Hybrid Quantum-Classical Path Planning for Autonomous Mobile Robots in Smart Warehouses

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***Abstract*—Smart warehouses increasingly rely on Autonomous Mobile Robots (AMRs) to optimize logistics operations. However, dynamic and congested environments make path planning challenging. Classical algorithms like A* and Ant Colony Optimization (ACO) often struggle to adapt to real-time changes. This paper proposes a Hybrid Quantum–Classical Path Planning (HQCPP) approach combining Grover's Quantum Search with ACO to enhance goal selection and route optimization. Simulations in dynamic warehouse environments demonstrate that the hybrid model achieves faster convergence, lower computational cost, and improved path efficiency compared to classical ACO. These results show that quantum-inspired techniques can enhance decision-making in next-generation smart logistics systems.**

***Index Terms*—Smart Warehouse, Quantum Computing, Grover Search, Ant Colony Optimization, Path Planning, Autonomous Mobile Robots**

I. Introduction

The rapid advancement of smart logistics has increased the deployment of Autonomous Mobile Robots (AMRs) for handling, transport, and delivery tasks. These robots require efficient path planning to avoid obstacles, minimize travel time, and adapt to dynamic environments. Path planning is an NP-hard problem [1], where computational complexity grows rapidly with the number of routes and obstacles. Classical algorithms such as A*, Dijkstra, and ACO perform well in static settings but degrade in dynamic, multi-agent environments. Quantum computing introduces a new paradigm for complex optimization, with Grover's algorithm providing quadratic speed-up in unstructured search, enabling faster identification of optimal or near-optimal goals. The main contributions of this work are:

1) A hybrid Grover-ACO framework for multi-target robotic path planning. This approach integrates Grover's quantum search algorithm with Ant Colony Optimization (ACO) to efficiently address complex path planning challenges involving multiple targets. Automatic quantum-assisted goal selection without manual qubit encoding.
2) Comprehensive performance comparison between classical and hybrid-quantum metrics. The framework is empirically validated, reporting metrics such as path length, travel time, and iteration count for each goal.

This work integrates Grover Search for intelligent goal selection and ACO for efficient path planning.

II. Related Work

Classical algorithms such as A*, Dijkstra, and Ant Colony Optimization (ACO) have been widely applied in mobile robot navigation [1], [2]. However, these methods encounter scalability and computation time challenges, particularly in dynamic or multi-target environments.

With the emergence of quantum computing, new avenues have been explored to enhance path planning performance. Notably, quantum ant colony optimization (QACO) algorithms have been introduced, where qubits represent path probabilities, often achieving faster convergence in simulated scenarios [3].

Hybrid methods have emerged to enhance optimization. de Andoin and Echanobe [4] showed that combining quantum probabilistic search with classical computation improves hybrid quantum ant colony optimization. However, existing quantum and hybrid approaches are often limited to small-scale or single-target tasks and require manual encoding. To address this, we propose a hybrid classical–quantum framework integrating Grover's quantum search with classical ACO for multi-target path planning. The QPU accelerates probabilistic goal selection, while the CPU handles deterministic path construction and metric evaluation, improving goal prioritization and reducing iterations, computation, and travel time.

III. Methodology

This section details the HQCPP framework and the metrics used for evaluation. The implementation integrates a Grover-based quantum selection with a classical ACO planner for path refinement.

A. Problem statement

Given a grid-based warehouse map where each cell is either free, obstacle, or a goal, and a robot at a start location, the objective is to visit all goals while minimizing cumulative path length, travel time, and computation cost. The planner must produce collision-free routes and be robust to changes in the environment.

B. Hybrid architecture

QCPP alternates between two stages:

1) **Quantum Goal Selection.** Grover's search is used to select the next goal among remaining candidates. Each candidate goal is associated with a basis state. A classical distance measure (e.g., Manhattan distance)

serves as the oracle criterion: the oracle marks the goal with minimal distance to the robot's current position. The diffusion operator amplifies its amplitude so that measurement yields the nearest candidate with high probability.

2) **Classical Path Optimization.** After the goal is selected, ACO is executed on the classical CPU. Ants explore the grid, build paths from the current robot position to the selected goal, and pheromone trails are updated using evaporation and deposition rules.

C. *Ant Colony Optimization details*

The ACO path finder uses the standard probabilistic transition rule:

$$P_{ij} = \frac{\tau_{ij}\eta_{ij}}{\sum_{n \in N_i} \tau_{in}\eta_{in}}, \tag{1}$$

where τ_{ij} denotes the pheromone on edge $(i, \ )$, η_{ij} is the heuristic desirability (inverse Manhattan distance), and α, β control pheromone and heuristic importance. Pheromone update follows:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}, \tag{2}$$

with ρ the evaporation rate, m the number of ants, and $\Delta\tau_{ij}^{k}$ the pheromone deposited by ant k (commonly Q/L_k where L_k is the ant's path length).

IV. Results

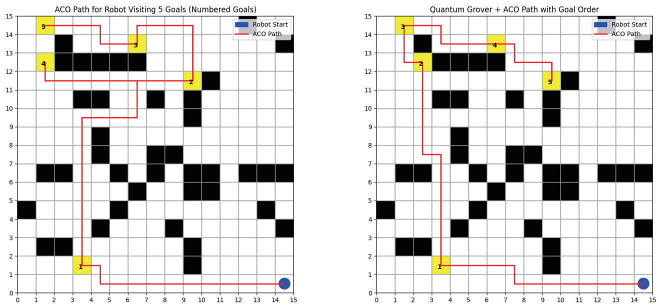
The experimental results on a 15×15 grid with five goals demonstrate that the proposed Hybrid Quantum–Classical Path Planning (QCPP) method outperforms the classical Ant Colony Optimization (ACO) algorithm. As shown in Figures 5(a) and 5(b), the hybrid approach integrates Grover's quantum search for efficient goal selection, resulting in shorter routes and fewer iterations. The classical ACO required a total travel time of 78 units over 24 iterations with 22.87 s computation time, whereas the Hybrid Grover + ACO reduced the travel time to 43 units and iterations to 14, with a comparable computation time of 22.68 s. These results confirm that the hybrid method significantly improves path efficiency while maintaining similar computational complexity.

TABLE I: Classical ACO Metrics

Travel Time	Iteration Found	Computation Time (s)
13	2	4.5735
17	18	4.5735
8	1	4.5735
17	2	4.5735
23	1	4.5735

TABLE II: Hybrid Grover + ACO Metrics

Travel Time	Iteration Found	Computation Time (s)
13	2	7.2846
13	9	7.8475
4	1	1.8263
7	1	3.0222
6	1	2.6956



(a) Ant Colony Optimization (b) Hybrid Grover's + ACO

Fig. 1: Comparison between Classical ACO and Hybrid Quantum–ACO algorithms.

V. Conclusion and Future Work

This paper presented a Hybrid Quantum–Classical Path Planning (HQCPP) framework for autonomous mobile robots in dynamic warehouse environments, combining Grover's quantum search for goal selection with Ant Colony Optimization for path planning. Results show that the hybrid approach reduces travel time and iterations while maintaining comparable computation time, demonstrating improved path efficiency over classical ACO. Future work will focus on integrating digital twins for real-time training and testing, extending the framework to multi-robot coordination, and exploring practical deployment using quantum-classical co-processing to enhance scalability, adaptability, and robustness in next-generation smart logistics systems.

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