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Crowd navigation for dynamic hazard avoidance in evacuation using emotional reciprocal velocity obstacles

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ABSTRACT

Crowd evacuation can be a challenging task, especially in emergency situations involving dynamically moving hazards. Effective obstacle avoidance is crucial for successful crowd evacuation, particularly in scenarios involving dynamic hazards such as natural or man-made disasters. In this paper, we propose a novel application of the emotional reciprocal velocity obstacles (ERVO) method for obstacle avoidance in dynamic hazard scenarios. ERVO is an established method that incorporates agent emotions and obstacle avoidance to produce more efficient and effective crowd navigation. Our approach improves on previous research by using ERVO to model the perceptive danger posed by dynamic hazards in real-time, which is crucial for rapid response in emergency situations. We conducted experiments to evaluate our approach and compared our results with other velocity obstacle methods. Our findings demonstrate that our approach is able to improve agent coordination, reduce congestion, and produce superior avoidance behavior. Our study shows that incorporating emotional reciprocity into obstacle avoidance can enhance crowd behavior in dynamic hazard scenarios.

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1. INTRODUCTION

Crowd evacuation is a complex and challenging problem, particularly in scenarios involving dynamically moving hazards [1]–[5]. The ability to navigate safely and efficiently while avoiding obstacles is critical for successful evacuation [1], [2], [6]–[9]. This paper proposes a novel application of the emotional reciprocal velocity obstacles (ERVO) method for obstacle avoidance in dynamic hazard scenarios.

The ERVO method is a velocity obstacles (VO)-based method that integrates emotional contagion into crowd movement planning [10]. It covers the panic emotion model invoked from the hazard itself, the individual panic that propagates in a crowd, and the attenuation of the said panic. In previous researches, the ERVO method was used to model the perceptive danger posed by static hazards in real-time, which demonstrated improved agent coordination and reduced congestion [10]–[15]. Our study seeks to improve on previous research by using ERVO to model the perceptive danger posed by dynamic hazards in real-time, which is crucial for rapid response in emergency situations.

Many VO based-methods offer no specific denotation to handle hazards and see them as typical obstacles [16]–[42]. This is problematic because hazards in evacuation scenarios can invoke panic in the crowd. Therefore, we aim to utilize ERVO for dynamically moving hazards by influencing the already established emotional model used in ERVO with several obstacles parameters that are governed by some desirability value to select the agent velocity based on perceived danger and safety direction.

We conducted experiments to evaluate our approach and compared our results with other VO methods. Our findings demonstrate that our approach is able to improve agent coordination, reduce congestion, and produce superior avoidance behavior. The objective of this paper is to propose a ERVO-based approach to improve avoidance in crowd evacuation scenarios involving dynamically moving hazards. we describe our approach in detail and present experimental results that demonstrate its effectiveness compared to other VO methods. Our study shows that incorporating emotional reciprocity into obstacle avoidance can enhance crowd behavior in dynamic hazard scenarios, and our findings have important implications for emergency management and evacuation planning. We believe that our approach, which incorporates the ERVO method and dynamically changing hazard parameters, offers a significant improvement over existing methods and has the potential to enhance crowd behavior in dynamic hazard scenarios.

2. METHOD

Our proposed method is based on the ERVO model [10] which is derived from e reciprocal velocity obstacles (RVO) with the addition of the emotional contagion model in multihazard scenarios. The original RVO model assigns velocity for the agent to navigate based on admissible velocities with subject to kinematic and dynamic constraints denoted by the expected time to collision toward the obstacles [43]. The ERVO takes the avoidance of RVO to avoid a hazard in crowd simulation. It takes the emotional contagion model to model a panic emotion induced by the source of hazard and by another agent that propagates the panic. We improve the ERVO capability by assigning desirability value to the set of agents' admissible velocities to deal with a hazard that dynamically moves in navigation space.

The ERVO formulation, given by (1), provides a measure of the ERVO of entity j invoked to agent i. If the current velocity of agent i, $\mathbf{V}i$, lies outside the ERVO of entity j, it is considered collision-free. In the virtual world, each agent i has a current position *P*, a current velocity $\mathbf{V}i$, an updated velocity $\mathbf{V}i^c$, a current panic emotion $Ei^h(P,t)$, and a goal location *Gi*. The effort of avoidance is governed by αj^i.

$$\mathrm{ERVO}_j^i\left(\mathbf{V}_j, \mathbf{V}_i, \mathbf{V}_i^c, \alpha_j^i\right)=\left\{\mathbf{V}_i' \mid \frac{1}{\alpha_j^i}\left(\mathbf{V}_i'+\mathbf{V}_i^c\right) \quad+\left(1-\frac{1}{\alpha_j^i}\right) \mathbf{V}_i \in \mathrm{VO}_j^i\left(\mathbf{V}_j\right)\right\} \tag{1}$$

ERVO was first introduced for crowd simulation in a multi-hazard situation. The ERVO covers the panic emotion model invoked from the hazard itself, the individual panic that propagates in a crowd, and the attenuation of the said panic. We will briefly explain the ERVO model. We will also explain our proposed method based on the ERVO to deal with dynamically moving hazard. The emotional matter for each agent is obtained by summing up these panic emotion elements. In (2) shows the degree of danger in invoking panic emotion in a certain agent, where the panic value of agent i is denoted as $E_i^h(P,t)$. It is influenced by all hazards s with a total number of n at a certain position p at time t.

$$E_i^h(P,t)=\sum_{s=1}^{n}\Gamma_s(P,t) \tag{2}$$

The panic emotion of agent i due to emotional contagion is given by (3), where $E_i^c(P,t)$ denotes the panic emotion of agent i at time t and position P. The panic emotion of agent j within the range of agent i at time t' is denoted by $E_j^{c'}\left(P_j,t'\right)$, and $d_i\left(t'\right)$ represents the amount of panic emotion received by agent i from agent j at time t'. The value of k determines the number of consecutive time steps over which the emotional accumulation of agent i is calculated.

$$E_i^c(P,t) = \sum_{t'=t-k+1}^{t} \sum_{j=1}^{n} d_i(t')\, E_j^{c'}(P_j, t') \tag{3}$$

The emotional attenuation function is incorporated in the model to account for the decline in panic emotion over time. The new value of panic emotion for agent i at time step t after being influenced by the decay rate η is given by (4), where $E_i^d(P,t)$ denotes the panic emotion of agent i at time t and position P.

$$E_i^d(P,t) = E_i\left(P^{\mathrm{pre}}, t-1\right) \cdot \eta \quad \eta \in (0,1) \tag{4}$$

The current panic emotion of agent i at time t and position P is given by (5), where $E_i(P,t)$ is the combined panic emotion, and $\Delta E_i(P,t)$ represents the change in panic emotion due to the hazard and emotional contagion. The change in panic emotion due to the hazard and emotional contagion is given by (6).

$$E_i(P,t) = E_i\left(P^{\text{pre}}, t-1\right) + \Delta E_i(P,t) \tag{5}$$

$$\Delta E_i(P,t) = E_i^h(P,t) + E_i^c(P,t) - E_i^d(P,t) \tag{6}$$

In a multi-hazard environment, the behavior of agents affected by panic emotion can impact their movement. We denote this as $V_i^s(\mathbf{P},t)$ in (7). Here, $\mathbf{P_S P}$ represents the stress safety direction, causing the agent to steer away from the hazard within the impacted area. In multi-hazard scenarios, the stress safety direction is the result of weighted sums of multiple hazards s.

$$V_i^s(\mathbf{P},t) = \begin{cases} \sum_{s=0}^{n-1} \Gamma_s(P,t) \cdot \mathbf{P_S P} & \text{if } \|P - P_s\| < r_s \\ & \text{and } t \in U \\ \mathbf{V} & \text{otherwise.} \end{cases} \tag{7}$$

$E_i(P,t)$ influences $V_i^s(\mathbf{P},t)$, determining the moving direction of agent i at position P and time t as V_i^c equation (8). Here, $\sum_{j \in R(i)} V_j^c(\mathbf{P}_j,t)$ denotes the unified direction for each agent j within the emotional perception range of agent i.

$$V_i^c(\mathbf{P},t) = E_i(P,t) V_i^s(\mathbf{P},t) + (1 - E_i(P,t)) \sum_{j \in R(i)} V_j^c(\mathbf{P}_j,t) \tag{8}$$

We apply the value of V_i^c from (8) in the ERVO model as shown in (1). This approach enables the ERVO model to consider not only the velocities of existing agents as in the RVO model [43], but also the emotional impact caused by panic emotion in multi-hazard situations. We augment the model to enhance the ERVO capability to deal with a hazard that dynamically moves in navigation space. Due to the fact that the incoming hazard toward the agent is more daunting than the hazard that moves away from the agent, we devised a desirability value based on the agent's perceived safety direction and predicted hazard collision toward the agent. Agent i desirability value of velocity $\mathbf{v}_i'$ is given by (9) which is inversely proportional to the (tts) (predicted time to safety) for velocities in $V_i^s(\mathbf{P},t)$, whereas predicted time to hazard (tth) is directly proportional. This is due to the fact that incoming hazard is prioritized to be evaded and less time toward perceived safety is favored. w_s and w_h is a weighting factors, and $\mathbf{v}_i^{pref}$ is the velocity preference that drives the agent's toward their original destination. The velocities with highest desirability value D_i will be selected.

$$\mathrm{D}_i\left(\mathbf{v}_i'\right) = \begin{cases} w_s \frac{1}{tts_{\phi_k}\left(\mathbf{v}_i'\right)} + \left\|\mathbf{v}_i^{pref} - \mathbf{v}_i'\right\|, & \text{if } \mathbf{v}_i' \in V_i^s(\mathbf{P},t) \\ w_h tth\left(\mathbf{v}_i'\right) + \left\|\mathbf{v}_i^{pref} - \mathbf{v}_i'\right\|, & \text{if } \mathbf{v}_i' \in \mathrm{VO}_h^i \end{cases} \tag{9}$$

3. RESULTS AND DISCUSSION

To evaluate the effectiveness of our method for crowd simulation in an evacuation scenario, we compared it with the RVO method [43]. RVO is a commonly used method in crowd simulation that considers moving hazards as obstacles and penalizes agents' velocity based on the time required to collide with obstacles. However, RVO does not consider moving hazards as a source of perceived danger. Our method, on the other hand, considers moving hazards as a source of perceived danger, which allows agents to avoid potential hazards and improve the overall evacuation performance.

$$\text{Interaction Overhead } = \mathrm{TTime}(A) - \mathrm{MinTTime}(A) \tag{10}$$

$$\mathrm{TTime}(A) = \mu(\mathrm{TimeToGoal}(A)) + 3\sigma(\mathrm{TimeToGoal}(A)) \tag{11}$$

$$\mathrm{MinTTime}(A) = \mu(\text{MinimumGoalTime}(A)) + 3\sigma(\text{MinimumGoalTime}(A)) \tag{12}$$

To measure the performance of our method and compare it with RVO, we used two metrics: collision occurrence and interaction overhead. The collision occurrence metric evaluates the effectiveness of the avoidance maneuvers produced by each method. A lower occurrence of collisions indicates better avoidance performance. The interaction overhead metric measures the time it takes for agents to reach their destination compared to the unconstrained travel time from the agent's initial to goal positions [44]. Unlike simply comparing consumed travel time, this metric takes into account the time agents spend maneuvering around other agents and obstacles in the navigation space, which is a crucial factor in evaluating the performance of crowd simulation methods.

To calculate the interaction overhead, we use in (10). Here, $\mathrm{TTime}(A)$ represents the travel time for a set of agents A, which includes all agents in our simulation. We calculate this value using (11), which takes into account the travel times from the start to end position of each agent ($\mathrm{TimeToGoal}(A)$), and calculates the average and standard deviation using $\mu(.)$ and $\sigma(.)$, respectively. Additionally, $\mathrm{MinTTime}(A)$, which we use in 10, is the average and spread of the theoretical minimum travel time for the set of agents A, as calculated using (12). The theoretical minimum travel time represents the travel time of agents if they were able to take the shortest possible route at optimal speed without any constraints from other agents or obstacles, as shown in (12) as $\text{MinimumGoalTime}(A)$.

3.1. Crowd simulation scenario

To evaluate the effectiveness of our proposed method, we conduct a series of crowd simulations using the Steerbench framework [45]. The Steerbench framework provides a comprehensive set of test cases and scenarios that allow for the evaluation of virtual agent steering behaviors. Our focus is on the evacuation scenarios that are particularly suited for hazard avoidance cases, where agents must travel to their destination which is the evacuation area as quickly as possible while avoiding hazards.

The Steerbench framework allows for scenarios with varying quantities and relations of agents, including singular, multiple, and groups of agents. This diversity of scenarios allows for a robust evaluation and comparison of the crowd navigation methods. Initially, the evacuation scenario in Steerbench only included building corridors as obstacles. However, in our simulation, we introduce numerous moving obstacles as hazards. These hazards are moving using fractal Brownian motion and are dynamically shifting throughout the simulation [46], [47].

The simulation environment depicted in Figure 1 provides a comprehensive view of the scenario's complexity, where multiple hazards are present. The figure illustrates the starting and evacuation areas of the agents, marked in blue and green, respectively. The agents must leave a crowded room through a narrow door and fan-out from the exit. The choke point of the scenario, represented by the red circle, highlights the challenge for agents to navigate through a restricted area and avoid collisions. The simulation environment is an extension of the Steerbench framework, which we used to evaluate the effectiveness of our proposed method. The additional hazards, which move dynamically based on fractal brownian motion, add another layer of complexity to the scenario, testing the algorithm's ability to handle different types of obstacles. The simulation environment provides a practical and realistic setting for assessing the algorithm's performance in the context of an evacuation scenario.

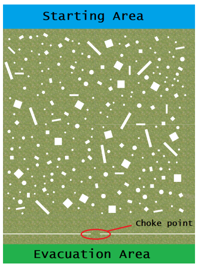

Figure 1. Simulation area with the information of starting and evacuation area

3.2. Crowd simulation result and evaluation

The crowd simulation produces collision occurrence and interaction overhead comparison. The overall collision occurrence is shown in the graph in Figure 2. We found that our method outperformed RVO in terms of collision occurrence. Specifically, the ERVO method showed a significantly lower collision occurrence rate than RVO, indicating that emotional contagion caused by hazards and neighborhood agents is able to affect agent avoidance effectively. The collision reduction is 43.61% on average compared to RVO which only takes the hazard as an obstacle rather than perceiving it as a dangerous entity to avoid. The reduction occurs not only in regard to collision from agents against obstacles (or source of hazard) as shown in Figure 3, but also from the agent-to-agent collision as shown in Figure 4

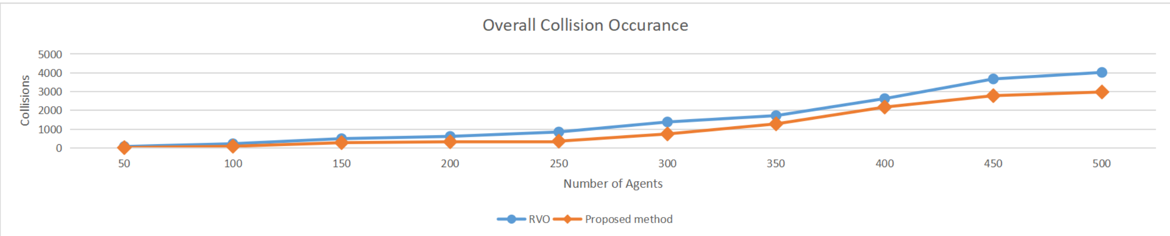

Figure 2. Overall collision occurance in the crowd simulation

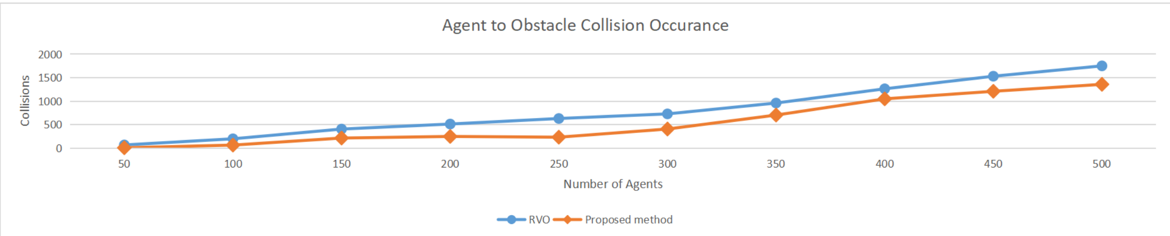

Figure 3. Agent-to-obstacles collision occurance in the crowd simulation

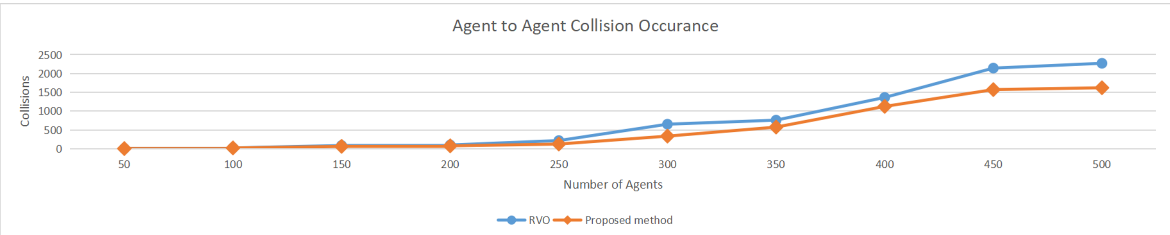

Figure 4. Agent-to-agent collision occurance in the crowd simulation

Unfortunately, the safer avoidance maneuvers caused the interaction overhead of ERVO to increase by 24.39% as shown in Figure 5. This means ERVO caused the behavior of agents' interaction with the hazard to produce major divagation as the agent digresses to the perceived danger induced by the hazard itself and other agents subject to the same hazard. This caused the agents to favor velocity toward the perceived safety direction that may deviate further toward the evacuation area if the hazard is perceived as imminent danger. This causes higher interaction overhead in ERVO.

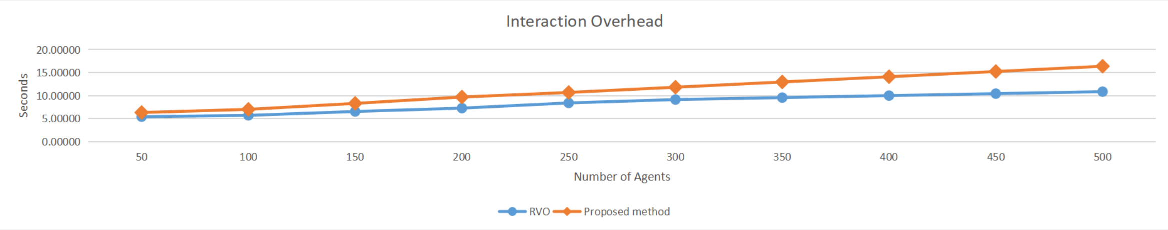

Figure 5. Interaction overhead in the crowd simulation

In summary, the ERVO for crowd simulation in an evacuation scenario with moving hazards over a significant improvement with the emotional model it provides. The awareness of perceived danger by considering moving hazards as a source of perceived danger and using effective avoidance maneuvers, the application of the ERVO method with desirability value to select agent velocity provides better performance in terms of collision occurrence with the trade-off in the interaction overhead. These results have important implications for designing effective crowd evacuation strategies in various scenarios, including emergency situations and large-scale events.

4. CONCLUSION

This study aimed to improve the efficiency of crowd evacuation by using an ERVO-based method. The results indicate that the ERVO method was able to reduce the occurrence of collisions during evacuation by 43.61% compared to conventional methods. This improvement in safety can have significant implications in emergency situations where quick and safe evacuation is critical. Further research could explore the potential of combining the ERVO method with other crowd evacuation strategies to further enhance the effectiveness of evacuation procedures. It is important to note that the effectiveness of the ERVO method may vary depending on various factors, such as environment conditions, agent behavior, and relation. Further research is needed to investigate the long-term effectiveness and potential limitations of the ERVO method. As such, we recommend that further research be conducted to evaluate the feasibility and benefits of implementing such method in a wider range of evacuation contexts.

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