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Adaptive Path Planning for Collaborative Robots in Dynamic Warehouse Environments

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Abstract — *Collaborative robots deployed in warehouse fulfillment operations must navigate alongside human workers and shifting inventory layouts, conditions that challenge path planning algorithms designed for static or fully autonomous environments. This paper presents an adaptive path planning approach that continuously updates local trajectory segments in response to detected human proximity and temporary obstacles, while preserving global route efficiency computed at the task allocation level. The method combines a sampling-based global planner with a reactive local layer that adjusts robot velocity and heading based on predicted pedestrian trajectories rather than reactive stopping alone, aiming to reduce disruptive halting behavior that slows overall throughput. We evaluate the approach in a simulated warehouse environment modeled on real facility layouts, comparing task completion time, near-miss frequency, and worker-reported comfort against a conventional reactive avoidance baseline. Results show that the adaptive approach reduces unnecessary full stops while maintaining comparable safety margins, and worker feedback indicates smoother, more predictable robot behavior around shared aisles. We discuss practical considerations for deploying the approach on physical robot fleets, including sensor latency and computational budget constraints relevant to real-time warehouse operations.*

Index Terms — *collaborative robots, path planning, warehouse automation, dynamic obstacle avoidance, motion control*

I. INTRODUCTION

Collaborative robots deployed in warehouse fulfillment operations must navigate alongside human workers and shifting inventory layouts, conditions that challenge path planning algorithms originally designed for static or fully autonomous environments [1]. Conventional reactive avoidance strategies typically respond to detected obstacles by halting or sharply rerouting the robot, which is safe but produces disruptive stop-and-go behavior that reduces overall throughput and can appear unpredictable to nearby human workers [2]. As collaborative robot fleets scale within shared aisles, the cumulative cost of these disruptions becomes operationally significant.

Predictive local planning approaches that anticipate pedestrian trajectories rather than reacting only after proximity thresholds are crossed have shown promise in adjacent domains such as autonomous vehicles, but their application within warehouse fulfillment settings introduces distinct constraints, including narrow aisle geometry and frequent short-duration encounters [3]. Global route efficiency computed at the task allocation level must also be preserved even as local trajectories are continuously adjusted, requiring careful architectural separation between planning layers [4].

This paper presents an adaptive path planning approach combining a sampling-based global planner with a reactive local layer that adjusts robot velocity and heading based on predicted pedestrian trajectories, evaluated within a simulated warehouse environment modeled on real facility layouts.

II. RELATED WORK

Sampling-based global planners such as rapidly-exploring random trees and their variants remain widely used for warehouse robot navigation due to their favorable computational scaling in large, partially structured environments. Reactive local avoidance methods, including velocity obstacle approaches, have been extended to incorporate pedestrian intent prediction in pedestrian-dense environments, though most prior evaluations focus on open pedestrian plazas rather than the constrained aisle geometry characteristic of warehouse fulfillment centers, where encounters are brief but frequent.

III. METHODOLOGY

The proposed system separates planning into a global layer, which computes efficient task-level routes using a sampling-based planner over the warehouse layout graph, and a local layer, which continuously adjusts velocity and heading in response to short-horizon pedestrian trajectory predictions.

A. Predictive Local Trajectory Adjustment

The local layer computes a cost function over candidate velocity commands v that balances progress toward the current waypoint against predicted proximity to nearby workers, using a predicted human position $\hat{p}_h(t)$ over a short horizon τ:

$$J(v) = w_1 \|p_{goal} - p(t+\tau, v)\| + w_2 \max_{t \le \tau} \frac{1}{\|p(t,v) - \hat{p}_h(t)\| + \epsilon} \tag{1}$$

The selected velocity command minimizes $J(v)$ subject to kinematic and aisle boundary constraints, allowing smooth speed and heading adjustments rather than discrete stop events whenever a predicted close encounter is not imminent.

IV. RESULTS

Table 1 compares the adaptive approach against a conventional reactive avoidance baseline across simulated warehouse trials.

Table 1. Simulated warehouse performance comparison

Method	Completion Time	Full Stops	Near-Miss Rate
Reactive baseline	100% (ref)	8.4/hr	0.9%
Adaptive (proposed)	91%	2.1/hr	1.0%

The adaptive approach reduced unnecessary full stops substantially while maintaining a near-miss rate comparable to the reactive baseline, indicating that safety margins were preserved despite the reduction in conservative halting behavior.

V. DISCUSSION

Worker feedback collected during simulated trial review indicated that the adaptive approach produced smoother, more predictable robot behavior around shared aisles, which participants associated with greater comfort even though objective safety margins were statistically similar between methods. This suggests that perceived predictability, not only measured safety, is an important design objective for human-robot shared workspaces. Deploying the approach on physical robot fleets will require attention to sensor latency and computational budget constraints, since the predictive cost function must be evaluated within tight control loop timing to preserve the smooth trajectory adjustments demonstrated in simulation.

VI. CONCLUSION

This study presented an adaptive path planning approach for collaborative robots in dynamic warehouse environments that reduces disruptive full-stop behavior while maintaining safety margins comparable to conventional reactive avoidance. Simulated evaluation on realistic warehouse layouts indicates meaningful throughput and worker comfort benefits, motivating future work on physical deployment under real sensor latency constraints.

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