TECHNISCHE UNIVERSITÄT WIEN

Multi-Robot Route Planner with MStar for ROS2

Seminar for Master Students in Computer Engineering

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Contents

1 Motivation & Problem Statement

Due to their agility and interoperability, mobile robots are used in different applications, such as warehouses, hospitals, manufacturing processes, and many more. In all scenarios listed, multiple mobile robots must work simultaneously in an environment and manipulate different objects following an individual path. This individual path may cross or block the track of other robots for a certain time, which can lead to collisions and even deadlocks. In order to avoid such scenarios, a global path planner for multiple robots takes care of potential threats during the planning phase of individual tracks.

A global path planner is aware of the environment and its constraints. Therefore the planner knows the map, including static objects, as well as the start and goal position of all robots. Using this information, the path planner computes a trajectory from the start to the goal configuration, avoiding collisions with known obstacles. A robot's state also referred to as robot configuration, is described by its position in X and Y coordinates and rotation angle. Mostly the A* path-finding algorithm or an optimised version of it is used to search through the map [1].

The map can be a simple floor plan of a small office room. Even in a small room, a robot can have infinitely many states, which makes a path calculation computationally infeasible. Thus the map needs to be abstracted using, for example, Voronoi partitioning. This algorithm converts the continuous map with infinitely many states into a graph representation with finitely many states.

2 Aim of the Work

The goal of this thesis is to study the M* search algorithm and compare its performance to existing approaches within the domain of Multi-Robot-Routing. Therefore the algorithm will be implemented in an existing framework and attempts to solve given real-world scenarios. For instance, two robots are meeting at a T-crossing.

The performance of M* is measured and evaluated against the existing planning approach described in this paper [2]. In addition, the M* algorithm is tested within a warehouse simulation.

By the end of this thesis the following questions should be answered:

- **RQ1:** To which extent is the M* algorithm applicable to real-world multi-robot applications in terms of runtime and scalability?

- **RQ2:** How does the M* perform in contrast to the currently implemented conflict-based search in the domain of multi-robot applications?

- **RQ3:** Is it possible to combine the M* search algorithm with a conflict based search algorithm?

In order to answer **RQ1** a simulated warehouse is used to test the capability of the M* algorithm in a real-world setting. Special attention is paid to the algorithm's runtime compared to the number of robots operating in the simulated warehouse.

The answer to the second research question **RQ2** is also supported by simulation results. Both algorithms are applied to the same scenarios; certain key factors are recorded and used later for comparison. An example scenario could be two robots driving in the opposite direction and meeting each other at a T-crossing. The key factors in evaluating these scenarios, for instance, are computation time, nodes expanded and if the algorithm could solve the scenario.

RQ3 can be answered by implementing the M* search algorithm into the existing framework.

3 Methodological Approach

In order to achieve the presented goal, the following steps are necessary. Starting with a literature review, followed by implementing and extending the multi-robot framework. Using the extended framework to simulate various scenarios and compare results to the existing robot planning framework beforehand.

Literature Review

A literature review is done to deepen the knowledge of the problem statement and to get an overview of existing solutions for path planners in a multi-robot environment. Already existing variations of the M* algorithm are of special interest during the review.

Implementation

The existing planning infrastructure should be extended by a planner capable of switching between different planning algorithms. Special attention is paid to the M* algorithm. Furthermore, various strategies should return a consistent plan structure so further processing steps do not depend on the used algorithm.

Evaluation

The extended planner is used to simulate different scenarios proposed in [2] with a various number of robots. The simulation results should be evaluated using different metrics, for example, scenario solved successfully, computation and execution time compared to the already used path planning approach.

4 State of the Art

Due to their flexibility and redundancy, multi-robot systems have become popular in different fields of application, such as warehouses, surveillance, manufacturing processes and many more. Path planning for multi-robot environments can become difficult due to the high dimensional configuration space and is a fundamental problem [3]. There are two categories for planning algorithms related to this problem: couples algorithms and decouples ones [4].

Coupled path planning algorithms search the full configuration space involving all system robots. The configuration space contains all possible paths, so computation time grows exponentially with the number of robots, and coupled planners may be guaranteed an optimal path. Nevertheless, in applications with a large number of robots, computation becomes infeasible.

In contrast to coupled planning algorithms, decoupled ones are most commonly used to plan for each robot individually. The occurring collisions are then resolved in the next step of planning. This reduces the configuration space and impacts the computational effort of the planning phase.

This work [3] proposes a combination of both approaches, which the authors call sub-dimensional expansion. It uses decoupled planning in order to search paths in smaller configuration spaces. If a collision of paths is seen, the algorithm uses the coupled approach and seeks a solution locally, within the full configuration space and increases it locally if there is no possible solution. Furthermore, the authors show that the planning algorithm is complete and will find an optimal solution.

According to the authors of this paper [5], most research focuses only on one goal per robot. However, in real-world applications, a robot often has multiple goals before successfully completing a task. Due to this, the generated robot routes could be more optimal for driving. In order to address this issue, the commonly known problem of multi-robot routing is extended with a multiple travelling salesperson problem (mTSP). Therefore the original M* is modified to solve the mTSP by policy construction and heuristic value and ignoring the conflicts in the first place. Afterwards, back-propagation similar to the original algorithm is performed. Additionally, back-propagating using the entire set of robots is also calculated. The authors also show that their solution is complete and optimal. Unfortunately, as the number of agents grows above ten, the success rate drops below 80% in a typical warehouse environment.

This paper [6] uses an attention-based neural network in combination with the M*. The authors are planning the robot fleet's paths and attempting to minimise the collisions that occur during the individual planning phase. Therefore the model is fed with the observation of each robot after every action taken by each robot individually. Additional information, such as the start and goal position, is also shared. The proposed approach, called Learning-assisted M* (LM*), can find solutions faster than the original M* due to the reduced number of conflicts that must be resolved. Furthermore, the authors showed that their solution is able to generalise, which means it still calculates paths faster on maps not seen during the training process. Nonetheless, the model does not find the optimal solution that results in an approximately 10% more comprehensive solution.

Most path planning algorithms focus on optimising one specific metric: the path length from a start to an endpoint. In order to address also multiple objectives such as fuel consumption or time-to-completion, the authors of this paper [7] extended the M* planning algorithm to consider more metrics during the planning process. Applying existing solutions for multi-objective single robot search algorithms might lead to an inefficient solution, but they are used as a baseline for comparison. The proposed algorithm can successfully handle four objectives and overcome the baseline in terms of average run time and solved scenarios.

5 Structure of the Work

1. Abstract
2. Introduction
3. Background
    3.1 State of the Art
    3.2 Robot Navigation
    3.3 Path Planning
4. Methodological Approach
5. Implementation
6. Simulation
7. Results
8. Discussion
9. Conclusion and future work

6 Topic Matching with Computer Engineering

This thesis contributes to the existing state-of-the-art multi-robot planning and navigation solutions based on modern robot control and simulation software.

Many topics of Computer Engineering studies will be covered during this thesis. The most relevant courses are listed below.

- 183.660 - Mobile Robotics
- 182.763 - Stochastic Foundations of Cyber-Physical Systems
- 191.119 - Autonomous Racing Cars
- 182.762 - Project Computer Engineering (Drone Localisation)

References

[1] D. Foead, A. Ghifari, M. B. Kusuma, N. Hanafiah, and E. Gunawan. “A Systematic Literature Review of A* Pathfinding”. In: *Procedia Computer Science* 179 (2021). 5th International Conference on Computer Science and Computational Intelligence 2020, pp. 507–514. ISSN: 1877-0509. DOI: https://doi.org/10.1016/j.procs.2021.01.034. URL: https://www.sciencedirect.com/science/article/pii/S1877050921000399.

[2] B. Binder, F. Beck, F. König, and M. Bader. “Multi Robot Route Planning (MRRP): Extended Spatial-Temporal Prioritized Planning”. In: *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2019, pp. 4133–4139. DOI: 10.1109/IROS40897.2019.8968465.

[3] G. Wagner and H. Choset. “Subdimensional expansion for multirobot path planning”. In: *Artificial Intelligence* 219 (2015), pp. 1–24. ISSN: 0004-3702. DOI: https://doi.org/10.1016/j.artint.2014.11.001. URL: https://www.sciencedirect.com/science/article/pii/S0004370214001271.

[4] S. M. LaValle. *Planning Algorithms*. Cambridge University Press, 2006. DOI: 10.1017/CBO9780511546877.

[5] Z. Ren, S. Rathinam, and H. Choset. “MS*: A New Exact Algorithm for Multi-agent Simultaneous Multi-goal Sequencing and Path Finding”. In: *2021 IEEE International Conference on Robotics and Automation (ICRA)*. 2021, pp. 11560–11565. DOI: 10.1109/ICRA48506.2021.9561779.

[6] L. Virmani, Z. Ren, S. Rathinam, and H. Choset. *Subdimensional Expansion Using Attention-Based Learning For Multi-Agent Path Finding*. 2021. DOI: 10.48550/ARXIV.2109.14695. URL: https://arxiv.org/abs/2109.14695.

[7] Z. Ren, S. Rathinam, and H. Choset. “Subdimensional Expansion for Multi-Objective Multi-Agent Path Finding”. In: *IEEE Robotics and Automation Letters* 6.4 (2021), pp. 7153–7160. DOI: 10.1109/LRA.2021.3096744.