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Agent-based evacuation modeling with multiple exits using NeuroEvolution of Augmenting Topologies

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ABSTRACT

Evacuation modeling offers challenging research topics to solve problems related to the development of emergency planning strategies. In this paper, we built an agent-based evacuation simulation model to study the pedestrian dynamics and learning process by applying the NeuroEvolution of Augmenting Topologies (NEAT) which is a powerful method to evolve artificial neural networks (ANNs) through genetic algorithms (GAs). The NEAT method strengthens the analogy between GAs and biological evolution by both optimizing and complexifying the solutions simultaneously. We set our main goal to develop a model by identifying the most appropriate fitness function for the agents that can learn how to change and improve their behaviors in a simulation environment such as moving towards the visible targets, producing efficient locomotion, communicating with each other, and avoiding obstacles while reaching targets. The fitness function we chose captured the learning process effectively and our NEAT-based implementation evolved suitable structures for the ANNs autonomously. According to our experiments and observations in the simulated environment, the agents accomplished their tasks successfully and found their ways to the exits.

1. Introduction

Evacuation modeling is an important part of pedestrian modeling expertise. It is the process of guiding evacuees to the exits when an emergency situation happens. It is developed to ensure the safest and most efficient evacuation time of all expected residents of a building or an area. It offers design capabilities that allow the simulation of complex scenarios in different types of environments [8]. Using evacuation models to optimize the flow of people allows much more ergonomic, effective and safe design at earlier stages of an evacuation plan in crowded places. Some of the benefits of evacuation modeling are: designing an effective layout with respect to areas, reducing congestion and queuing at key points, optimizing the position of objects and advertising signage in relation to population profile, facilitating successful operational planning of access, safety and security with regards to normal and emergency circumstances [18].

The simulation of a realistic human behavior is important for the virtual world and it has practical values such as emergency planning for evacuating the areas at risk. In real world, the safe evacuation of thousands of people is a crucial operation. In such cases, obtaining information on the nearest and fasted evacuation routes, the time to evacuate people, the time between the happening and the arrival of the emergency personnel, the procedures that the authorities should use to avoid confusion, and loss of life are all very important. By observing and understanding the possible scenarios in a simulated environment beforehand, the authorities (i.e., decision-makers, evacuation managers, safety planners, researchers) can train emergency personnel so that the response to the actual happening is successful [54,55]. Thus, we aimed to provide an advantage/benefit for the authorities by developing an agent-based simulation model to have an ideal understanding of the human behaviors and environmental characteristics in a specific zone, be able to estimate possible outcomes of different response and evacuation strategies under different conditions, and generate a series of evacuation plans accordingly.

In our study, we propose an agent-based evacuation modeling and simulation using the NEAT method [12,41,77,78,76,88] for emergency evacuation situation to help decision makers to determine the evacuation time for buildings or areas at risk. In our experiments, we observed successful evacuation behaviors and obstacle avoidance using autonomously-evolved neural networks. We also showed that the learning behavior is a crucial step in the direction of emergency planning and how we achieved sophisticated behaviors through our NEAT-based model.

2. Related work

Evacuation modeling contains iterative processes to determine the best suitable egress routes/paths and calculate the estimated time

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required to evacuate the areas at risk. Different models can be developed for evacuation applications depending on the scope, solution methodology, and input parameters. In general, existing studies concentrated on modeling evacuation problems that emphasize the estimation of evacuation time are closely related to different research topics such as path planning, navigation in large virtual environments, traffic assignment, operations research, process control, simulation, optimization, network flow and many others [14,43,44,66,73,74,80]. Based on the scope, the-state-of-the-art approaches in evacuation modeling research can be mainly classified as macroscopic and microscopic models, both of which can analyze the movements of evacuees over time.

2.1. Macroscopic models

Macroscopic evacuation models take into account the movement of evacuation as a homogeneous flow. They do not consider the individual behaviors and movements of evacuees, the interactions and decisions between evacuees for selecting the egress routes. They focus on the system as a whole. They are defined as a top-down approach in which collective evacuee movements are characterized by model parameters through closed-form expressions. Crowds are represented in an aggregate manner using some distinguishing key features such as spatial density, average velocity, and flow rate in relation to the location and time. Since the time is a decisive factor for evacuation process, macroscopic models are mostly used to generate good lower bounds for the evacuation time. These bounds can be used to analyze existing buildings or help planning new buildings [24,65]. Most of macroscopic models use mathematical or analytical methods which depends on static or dynamic network optimization formulations and some integer programming models to solve evacuation problems. However, they suffer from loss of accuracy as individual behaviors of evacuees can affect evacuation time [5,26,54].

Common macroscopic models are: *regression models* [42,48], *route-choice models* [32], *queuing models* [45], and *gas-kinetic models* [30]. *Regression models* use statistically determined relations between flow variables to predict pedestrian flow under specific conditions [60]. Pedestrian flow characteristics are related to infrastructures such as corridors, lobbies, stairs, ramps, walkways, and so on. *Route-choice models* define pedestrian wayfinding depending on the utility concepts. Pedestrians choose the best appropriate destinations to maximize the utility of their trips such as comfort, travel time, convenience, safety and cost. *Queuing models* benefit from Markov chains to describe how pedestrians move from one network node to another. In general, nodes represent rooms and links represent doors. Markov chains are defined by a set of states together using transition probabilities [60]. Only transitions causing state change are taken into account. *Gas-kinetics models* use an analogy with fluid or gas dynamics to determine how crowd density and velocity parameters change over time using partial differential equations [58,79].

Macroscopic evacuation models are mainly based on optimization approaches. They are computationally efficient and suitable for large-scale crowd simulations. While these models are good at producing the general density-flow profiles observed in crowd evacuation, they are unable to describe emergent crowd phenomena [26,56]. This restriction is understandable and acceptable given that macroscopic models are expressions of deductive reasoning. In so doing, many simplifying assumptions have to be made in order to keep such theorems tractable. On the contrary, emergent phenomena arises spontaneously from complex and dynamic interactions at lower levels that occur naturally without influence from external signals or conventions [58].

2.2. Microscopic models

Microscopic evacuation models analyze the evacuation situation in a detailed manner. They consider the individual behaviors and movements of evacuees (i.e., physical abilities, local directional changes, walking speeds, various physiological, psychological and social factors), the interactions and decisions among evacuees. They are defined as a bottom-up approach in which evacuees are modeled as individual entities that have unique characteristics such as age, gender, disability, body size and walking speed. They describe the time-space behaviors of the individual evacuees [38,58]. Formulas, expressions or rules involving spatial transition probabilities are repeatedly applied to temporal changes in situation or behavior. Microscopic models are computationally intensive. Performing simulation of large-scale crowds is difficult on traditional single-processor systems. However, parallel computing techniques can be used to achieve this problem successfully. The level of complexity in microscopic models can be overcome by using analytical methods (i.e., to define the path choice using mathematical equations). Analytical methods are cheap to use. However, they are limited to the complexity of evacuation problems. Because, as analytical methods become more sophisticated and more detailed in an evacuation model, they can become more complex to analyze the evacuation process. In addition, peak or transient conditions are not modeled, since analytical models assume that the system has reached a steady state or equilibrium. Finally, it is hard to determine whether the existing data characteristics can define the system under study without measuring various design parameters [92].

Although much study has been done on microscopic models to improve the behavioral realism, evacuation operations, natural locomotion and decision-making process, none of the existing models can realistically analyze the high-density crowds. In order to develop an efficient model, many choices and parameters (based on conditions, cases, events, environments, and so on) have to be considered. Some classifications can be helpful to facilitate these choices/parameters and get an overview of the available options. Zheng et al. [93] indicate seven classes for microscopic approaches which are: *social force models*, *cellular automata*, *agent-based models*, *lattice gas models*, *fluid-dynamic models*, *approaches depending on the experiments with animals*, and *game-theoretic models*. In the light of this information, we can present most common microscopic models which can be used to get better results for pedestrian simulation as follows: *social forces models* [29], *rule-based models* [63], *cellular automata* [17], *velocity-based models* [83,84], and *the optimal steps model* [71,70]. The difference between them is in the discretization of space and time. In addition, we can specify the conceptual similarities and differences of these models according to the perspective of scalar fields (also referred to as the superposition principle) for the simulation of pedestrian dynamics [70]. The perspective of scalar fields is a powerful method and provides a common mathematical basis for many models, and the different use of it produces distinct emergent effects. However, it has limitations such as the flexibility, superposition of binary interactions [50], calibration of model parameters [28,34,49]. Furthermore, models based on scalar fields concept that is used as potential, cost, utility, benefit, or probability can be efficient for practical applications but lack a plausible representation of the decision-making process and natural locomotion. Consequently, identifying similarities and differences is important to choose an appropriate model or develop a new method if no other model meets the requirements [69].

Social force models describe pedestrian behavior (i.e., route choice behavior, certain actions/motions) microscopically through social fields triggered by the social behavior of the individuals. In these models; social forces such as comfort zone, tension, stress, emotion, panic, anxiety, pushing and fighting for space, herding, flocking, arching and clogging are modeled, the interactions and decisions between individuals are tested and validated. Social force models enable us to create simulations that look more like particle animation than human movement [59]. They help researchers to find new relations and produce mathematical rules to understand crowd behaviors in normal and emergency conditions. However, they are more complex decision-making processes and require much more effort to achieve realistic results.