the robot and the environment at the different time scales of motion and incorporating sensing and feedback were considered. Manipulation planning was introduced as an extension to the basic motion planning problem, which can be modeled as a hybrid system of continuous configuration spaces arising from the act of grasping and moving parts in the environment. The important example of assembly motion has been discussed through the analysis of contact states and compliant motion control.

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