Pipe-Routing and Pathfinding in 3D (Student Abstract)

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Abstract

Pipe-routing in 3D is a common problem in the design of industrial plant layouts. Here, we aim to minimise the structural cost of the plant (which can have multi-billion dollar budgets), while maintaining safety and engineering constraints. We tackle this problem by developing efficient methods for optimal 3D search. We contribute an adaption of Jump Point Search, a well-known symmetry-breaking technique for 2D grids, into 3D: in contrast to related work, our algorithm preserves path feasibility. In combination with a novel method for limiting over-scanning, we report search time speedups of up to an order of magnitude on benchmarks in the literature. We further develop three new and varied voxel benchmark data sets sourced from 3D applications in the literature in order to provide better opportunities for differentiating competing techniques. Towards pipe-routing, this work also identifies several remaining issues for translating the size of industrial domains and their associated constraints into 3D search.

Introduction

Pipe-routing (PR) in 3D is a common industrial problem in the design of industrial plant layouts such as natural gas processing stations, water treatment facilities and power plants in ships and submarines. In this problem, we must plan 3D routes for each pipe to connect two pieces of equipment with the aim of minimising the total cost of the plant (which can run into multi-billion dollar budgets), while maintaining safety and engineering constraints.

Differences in the quality of the final layout solution can have a significant impact on the cost of these plants, where the cost of pipes and associated support structures can make up to 80% of the cost of purchased equipment or 20% of the fixed-capital investment (Peters et al. 2003). Due to the size of these plants and the complexity of the associated constraints, building high quality solutions is a remarkably difficult problem; as a result, layouts are still designed manually and may take multiple engineers many months or even years to complete. This process is inefficient, costly, and the solution quality may vary as it depends largely on the experience of piping and layout engineers.

As such, there is strong motivation for the development of automatic methods for generating chemical plant equipment layout and pipe-routing designs. Towards this end, I undertake my candidature under a Graduate Research Industry Partnership (GRIP) scholarship with Woodside Energy Ltd. as part of an ongoing multi-year project.

The full industrial problem is composed of two parts; (1) design of equipment layout allocations; and (2) planning subsequent pipe-routing solutions. Practitioners have tackled the full pipe-routing problem through both integrated or decomposed approaches (i.e., solving both equipment allocation and pipe-routing together or separately). However, the leading method is to approach plant design as a multi-stage process, whereby equipment allocation is determined first, then pipes routes are planned based on a fixed-layout. In this work, we focus on solving stage two: the pipe routing problem in 3D.

Related Work

Prior work has developed a range of heuristic techniques in the family of priority-based search (PBS) (Ma et al. 2018); a recent prioritised planning strategy for MAPF problems. Given enough time, this state-of-the-art method can often produce best known solutions to challenging industrial instances with up to hundreds of pipes. Refer to Belov et al. (2020) for details.

A significant limitation of the current model is that the low-level routing is extremely slow, taking up to hundreds of seconds for individual pipes). At present, each pipe is solved using a Mixed-Integer Programming solver MiniZinc 2.4.2 with the MIP backend Gurobi 9.0.1 (Belov et al. 2017). As a consequence, the high-level MAPF framework is often prohibited from performing more than a single dive (depth-first) in the PBS search tree due to the high cost of re-routing individual pipes; this gates improvements to solution quality.

In this work, we aim to improve both the efficiency and quality of planning individual pipes: we consider the pipe-routing problem through the lens of single-agent search in 3D. Due to the practical importance and associated cost of solution quality (improvements of even several percent can mean savings of millions of dollars), we are heavily interested in optimal pathfinding. This lends itself to searching on high-resolution voxel gridmaps which have smaller detours than more sparse representations of 3D space.

However, while 2D pathfinding algorithms are well studied, relatively little work has been done in 3D. There is no current algorithm for 3D search that is fast, optimal (at voxel resolution) and returns feasible solutions. Unsurprisingly, it also follows that there is very little clarity on state-of-the-art methods in the field: this is exacerbated by a lack of problem variety in available testing data sets.

Objectives

We identify four primary objectives as we move towards efficient automatic methods for pipe-routing in 3D:

1. Generation of varied and informative test sets to better understand the strengths and weaknesses of 3D search algorithms,
2. Development of methods for fast and optimal search in 3D that return feasible solutions,
3. Development of methods for considering pipe-routing constraints, cost, and feasibility during online search,
4. Development of methods for maintaining solution quality when searching in domains that are too large to store (such as industrial plants).

Completed Work

With these goals in mind, our work has thus far produced two primary contributions towards my thesis; (1) development of an efficient and optimal 3D pathfinding system, JPS-3D (Nobes et al. 2022), which finds feasible solutions; and (2) development of three voxel benchmark data sets using a novel method of varied and representative problem generation. These works have been submitted and accepted into the 15th and 16th International Symposium on Combinatorial Search (SoCS) conference in 2022 and 2023 respectively.

A main challenge for 3D search is that in combination with the 26-direction branching factor, there are many symmetric equivalents of minimum cost paths. We adapt Jump Point Search (JPS) to 3D, a well-known symmetry-breaking technique for 2D grids that prunes all but one canonical representation of an optimal path (Harabor and Grastien 2011). Previous formulations of JPS for 3D search allow corner-cutting moves that pass through the edge or vertex of an obstacle in order to simplify the space (Zhang 2021; Zhang, Zhang, and Low 2021). This subsequently results in infeasible solutions for many real applications where the agent has size; these works conduct post-processing to repair paths.

We run experiments on our new voxel benchmarks and others available from the literature, and record significant search-time speedups for JPS-3D relative to 3D A*. Planning with our generalised method for limiting scan depth reports additional speedups up to one order of magnitude over A* on available voxel benchmarks in the literature. The production of new and varied voxel data sets should allow us to gain further insights into the strengths and weaknesses of our approach in order to better tackle the 3D problem. In the future, our benchmarks will also provide more opportunity for differentiating competing solvers.

Conclusions and Future Work

While JPS-3D represents an important step towards efficient pathfinding in voxel grids, we perceive two primary issues with applying these techniques to automatic pipe-routing problems that we hope to tackle in the future.

Firstly, current routes for pipes do not consider pipe feasibility, nor structural metal cost in contrast to grid-optimality. At present, the existing method for re-routing individual pipes enforces the many safety and engineering considerations as global constraints. We instead hope to more efficiently handle such constraints locally during online search by altering successor generation rulesets. This aims to align efficient methods for 3D grid search to the specifics requirements of the pipe-routing domain.

Secondly, while our contributions thus far will allow us to efficiently solve pipe-routing problems at the resolution of hundreds of millions of voxels, this does not scale to resolutions required for precise pipe attachments (± 2 millimeter precision). This is prohibitive for 3D grid search, requiring trillions of voxels and terabytes to store! We aim to resolve this problem by developing mixed-resolution search frameworks that borrow advantages from both high and low-resolution search in order to jump quickly over large open regions of space, but retain solution quality at locations of importance (i.e., near equipment and other pipes).

References

Belov, G.; Czauderna, T.; Dzaferovic, A.; Garcia de la Banda, M.; Wybrow, M.; and Wallace, M. 2017. An Optimization Model for 3D Pipe Routing with Flexibility Constraints. In Beck, J. C., ed., *Principles and Practice of Constraint Programming*, volume 10416, 321–337. Cham: Springer International Publishing. ISBN 978-3-319-66157-5 978-3-319-66158-2.

Belov, G.; Du, W.; Garcia de la Banda, M.; Harabor, D.; Koenig, S.; and Wei, X. 2020. From Multi-Agent Pathfinding to Pipe Routing. *Proceedings of the 13th International Symposium on Combinatorial Search*, 11(1): 11–19.

Harabor, D.; and Grastien, A. 2011. Online Graph Pruning for Pathfinding on Grid Maps. In *Proceedings of the Twenty-Fifth AAAI Conference on Artificial Intelligence*, AAAI'11, 1114–1119. AAAI Press.

Ma, H.; Harabor, D.; Stuckey, P. J.; Li, J.; and Koenig, S. 2018. Searching with Consistent Prioritization for Multi-Agent Path Finding. arXiv:1812.06356.

Nobes, T.; Harabor, D.; Wybrow, M.; and Walsh, S. 2022. The Jump Point Search pathfinding system in 3D. *Proceedings of the 15th International Symposium on Combinatorial Search (SoCS)*, 15(1): 145–152.

Peters, M. S.; Timmerhaus, K. D.; West, R. E.; et al. 2003. *Plant design and economics for chemical engineers*, volume 4. McGraw-Hill New York.

Zhang, N.; Zhang, M.; and Low, K. H. 2021. 3D Path Planning and Real-Time Collision Resolution of Multirotor Drone Operations in Complex Urban Low-Altitude Airspace. *Transportation Research Part C: Emerging Technologies*, 129: 103–123.

Zhang, S. 2021. *Trajectory Planning Based on Optimized Jump Point Search Results Using Artificial Potential Field in 3-D Environments*. Master's thesis, University of California, Santa Cruz.