

# Optimal pattern-based near-field path planning for mobile robots, under consideration of obstacles in intralogistics environments

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## Abstract

## 1 Introduction

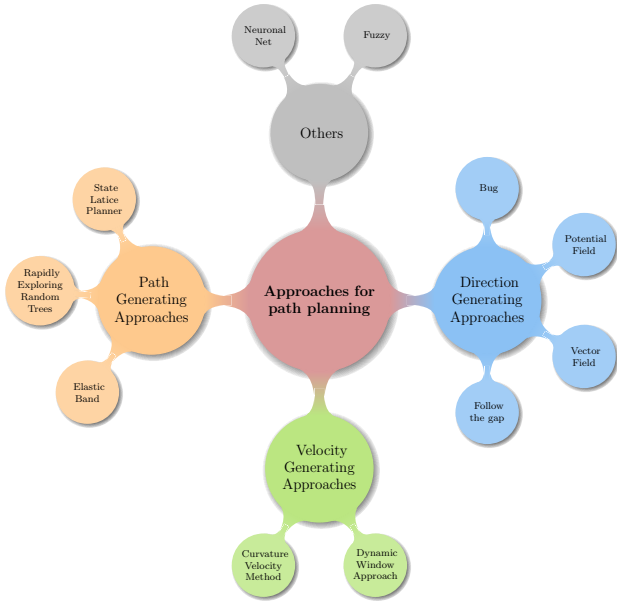
Brownfield environments in intralogistics are highly dynamic, complex and tight action areas for autonomous mobile robots (AMRs). These environments require AMRs to navigate aside human workers, other warehouse vehicles and existing infrastructure while being highly flexible, time efficient and safe. For the path planning domain additional challenges arise when they address logistical pickup or drop zones. These zones requiring higher accuracy due to the interaction with goods while being predictable for the surrounding workers in such warehouses. The general robotic path planning problem is a well-known problem, where the goal is to find a collision-free path to link the robots current pose with a target pose while adhering to kinematic constraints and avoiding obstacles in real-time. Current path planning methods often present limitations when addressing these application field in explainability, adaptability and computational efficiency and limiting therefore their practical deployment. Limitations found in the literature include also over simplified testing environments, simulation-only based results (see simulation reality gap) and extended planning times up to 31s for scenarios ranging from simple to very complex (e.g. using Particle Swarm Optimization (PSO) [1]). This paper introduces a nature-inspired optimization approach based on pattern-based paths for fast and efficient trajectory generation. By leveraging mathematical modelisation of the problem and real-time decision-making, the proposed methodology ensures smooth, kinematically feasible trajectories while minimizing travel distance, curvature changes and avoiding collisions. The approach is implemented within the Robotics Application Construction Kit (RACK) framework and validated through simulation and real-world tests, demonstrating improved trajectory accuracy, enhanced robotic explainability and reduced commissioning effort. This study contributes to optimization in robotics, making AMRs more adaptive and efficient in dynamic intralogistics environments.

## 2 State of the Art

Path planning is a fundamental challenge in robotics, with extensive research focusing on optimizing trajectory generation for mobile robots. Traditional approaches, such as A\* and Dijkstra algorithms, have been widely used to find optimal paths in static environments. However, these methods struggle to adapt to dynamic scenarios, where obstacles are constantly moving or changing. The essence of planar motion planning is the planning and executional link between the link between the current location and the desired destination through planar driving maneuvers. The movement planning can be splitted into into global movement planning and local movement planning. The local path planning links the current location with the desired destination pose through a series of driving maneuvers in the context of this project the pallet location. Compared to global path planning the local path planning tends to converge to local minima, due to the missing knowledge of the environment out of the sensorical view. The immense number of individual approaches, but also the development dynamics of the past decades try to answer the local path planning problem in mobile robotics does not allow a detailed discussion of individual publications within the scope of this work. For this reason, an evaluation based on a clustering was done. Starting from the early years of mobile robotics (Latombe [Lat84], Kathib [Kha85] or Lumelsky [LS87]) through to current developments, key characteristics are subsequently identified. After this clustering a consequent discriminating approach is done with the aim of selecting the most suitable cluster within this application field context.

The field of local path planning approaches can be clustered based on their underlying state spaces for the calculation the control outputs of the actuators (steering and traction drive). The clustering are therefore grouped into direction-, speed- and path-generating methods (see figure).

To address this limitation, researchers have explored metaheuristic optimization techniques, such as genetic algorithms, particle swarm optimization, and ant colony optimization, to enhance path planning efficiency and adaptability [1].



**Figure 1:** Mindmap showing the clustering of local path planning approaches, with example approaches in each category

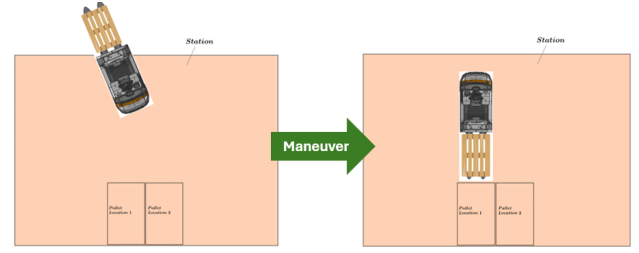
## 2.1 Problem Statement

Autonomous Mobile Robots (AMRs) in intralogistics face significant challenges in efficiently linking their starting positions to precise pallet docking locations while adapting to dynamic warehouse conditions. In brownfield warehouses, environments are often cluttered, with limited maneuvering space, requiring AMRs to efficiently navigate alongside human workers while maintaining safety and precision.

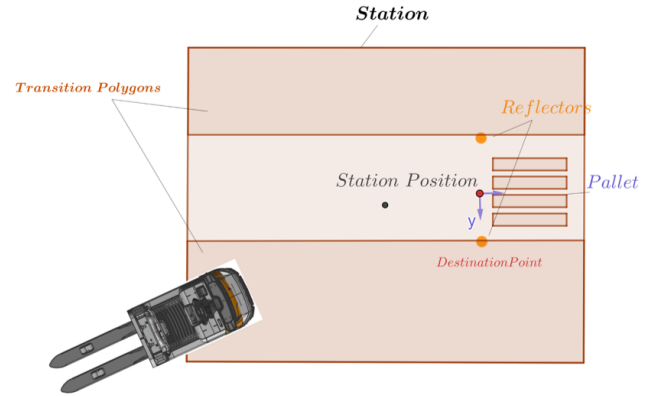
Key challenges include:

- Precision Docking: The AMR must reach a docking pose that aligns its forks with the pallet or shelf while maintaining minimal deviation.
- Obstacle Avoidance: The robot encounters obstacles that are considered before generating the trajectory.
- Kinematic Constraints: Due to limited turning capabilities, AMRs cannot always take direct paths to their targets and must generate feasible maneuvers.
- Adaptive Linking: The solution must be reliable and capable of dynamically adapting to different situations and environmental configurations.

Traditional approaches often struggle with high commissioning efforts and lack of explainability, making deployment and adaptability difficult. This paper proposes a pattern-based path planning approach integrated with optimization techniques to enhance explainability, efficiency, and adaptability in such environments.



**Figure 2:** Need to maneuver for target docking



**Figure 3:** Station Model with shelf, a forklift, and the transition polygons [2]

## 3 Methodology

The proposed solution is a pattern-based path that links the initial position of the AMR to the target position while performing a necessary maneuver to ensure direction changes between these positions: the truck arrives to the station driving in chassis direction, and needs to dock the target in forks directions as illustrated in figure 2.

The proposed methodology consists of several key components that work together to ensure real-time path generation and optimization:

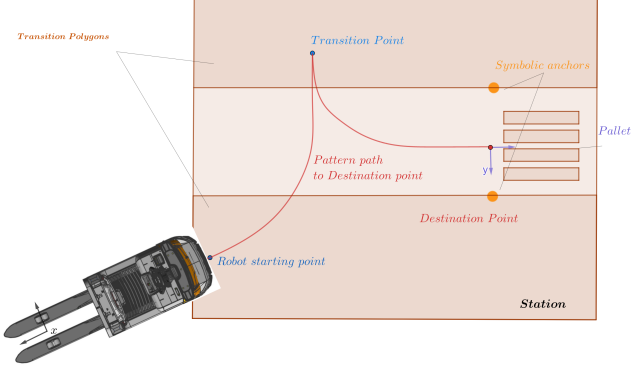
### 3.1 Geometric Partitioning

The warehouse is divided into predefined zones, ensuring the robot can adaptively plan movements between them. Each station is represented as a structured area where path linking would be optimized. Each station has a shelf to store the handled materials. The station is partitioned, according to its layout, into two free zones to serve as maneuver zones labeled on figure 3 as "transition polygons".

### 3.2 Pattern-Based Path Creation

The transition polygons are then used to maneuver: a transition position is set and through it, the AMR stops briefly to drive in the opposite direction. The pattern path is visible in figure 4.

The approach leverages splines to generate smooth paths between waypoints, ensuring high kinematic feasibility through continuous speed and acceleration.



**Figure 4:** Pattern path, linking the start position to the target, passing through a transition position to change directions [2]

### 3.3 Path Evaluation Metrics

Several evaluation criteria are implemented to assess path efficiency, including curvature change minimization to prevent abrupt changes in steering and unfeasible curves, travel distance, and obstacle avoidance. First colliding paths are omitted, then the paths are discriminated by their quality. Using the developed cost function, each path's quality is quantified by a value measured using a cost function. The smaller the value, the better the path.

$$CF = \omega_C \cdot \underbrace{\frac{\sum_{i=j \text{ min par}}^j \max \text{ par} \frac{\Delta k(i)_j}{\Delta s(i)_j}}{\sum_{i=\text{ref min par}}^{\text{ref max par}} \max \text{ par} \frac{\Delta k(i)_{\text{ref}}}{\Delta s(i)_{\text{ref}}}}}_C + \omega_L \cdot \underbrace{\frac{\sum_{i=\text{min par}}^{\text{max par}} s(i)_j}{\sum_{i=\text{min par}}^{\text{max par}} s(i)_{\text{ref}}}}_D \quad (1)$$

Where:

- $\omega_C$  and  $\omega_L$  are the weights assigned to the curvature change term and the length term, respectively. These weights determine the relative importance of curvature change and path length in the overall evaluation.
- C is the Curvature Change Term.
- D is the Length Term.

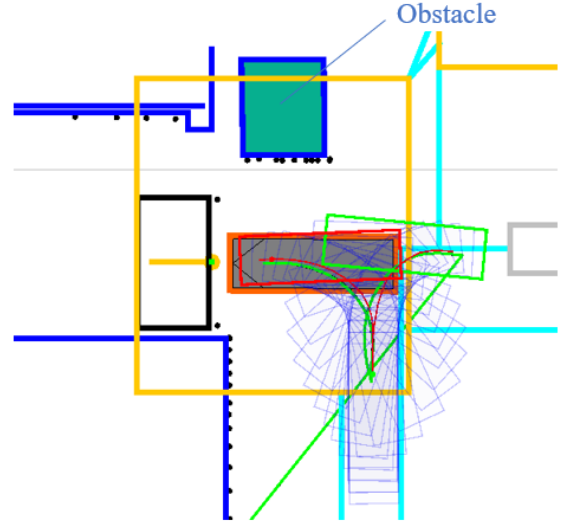
These terms are normalized by division by a reference value of a random path and weighted to control the influence of each term on the outcome, then summed [3].

### 3.4 Meta-heuristic Optimization

Various optimization techniques, such as genetic algorithms (GA), Ant Colony Optimization (ACO), and particle swarm optimization (PSO), are used to refine path selection and dynamically adapt to new environmental constraints. The algorithms were integrated using the PAGMO library and the minimization of the cost function as an objective function.

### 3.5 Obstacle Avoidance

The system uses the B-Splines property of interpolating new waypoints without affecting the general shapes of the



**Figure 5:** Simulation environment of a complex situation overview inside a station (yellow frame) with initial position (green frame), target position (red frame), generated path (green), and obstacle (green square)

curve. In case of obstacles, the algorithms sets waypoints that influence that path to stray away from them.

### 3.6 Implementation in RACK Framework

The Robotics Application Construction Kit (RACK) is used to validate the approach through simulation then real-world deployment in a warehouse setting.

## 4 Experimental Results and Discussion

The proposed approach was rigorously tested in simulation and real-world scenarios, validating its efficiency, reliability, and adaptability. The results confirm that the system efficiently generates optimized, explainable, and collision-free paths in minimal time.

**Path Creation and Validation:** The pattern-based approach successfully generated smooth, kinematically feasible paths that adhered to warehouse constraints and linked the AMR in start position to the specified target. Tests in both simulation and real-world environments confirmed the effectiveness of transition points in reducing curvature and improving maneuverability. An overview of a situation with an obstacle in the environment is visible in figure 5.

**Path Evaluation and Optimization:** Tests in simple and complex environment settings were executed using the RACK Simulation Environment to compare the performance of the Meta-heuristic algorithms: Genetic Algorithms (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Simulated Annealing (SA). After each processing of the situation and test environment the best feasible path among all the generated ones is saved as the champion path. A

comparative analysis of the algorithms based on fitness values of the champion paths and planning time demonstrated that PSO provided the most balanced performance in terms of planning time and path quality. The selected evaluation method effectively discriminated between high- and low-quality paths, ensuring optimal trajectory selection.

**Performance Metrics:** The solution demonstrated significant improvements in computational efficiency, achieving path planning times as low as 59ms in simple environments and 67ms in complex scenarios. Real-world execution times remained within acceptable limits, validating the approach's practicality.

These results highlight the robustness of the proposed solution in optimizing AMR path planning while maintaining high levels of explainability and adaptability.

## 5 Conclusion and Future Work

This research presents an optimized path-planning approach for Autonomous Mobile Robots (AMRs), focusing on repeatable, station-specific paths that ensure precise docking. The method integrates metaheuristic optimization to minimize path length and curvature while adhering to kinematic constraints. Unlike traditional approaches, which suffer from high computational costs and long planning times (13–31 s), this solution achieves significantly faster results: 40–50 ms in simulation and a maximum of 400 ms in real-world tests.

The approach enhances explainability and predictability by generating human-interpretable paths, with well-defined optimization parameters. It also improves adaptability, allowing seamless deployment in varying station layouts. Field tests confirm the method's robustness, demonstrating its practical applicability in real-world AMR operations. Looking ahead, this research can be refined by integrating more transition zones to improve the exploration of the entire free space within the station and optimizing the use of transition polygons based on the AMR's position to reduce the risk of low-quality reference points and generated paths. Additionally, further work can focus on documenting the findings in a scientific article to contribute to the field and enhance knowledge dissemination. These refinements will improve the approach's efficiency, adaptability, and practical implementation in industrial robotics applications.

## References

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