Autonomous Mobile Robot Movement Algorithm with Human Collision Avoidance Perception

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***Abstract*—In shared spaces, Autonomous Mobile Robots (AMRs) must efficiently reach their goals while remaining physically safe and psychologically nonthreatening. Conventional Social Force Model (SFM) control uses distance-based repulsion and can underestimate future collision risk, which worsens the safety-efficiency tradeoff at higher speeds. We propose a collision-predictive SFM that weighs repulsion based on the anticipated risk of collision at the closest approach, as determined by distance and time. This is mapped through a braking-indicator probability. Simulations compared random, crossing, and straight flows across desired AMR speeds. The method kept close encounters low while shortening completion time in the Straight flow.**

***Keywords*-Autonomous mobile robot; Social force model; Collision predictive avoidance algorithm.**

I. INTRODUCTION

In recent years, shared spaces, where pedestrians, bicyclists, and other users share the same space, have been expanding in urban areas [1][2]. These spaces have limited explicit traffic controls, such as signals and lanes, and order is maintained through mutual coordination among users, including yielding, adjusting speed, and changing paths [3]. This paper addresses the scenario of a single Autonomous Mobile Robot (AMR) operating within an environment of numerous moving pedestrians and performing tasks such as delivery and mobility assistance.

Transportation by AMR is promising due to its convenience. In this context, the AMR requires a navigation strategy that ensures safety while reaching its destination as efficiently as possible [2]. However, a trade-off is anticipated: increasing safety often reduces efficiency metrics, such as travel speed [2][4].

A key challenge when introducing AMRs into shared spaces is achieving “predictable and non-threatening” behavior within pedestrian groups [5][6]. Pedestrians avoid collisions by interpreting the intentions of others through their gaze, body orientation, and subtle changes in speed. If an AMR’s behavior lacks human-like cues or consistency, however, it can trigger unnecessary avoidance actions and anxiety, which can disrupt the overall flow of the space [5].

The Social Force Model (SFM) is a well-known model that describes crowd behavior [7][8]. It describes crowd flow and avoidance by combining the driving force toward a destination with repulsive forces from others and obstacles. Applying the SFM to AMR movement could provide a unified approach to handling avoidance actions within pedestrian groups [5][9]. However, SFM’s simple, distance-based avoidance is predicted to inadequately reflect differences in future risk based on congestion levels and crossing angles [10]. This makes the trade-off between efficiency and safety more apparent.

Safety in shared spaces must be considered from two perspectives: physical safety, which prevents collisions and excessive proximity, and psychological safety, which mitigates feelings of anxiety, surprise, and pressure experienced by pedestrians [1][2][11]. The widely used traditional risk metric, Time To Collision (TTC) [12], assumes one-dimensional movement. It is difficult to apply to two-dimensional movement, such as when an AMR’s trajectory intersects with a pedestrian group’s movement. Furthermore, the potential disconnect between the objective danger level and the subjective sense of safety is a unique design challenge of shared spaces [1][11].

Therefore, this study focuses on a braking indicator [13] that assigns a hazard level based on the probability that a person will apply the brakes. This probability is derived from the Distance of Closest Point Approach (DCPA) and the Time of Closest Point Approach (TCPA). We propose a collision-predictive avoidance algorithm that integrates this indicator into SFM. The proposed method aims to reduce travel time while avoiding sudden approaches to pedestrians. It accomplishes this by adjusting the evasion amount (reaction force) based on the “potential for future collision” rather than merely avoiding proximity. Furthermore, the evaluation criteria include the ripple effect on indirect groups of pedestrians (smoothing flow/eliminating congestion), as well as pedestrians who are directly interacting with the AMR. This allows for consideration

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of safety and efficiency from the perspective of the entire shared space.

In Section 2, we describe the proposed method and the simulation setting, including the AMR control strategies and evaluation measures. In Section 3, we present the simulation results under the different pedestrian flow conditions. Finally, in Section 4, we discuss the implications of the findings, outline the limitations of the study, and suggest directions for future research.

II. METHOD

A. Overview

This study examines scenarios in which a single AMR enters an environment with numerous pedestrians moving within a shared space. The AMR traverses pedestrian flows while navigating to its destination. The evaluation aims to verify whether the proposed collision-predictive avoidance algorithm can efficiently reach the destination while ensuring safety by preventing excessive proximity to pedestrians. For comparison, a baseline (distance-based avoidance) was established using the SFM to describe the AMR's motion. The performance difference between the baseline and the proposed method was then compared under various pedestrian flow types and AMR desired speed conditions.

B. AMR Movement Control

Two control methods were set for the AMR:

- **Baseline (SFM-based avoidance):** The AMR performs avoidance actions based on the SFM, using repulsive forces proportional to its distance from pedestrians. The avoidance intensity primarily depends on distance and does not directly reflect differences in future collision risk.
- **Proposed (collision-predictive avoidance):** The proposed method retains the SFM framework, but it also estimates the potential for the AMR to make dangerously close approaches to pedestrians in the future. It then adjusts the avoidance intensity according to this risk level. The method uses the distance to closest point of approach (DCPA) and time to closest point of approach (TCPA) to estimate risk. These are calculated from the relative motion between the AMR and the pedestrian. These values are then input into a brake indicator [13], which assigns a risk level as a "probability of braking." The AMR's repulsive force is weighted by this risk level, strengthening avoidance for high-risk targets while mitigating it for low-risk ones. This enables avoidance based on "potential future collision risk" rather than mere proximity avoidance. The method simultaneously aims to maintain safety and suppress reduced mobility efficiency.

C. Simulation Environment

The simulation space was defined as a 20-meter-by-20-meter square field on a two-dimensional plane. Pedestrian agents and one AMR agent were placed within this space. Each agent moved from its starting point toward a destination (goal area). The simulation progressed in discrete time, updating acceleration, velocity, and position at each step. This study defined 1,000 steps as one trial and performed 500 trials. The final performance was calculated as the average of these trials.

D. Pedestrian Flow Scenarios

The SFM was used for the motion model of all pedestrians. The SFM default value of 1.34 m/s was set for all pedestrians to achieve the desired crowd speed. To reproduce typical pedestrian flows in shared spaces, three types of pedestrian flows were created by varying the placement of starting and destination positions: Random, Crossing, and Straight. "Random" represents mixed, multidirectional movement; "Crossing" represents intersecting flows; and "Straight" represents unidirectional, straight-line flow. These conditions include scenarios with different avoidance patterns, such as intersecting, overtaking, and oncoming traffic, enabling a cross-situational evaluation of the effectiveness of the proposed method.

E. Experimental Factors

In this simulation, the AMR's desired speed was the primary operational factor. It was set in steps within the range of 0.5–2.0 m/s to examine how the trade-off between increased efficiency from higher speeds and potential safety compromises could be mitigated. For each pedestrian flow scenario, all combinations of the AMR control method (baseline or proposed) and desired speed were executed.

F. Dependent Measures

Performance evaluation was conducted along two axes: AMR efficiency and safety.

- **Efficiency**: The completion time for the AMR to reach the goal area from its starting point was calculated.
- **Safety**: Events in which the distance between the AMR and a pedestrian fell below a certain threshold were defined as proximity events. The total number of these events (i.e., close encounters) was calculated (e.g., distance <0.1 m).

To examine the ripple effect of the AMR's presence on pedestrian crowd movement, pedestrians were classified into two groups: those that directly interacted with the AMR and those that did not. Direct interaction was defined as pedestrians whose field of view included the AMR during the simulation and who were included in the avoidance calculations. Similar to the AMR, completion time and number of close encounters were measured for both direct and indirect interaction groups.

III. RESULTS

Figures 1 to 3 illustrate the changes in (i) efficiency (completion time) and (ii) safety (number of close encounters) as the desired speed of the AMR is manipulated (0.5–2.0 m/s), categorized by pedestrian flow scenario. The figure shows the results for three groups—Mobility (AMR), Direct-interaction Pedestrians, and Indirect-interaction Pedestrians—and compares SFM (Baseline) with the collision predictive avoidance algorithm (Proposed). Error bars indicate standard errors.

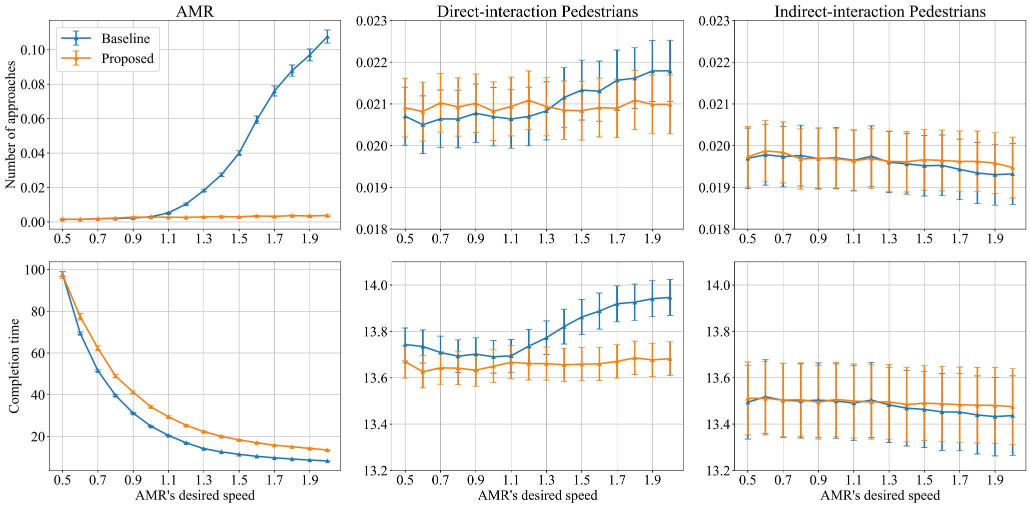

Figure 1. Trade-off between efficiency and safety in random situation.

A. Random Condition

Figure 1 illustrates the results in the random situation.

Focusing on AMR under the random condition, SFM showed an increase in the number of close encounters as the desired speed increased. In contrast, the collision predictive avoidance algorithm maintained a nearly constant number of close encounters regardless of changes in desired speed. Overall, however, SFM had slightly shorter completion times. Under random conditions, SFM exhibited a trade-off where "increased speed → shorter completion time" was accompanied by "increased number of close encounters." In contrast, the collision predictive avoidance algorithm exhibited a more desirable pattern of change: "shortening completion time without increasing the number of close encounters." Next, no clear difference in the number of close encounters was observed for Direct-Interaction Pedestrians based on desired speed or algorithm. Regarding completion time, however, under conditions with relatively high desired speeds (1.4 m/s or higher), the collision predictive avoidance algorithm had shorter completion times than SFM. For indirect-interaction pedestrians, no changes in the number of close encounters or completion time were observed due to differences in desired speed or algorithm.

B. Crossing Condition

Figure 2 illustrates the results in the crossing situation.

Mobility and pedestrian change patterns in the crossing condition were similar to those in the random condition. Specifically, SFM increased close encounters frequency with rising desired speed, while the collision predictive avoidance algorithm maintained a nearly constant close encounters frequency. Completion time shortened with increasing desired speed for both algorithms.

C. Straight Condition

Figure 3 illustrates the results in the straight situation.

The mobility change pattern in the straight condition was similar to that in the random and crossing conditions. However, different characteristics were observed in pedestrian movement performance.

For direct-interaction pedestrians, the collision predictive avoidance algorithm resulted in fewer close encounters than SFM under conditions with high desired speeds. Similarly, completion times tended to be shorter for the collision predictive avoidance algorithm. Furthermore, as with direct-interaction pedestrians, the collision predictive avoidance algorithm simultaneously reduced the number of close encounters and shortened completion times for indirect-interaction pedestrians.

IV. DISCUSSION

This study examined the effectiveness of a collision-predictive avoidance algorithm that aims to balance safety and efficiency in a shared space environment with a single AMR and numerous moving pedestrians. A Baseline SFM performing distance-based avoidance was set as a point of comparison. Performance was evaluated by manipulating pedestrian flow scenarios and the desired speed of the AMR. The results showed that, under the Random, Crossing, and Straight conditions, the Baseline exhibited a clear trade-off between improved efficiency and reduced safety as the desired speed increased. In contrast, the proposed method tended to shorten completion time while maintaining a low number of close encounters. This supports the possibility of improving speed without sacrificing safety.

This difference is thought to stem from the disparity in the risk representation used for avoidance decision-making. The baseline method performs avoidance based on repulsive forces derived from distance (or instantaneous configuration). Consequently, as speed increases, situations arise where the heightened risk of future collisions is not sufficiently reflected in the avoidance strength. This results in more approach events at high speeds, making safety degradation more apparent. In contrast, the proposed method uses a braking indicator based

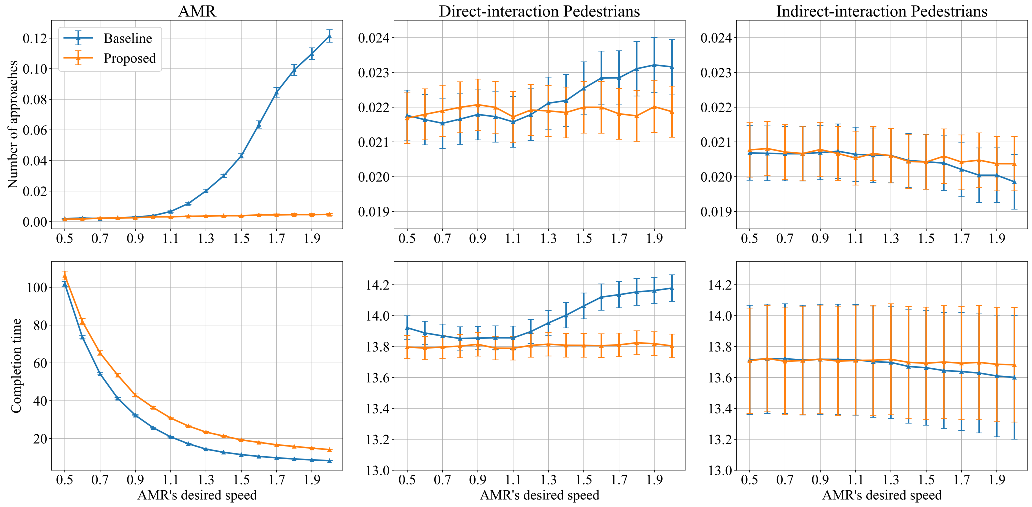

Figure 2. Trade-off between efficiency and safety in crossing situation.

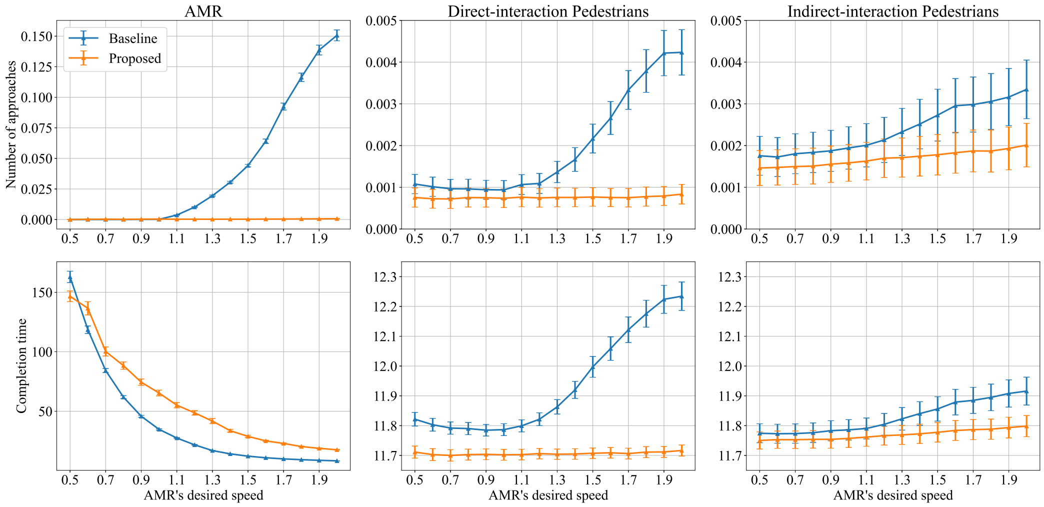

Figure 3. Trade-off between efficiency and safety in straight situation.

on DCPA/TCPA that adjusts the avoidance intensity according to the anticipated danger level of the future closest approach. This enables strong, early avoidance activation for "dangerous crossings" at high speeds while preventing overreaction to lower-risk targets. Therefore, it can be interpreted as achieving improved efficiency while maintaining safety.

The pedestrian-side results suggest that the effectiveness of the proposed method may extend beyond "the AMR's own safe operation." Under random/crossing conditions, significant differences were less apparent for indirect-interaction pedestrians, with effects primarily manifesting locally where AMRs interacted directly. This suggests that, in multidirectional, intersecting flows, localized avoidance actions are less likely to propagate order across the entire space. Thus, improvements for AMRs are less reflected in the travel time of indirectly interacting pedestrian groups. Conversely, under the straight condition, the proposed method reduced the number of approaches and shortened completion times for direct- and indirect-interaction pedestrians. This result indicates that, in situations with aligned flow directions, AMR behavior may suppress localized disruptions, such as congestion or chains of excessive avoidance, and propagate smoother flow throughout the entire pedestrian stream more readily.

This study has several limitations. First, the results reported here are from a homogeneous pedestrian group with specific properties. Robustness under realistic conditions, including variations among individuals (desired speed, reaction time, field of view, etc.), requires separate investigation. Second, safety metrics were defined based on the number of close encounters below a threshold; thus, they did not directly evaluate the "severity" of encounters or the abruptness of avoidance maneuvers (i.e., acceleration/jerk related to pedestrian discomfort). Third, only one AMR was tested. In scenarios with multiple AMRs, avoidance interactions could amplify nonlinearly. Future work should use multifaceted metrics to evaluate performance, including approach distribution, avoidance smoothness, and pedestrian subjective evaluations. This work should also extend to multiple AMRs and real-world experiments.

As an important next step, real-world validation should be conducted to examine whether the proposed method also improves pedestrians' sense of psychological safety. In addition to field experiments in shared spaces, user studies could assess subjective reactions such as perceived safety, comfort, predictability, and threat while people interact with AMRs using different avoidance strategies. Such evaluations would help substantiate the claim that the proposed algorithm is not only physically safe, but also psychologically nonthreatening.

V. CONCLUSIONS

In this paper, we proposed a collision-predictive avoidance algorithm, showing promise in mitigating the safety-efficiency trade-off that is typically observed in distance-based AMR navigation in shared spaces. By incorporating anticipated collision risk through DCPA/TCPA-based braking indicators, the method reduced close encounters while maintaining or improving travel efficiency across multiple pedestrian flow conditions. The findings also suggest that its benefits may extend beyond the AMR itself to surrounding pedestrians, particularly in aligned flow environments. Although further validation under more realistic and complex conditions is necessary, the present results provide initial support for the usefulness of collision-predictive avoidance as a framework for achieving both physically safe and psychologically acceptable AMR behavior in shared spaces.

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