CHAPTER
EIGHT

CONCLUSION

In this thesis, we studied a central problem in robotics: planning a collision-free path for a moving robot in a static and known environment. We restricted ourselves to motion planning for rigid bodies and articulated robots. We compared and analyzed multiple-shot sampling-based motion planning techniques, in particular variants of the Probabilistic Roadmap Method (PRM).

Sampling-based planners can successfully handle a large diversity of problems. The success of these planners in solving problems with possibly many degrees of freedom and many obstacles can be explained by the fact that no explicit representation of the free configuration space is required. The main operation of these planners is checking placements of the robot for collisions with obstacles in the environment, which can be efficiently performed by the current generation of collision checkers. In contrast, exact methods always have to take each obstacle into account, even when the solution path is simple. The second reason for their success is that problems which are not pathological have favorable reachability properties. That is, the free configuration space of a reasonable problem can often be captured by few nodes where each node can reach a large portion of the free space using a local planner. Therefore, a PRM usually finds a solution quickly, even if the geometric complexity is high.

If the length of the allowed connections between nodes in the roadmap is considerably limited, the PRM starts looking like grid-based techniques in which nodes are only connected to their adjacent neighbors in the grid. Experiments showed that this had a dramatic negative impact on the running times. The PRM also tends to perform poorly when crucial configurations lie in and around very narrow regions of the configuration space, which has been identified as the narrow passage problem. The probability of randomly guessing such a configuration can be very small, especially when the rest of the free space is large compared to these regions. Moreover, creating a set of configurations that covers a path going through the passage is not necessarily sufficient to solve the problem. The problem is only solved when all configurations in the set belong to the same connected component. Experiments showed that this last criterion, which we call maximal connectivity, is much more difficult to satisfy than the coverage criterion, especially when we have to deal with a narrow passage.

The narrow passage problem can be tackled by incorporating a hybrid or adaptive sampling strategy that concentrates samples in difficult areas on the one hand, and generates some samples in large open areas on the other hand. Hence, using a uniform sampling strategy is not a good choice for environments involving narrow passages. Another tactic is to employ a more powerful local planner. We presented a potential field local planner that creates larger reachability regions which eases making connections. This planner is also better able to find the entry of a narrow passage, decreasing the number of samples needed to obey the maximal connectivity criterion.

When a passage is extremely narrow, the PRM may not always find a solution within the allowed amount of time as this method is (only) probabilistically complete. In this case, or when the robot needs to maintain contact with the obstacles, using a PRM is a poor choice. In such cases, a problem may only be solved in practice by a careful analysis before it is fed to a complete planner.

In conclusion, when we have to deal with a problem with many degrees of freedom (DOFs) and the passages are not pathologically narrow, a PRM seems to be a logical choice as sampling-based planners can successfully handle the curse of dimensionality. These planners have been used successfully for many applications, including CAD/CAM, computer simulation, computer animation, biology, medical applications, and virtual environments. Our analysis and experiments have provided further insight in the effects of the different choices which should be of use in improving these applications.

In most applications, a path should preferably be short because redundant motions will take longer to execute. Although reasonably short paths can be obtained from a roadmap with cycles, yet even shorter paths can be obtained by creating Partial shortcuts. Experiments showed that this new technique is successfully able to remove redundant (rotational) motions of the robot, improving on existing algorithms. Besides having a short path, the robot often has to keep some minimum amount of clearance to the obstacles because it can be difficult to measure and control the precise position of a robot. Traveling along a path with a certain amount of minimum clearance reduces the chances of collisions due to these uncertainties. We proposed a new technique that increases the clearance along a path without using complex data structures and algorithms. Both techniques can be applied to a wide range of robots which may reside in high-dimensional configuration spaces.

Interactive applications are getting more and more attention from robotics. Research includes planning the motions for a group of entities, the generation of camera motion to track a moving guide and the animation of the entities. The entity that moves in the environment is often represented by a translating cylinder or box. As such an entity only has two or three DOFs, we can often employ a more efficient and more specific algorithm than the PRM. We introduced the Reachability Roadmap Method which can be used efficiently to create small roadmaps for these environments. Such a small roadmap ensures low query times and low memory consumption and is easy to adjust to fit the user's wishes. If there exists a path in the (discretized) free space that connects the start and goal of the query, the algorithm ensures that a path can be found in the roadmap. Hence, the algorithm is resolution complete. Another criterion these roadmaps have to satisfy is that alternative routes and short paths can be extracted. This was met by adding useful nodes and useful cycles. Besides the possibility to extract short paths, paths are often required to have much clearance, as this leads to natural looking motions. For example, high-clearance paths work well with entities that have large width, such as a wide formation of characters. We met this goal by retracting a roadmap to the medial axis which allowed extraction of such paths in real-time.

While the paths we computed may be perfectly suitable for robots operating in virtual environments, they cannot be used directly for controlling real robots due to inexact control and dynamic constraints. The first problem is caused by robots not following a precomputed path exactly. Sensor information may be incorporated into the motion planning algorithm to adjust the robot's actions and to reduce the errors in its position. The second problem exists because we do not take into account constraints such as velocities and acceleration. This problem can be handled by adding extra information in the nodes of the roadmap which can be used by a suitable local planner. Another approach would be transforming the geometric path to a path that can be executed by searching within the neighborhood of the geometric path for a real solution [140].

The PRM was first described some years ago. Originally, there was much doubt about its usefulness, but soon, people realized its power in many different applications. We have come a long way since then. By a combination of faster computers and improvements in the technique, we are now able to solve complex motion planning problems efficiently.

A next step is to create a library of motion planning techniques that can be used as a 'black-box'. That is, users should not have to think about parameter choices that usually have no meaning to them. In this thesis, we tried to automate these choices as much as possible. We also provided insight in the effect these parameters have on the PRM. While our SAMPLE system, algorithms and results provide a foundation for such a library, more research will be needed to enable the black-box to automatically choose parameters, such as an appropriate metric, a step size of the local planner, the maximum connection distance, a hybrid sampling strategy, and a termination criterion.

Creating such a library may prove essential to the development of autonomous robots.