高次元経路探索アルゴリズムの性能評価
Performance Benchmarks for Path Planning in High Dimensions

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We present an overview of test cases that have been designed to experimentally evaluate the performance of path planning techniques in high-dimensional search spaces. The well-known "narrow passage" problem associated with successful randomized planning methods is considered in the context of path planning for humanoid robots. We discuss some computed examples and give a brief summary of experimental results.

Key Words : Path Planning Algorithms, Benchmarks, Humanoid Robots, Heuristic Search

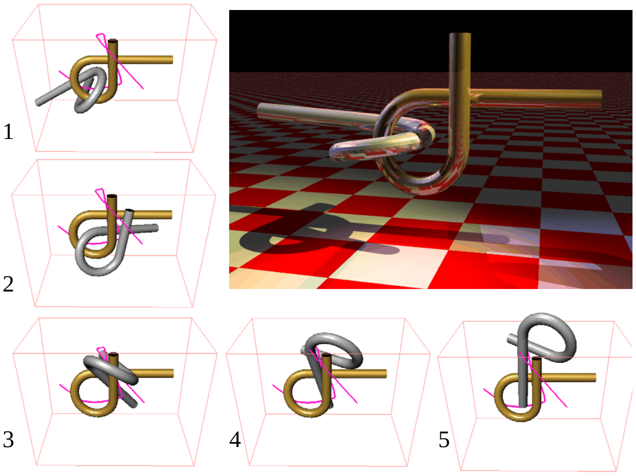

Fig. 1: The "Alpha Puzzle" Motion Planning Benchmark.

1 Introduction

As technology and algorithms for real-time 3D vision and tactile sensing improve, humanoid robots will be able to perform tasks that involve complex interactions with the environment (e.g. grasping and manipulating objects). The enabling software for such tasks includes motion planning for obstacle avoidance, and integrating planning with visual and tactile sensing data.

We are currently developing a graphical simulation environment that includes algorithms for autonomous motion planning. This paper gives a brief overview of some of the theoretical and practical issues related to path planning algorithms. In particular, two fundamental challenges include the ability to efficiently search high-dimensional configuration spaces, and to develop methods that are robust and immune to pathological cases.

2 Path Planning

Path planning problems involve searching a system configuration space for a collision-free path connecting a given start and goal configuration[1]. For problems in low dimensions, the configuration space can often be explicitly represented and exact algorithms can be used effectively. For high-dimensional configuration spaces however (such as 6 DOF robot arms or legs), it is typically impractical to explicitly represent the configuration space. Instead, the space is *sampled* in order to discover free configurations (for example, see [2]). Here, the fundamental challenge lies in devising a practical and efficient sampling strategy that can be used to reliably solve path planning problems.

2.1 Fighting the Curse of Dimensionality: Path planning in high dimensions shares much in common with classical AI search in that it must contend with large search spaces. Due to the complexity of motion planning in its general form [3], the use of *complete* algorithms [4, 5] is limited to low-dimensional configuration spaces. However, many practical, *incomplete* algorithms have been devised employing a variety of heuristics designed to decrease computational costs, while maintaining reliability. Most heuristics can be roughly categorized in terms of how they affect the search strategy:

- **Greediness:** Since brute-force, exhaustive search is infeasible, these heuristics attempt to guide the search algorithm to more promising areas of the search space in a greedy fashion (e.g. gradient descent on artificial potential fields).
- **Randomization:** Monte Carlo techniques are often used to avoid the bias inherent to some deterministic algorithms, and attempt to reduce their susceptibility to pathological cases.
- **Uniformity:** In order to prevent a search algorithm from becoming trapped in only a portion of the search space, these heuristics attempt to cause the search to eventually explore the entire space uniformly. These heuristics along with randomization are often needed to counter side-effects introduced by greedy heuristics.

Although methods employing heuristics are incomplete, many have been shown to find paths in high-dimensional configuration spaces with high probability (for example, see [2, 6]).

2.2 The Problem of "Narrow Passages": Since no explicit representation of the C-space obstacles is used, heuristic path planning algorithms based on sampling face the problem of discovering "narrow passages" that must be traversed in order to solve some planning queries. For intuition and visualization purposes, consider the example queries involving narrow passages for a 2D translating robot shown in Figure 2. The search trees and solution paths shown were generated by a path planning method known as *RRT-Connect*, an efficient randomized search strategy that ultimately converges toward a uniform distribution over the free configuration space[6]. In two dimensions, the presences of narrow passages in the configuration space can easily be visualized by the workspace geometry.

For problems in higher dimensions, the existence of narrow passages is affected by both the workspace obstacle geometry and the topology of the configuration space. Consider the example of the "alpha puzzle" involving two twisted, interlocking rings shown in Figure 1. One ring is a fixed obstacle, while the other is modeled as a rigid body 3D with a 6-dimensional configuration space. This example has been analyzed and made publicly available for research purposes[7].

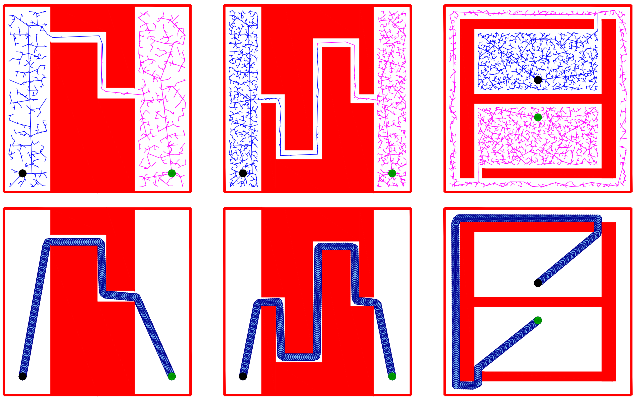

Fig. 2: Paths involving narrow passages in a 2D workspace.

3 Humanoid Robot Planning Experiments

Motion planning for humanoid robots poses a particular challenge. Developing practical motion planning algorithms for humanoid robots is a daunting task given that humanoid robots typically have 30 or more degrees of freedom. The problem is further complicated by the fact that humanoid robots must be controlled very carefully in order to maintain overall static and dynamic stability. These constraints severely restrict the set of allowable configurations, potentially introducing narrow passages into the search space. Techniques for full-body path planning for humanoid robots is beyond the scope of this short paper[8]. However, we are presently designing performance benchmarks for subproblems, such as motion planning of a single limb (arm or leg), and dual-leg planning with balance constraints.

Consider the case of planning the motion for the humanoid robot "H6", which has a 7-DOF arm. If the torso position is held fixed, the path planning problem involves searching the 7-dimensional arm configuration space for a collision-free path. The left image of Figure 3 shows the initial robot posture, and the right image shows a goal configuration involving an obstacle with a hole. The hole represents a narrow passage in the workspace that produces a corresponding narrow passage in the configuration space. The size of the hole h relative to the width of the end-effector w determines the relative difficulty $\rho = \frac{h}{w}$ of the planning query. By varying the size of the hole, the performance of path planning algorithms in reliably finding paths through narrow passages in the configuration space can be estimated. Table 1 shows some experimental results for different values of ρ for both the single arm (7 DOF), and a dual-leg dynamic balance (12 DOF) example involving placing one foot inside of a hole(Figure 4). The dual-leg example involves searching the combined configuration space of two 6-DOF legs under obstacle, kinematic, and dynamic balance constraints. The torso, head, and arm configurations are held fixed during planning. The execution times in Table 1 were computed based on 20 independent trials whose minimum, maximum, and average execution times were normalized to the average execution time for $\rho = 2.0$. Both examples incurred an exponential increase in computation times for decreasing values of ρ. However, it is interesting to note the relatively slow rate of growth for minimum execution times compared to the rapid increase in maximum execution times. These data indicate that worst-case performance is more adversely affected by the presence of a narrow passage in the search space for the RRT-Connect planning algorithm tested.

4 Summary

Our experiments suggest that the geometry of the configuration space (and in particular, the presence of narrow passages) has a significant effect on the performance of heuristic path planning algorithms. Thus, devising techniques for minimizing this effect should be a research priority, and standard benchmarks should be used for evaluation. Through such research efforts, the current and future capabilities of complex robots such as humanoids can be improved.

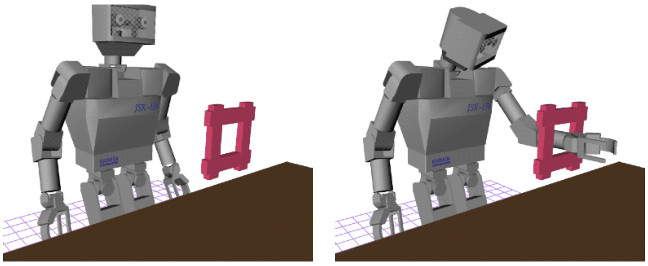

Fig. 3: Narrow Passage for a 7-DOF Humanoid Robot Arm.

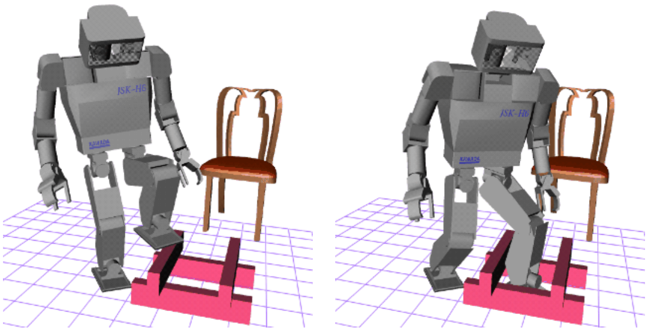

Fig. 4: Narrow Passage for Humanoid Robot Legs.

Benchmark Description	Time ($\rho = 2$ normalized)		
	min	max	avg
Arm ($dof = 7, \rho = 2.00$)	0.067	16.50	1.00
Arm ($dof = 7, \rho = 1.75$)	0.068	22.69	2.01
Arm ($dof = 7, \rho = 1.50$)	0.078	119.90	5.95
Arm ($dof = 7, \rho = 1.25$)	0.249	220.84	26.35
Legs ($dof = 12, \rho = 2.00$)	0.232	12.24	1.00
Legs ($dof = 12, \rho = 1.75$)	0.341	27.63	2.53
Legs ($dof = 12, \rho = 1.50$)	1.778	207.04	8.76
Legs ($dof = 12, \rho = 1.25$)	5.604	731.50	42.36

Table 1: Humanoid Benchmark Results ($n = 20$ *trials*).

Acknowledgments: This research is supported in part by a Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellowship for Foreign Scholars in Science and Engineering.

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