Crowd Evacuation Simulation

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Abstract

Evacuation simulation systems simulate the evacuation behaviors of people during emergencies. In an emergency, people are upset and hence do not behave as they do during evacuation drills. Reports on past disasters reveal various unusual human behaviors. An agent-based system enables an evacuation simulation to consider these human behaviors, including their mental and social status. Simulation results that take the human factor into consideration seem to be a good tool for creating and improving preventions plans. However, it is important to verify and validate the simulation results for evacuations in unusual scenarios that have not yet occurred. This chapter shows that the combination of an agent's physical and mental status and pedestrian dynamics is the key to replicating various human behaviors in crowd evacuation simulation. This realistic crowd evacuation simulation has the potential for practical application in the field.

Keywords

Evacuation behavior • Emergency scenario • Agent-based simulation • Cognitive map • Psychological factor • Belief-desire-intention • Information transfer and sharing model • Verification and validation

Contents

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B. Müller, S.I. Wolf (eds.), *Handbook of Human Motion*,
https://doi.org/10.1007/978-3-319-14418-4_17

Introduction

Emergencies such as fires, earthquakes, or terrorist attacks can occur at any time in any location. Human lives are at risk both from man-made and natural disasters. The importance of emergency management has been reaffirmed by a number of reports related to various disasters. The September 11, 2001 World Trade Center (WTC) attacks and the Great East Japan Earthquake (GEJE) and ensuing tsunami that occurred on March 11, 2011 took many lives and caused serious injuries. Detailed reports that focus on occupant behavior during the WTC disaster and evacuation behavior after the tsunami alarm indicate that safety measures implemented beforehand and evacuation announcements on site can exert significant influence on individual evacuation behaviors (de Walle and Murray 2007; Averill et al. 2005; Cabinet Office Government of Japan).

Many organizations engage in emergency preparation and provide training to save human lives during emergencies and reduce damage during future disasters (Cabinet Office of UK 2011; Turoff 2002). The disaster-prevention departments of governments, buildings, and other organizations develop these training programs. This training, executed beforehand, is useful to check whether the people are well prepared for unseen emergencies, can operate according to prevention plans, and evacuate quickly to safer locations.

It is difficult to replicate emergent situations in the real world and drill for these situations while involving real humans. It is well known that humans behave differently when training and during emergencies. Sometimes, a drill can cause accidents. In fact, in December 2015, a university in Nairobi executed an anti-terror exercise. The drill included the use of gunshots and this caused students and staff to panic. A number of people jumped from windows of the university buildings and were injured (News). Even statutory training in real situations can create risks for disabled people and some vulnerable groups.

Simulation of the movement of people has been studied in various fields including computer graphics, movie special effects, and evacuations (Hawe et al. 2012; Dridi 2015). This technology allows a prevention center to simulate crowd evacuation behavior in multiple emergency scenarios that cannot be executed in the real world. Computer simulations help the prevention center to assess their plans for all emergencies that need to be considered. Crowd evacuation simulation is a key technology for making safety plans for future emergencies.

State of the Art

Lessons from the Past and Requirements for Simulation Systems

A number of studies have focused on human behavior during past disasters. The National Institute of Standards and Technology (NIST) examined occupant behavior during the attacks on the WTC buildings (Averill et al. 2005; Galea et al. 2008). The Cabinet Office of Japan also reported on evacuations of individuals during the GEJE (Cabinet Office Government of Japan). Common types of evacuation behaviors have been discovered: some individuals evacuated immediately when the disasters occurred, but others did not evacuate, even though they heard emergency alarms provided by the authorities. These people consisted of individuals who had family members located in remote areas, individuals who attempted to contact their families by phone, and individuals who continued to work because they believed they were safe.

It is interesting to note that the individuals' behaviors during these two disasters were similar to the behaviors of individuals during a flood in Denver, USA, on June 16, 1965, even though communication methods have changed over the past 50 years (Drabek 2013). Approximately 3,700 families were suddenly told to evacuate from their homes. The family behaviors that occurred following the warnings were categorized as follows: those who evacuated immediately, those who attempted to confirm the threat of disaster, and those who ignored the initial warning and continued with routine activities.

Other features of human behaviors have been reported in other disasters. (1) In the 2003 fire in the Station nightclub, Rhode Island, most building occupants attempted to retract their steps to the entrance rather than follow emergency signs, even though the emergency exit was adequately signposted (Grosshandler et al. 2005). (2) In emergencies, humans tend to fulfill the roles assigned to them beforehand. For instance, trained people led the others in their offices promptly to safe places in the WTC attacks (Ripley 2008). (3) In contrast, a tragedy that occurred at the Okawa Elementary School during the GEJE demonstrates how untrained leaders may lead to tragedies (Saijo 2014). The school was located 5 km from the sea and had never practiced evacuation drills. When the earthquake occurred, an hour elapsed before teachers decided on an evacuation location. When moving to that location, they were informed that the tsunami was imminent and that their evacuation location was unsafe. They tried to evacuate to a higher location, but their efforts were too late. Most of the students and staff of the Okawa Elementary School were engulfed by the tsunami and died.

The human behaviors that typically occur during emergencies vary by individual, and the behaviors may be different from those that are planned. The fluctuations in these behaviors are the key features that must be simulated in evacuation simulations. The evacuation behaviors depend on the individual who makes decisions and changes his/her actions according to his/her conditions and information. This information includes signs and public announcements (PAs) and is thought to affect human behavior and be useful for guiding people quickly to safe places during dynamically changing situations.

Agent-Based Approach to Evacuation Simulations

NIST simulated some evacuation scenarios to estimate the evacuation time from the WTC buildings (Kuligowski 2005). The travel times of several cases were simulated using several evacuation simulation systems, all which assume the following:

- People are equal mentally and functionally. In some simulators, sex and age are taken into consideration as parameters for walking speed in pedestrian dynamics models. To address roles in society, only human behaviors such as leaders in an office guiding people to get out of the building immediately were modeled.
- All people start their evacuation simultaneously. In fact, some people evacuate after they finish their jobs. The difference in premovement time of the individuals is not considered in these simulations.
- All people have the same knowledge about the building. They use one route when they evacuate from the building. Indeed, knowledge about the evacuation route differs among people, and the evacuation routes can be different.

An agent-based approach provides a platform that corrects these assumptions. An agent-based simulation system (ABSS) models and computes individuals' behaviors related to evacuation (Musse and Thalmann 2007). Various types of human behavior have been studied using the ABSS platform, for example, simulation of human behavior in a hypothetical human-initiated crisis in the center of Washington DC and a simulation tool incorporating different agent types and three kinds of interaction: emotion, information, and behavior (Tsai et al. 2011; Parikh et al. 2013).

An ABSS consists of three parts: the agents, the interaction methods among agents and environments, and the surrounding environment. Agents perceive data from the environment and determine their actions according to their goals. An agent has the properties of physical features, social roles, mentality, and others. The actions are interactions with other agents and the environment. Information exchanges among agents and starting to evacuate are examples of actions. The interactions with the environment are simulated by sub-simulators and affect the status of the environment. The ABSS repeats these simulation steps: agent perception, agent decision-making, and environment calculations. The environment involves CAD models of buildings and scenarios of disaster situations.

The following example demonstrates the ABSS process applied to an evacuation from a building during a fire. Agents hear alarms and PAs directing them to evacuate the building. The alarm noise and announcements can increase the anxiety of the agents, which is calculated using a psychological status model. The mental status and individual knowledge of the agent determine its actions. When it decides to go to a safe place, it visualizes the route to that place and moves. One sub-simulator calculates the agent locations and the status of pedestrian jams inside the building, and the other sub-simulator calculates the spread of the fire.

Crowd Evacuation Using Agent-Based Simulations

Evacuation Scenarios and Environment

The environment corresponds to the tasks that the ABSS is applied to. The parameters in the environment affect the results of the simulations. Table 1 lists the categories of building evacuation scenarios. Case 1 is a situation in everyday life and the scenario corresponds to an emergency drill. The other four cases correspond to emergency situations in which some accident happens, but people do not have all the information they need. The conditions of each situation worsen from Cases 2 to 5. Providing a real-time evacuation guide for dynamically changing situations is thought to effectively reduce evacuation time. Case 2 corresponds to a minor emergency such as a small fire inside a building. The layout of the floor inside the buildings remains the same during the evacuation, as in Case 1. People also keep calm in this case. Cases 3, 4, and 5 correspond to situations where some people become distressed and may have trouble evacuating safely to exits. Case 3 is a situation where an earthquake causes furniture to fall to the floor that hinders or prevents evacuation. A case in which fire spreads and humans operate fire shutters to prevent the fire from spreading further is modeled in Case 4. This operation may block the evacuation routes and cause differences between the cognitive map of the evacuees and the real situation. Case 5 is the situation in extreme disasters, where large earthquakes cause so much destruction to parts of the building that the floor layout is completely changed.

In Cases 3, 4, and 5, it is necessary to improve prevention plans in terms of available safe-escape time and required safe-escape time (ISO TR16738 2009). However, it is difficult to execute evacuation drills for such situations, as the case in Nairobi demonstrated. Evacuation simulation systems are instead proposed to simulate the evacuation behaviors of people in such situations.

Table 1 Category of changing situations at evacuations

		Map		Agent		
Case	Situation	Map (3D)	Layout	Mental state	Interaction mode	Fitness for drills
1	Everyday	Static environment	Same	Normal (getting more anxious)	Normal (getting more confusing)	Fit (getting more unexpected)
2	Emergency					
3		Dynamic environment	Different			
4						
5			Unknown	Distressed	Crisis	Beyond the scope of drill

Agent Mental States and their Action Selection

People's state of distress reflects the motions of agents during emergencies. As a result, the agents take various actions according to the information that they have. Some people may prefer to trust only information from an authority figure, but others will trust their neighbors or heed messages sent from their acquaintances. These individual behaviors form into crowd behavior in emergencies. During the GEJE, about 34 % of 496 evacuees began their evacuation by taking the advice of acquaintances who themselves took the evacuation guidance seriously (Cabinet Office Government of Japan). The value of 34 % is the average of three prefectures, Iwate, Miyagi, and Fukushima. Their averages are 44 %, 30 %, and 3 %, respectively.

The question then arises as to where and how people evacuate during emergencies. Abe, et al. conducted a questionnaire survey with individuals who shopped at a Tokyo department store (Abe 1986). Three hundred subjects were selected from shoppers in the department store. The number of male and female participants was equal, and participants ranged in age from teenagers to adults in their 60s. The questions addressed the following factors that occur during emergencies: the provision of evacuation instructions during emergencies, knowledge of emergency exit locations, an individual's ability to evacuate safely, and other factors. The results in Table 2 reveal that:

- Individuals' intentions during emergencies were diverse. Differences were apparent between the sexes and between age groups.
- Half of all surveyed individuals stated they would follow the authorities' instructions. The other half stated they would select directions by themselves, and individuals who chose the fourth and fifth strategies (in Table 2) tended to choose opposite directions.

Agents act according to their code of conduct or will, and social psychological factors affect human behavior. The implementation of autonomous agents includes modeling the process of an individual's perception, planning, and decision-making. Modeling the mental state of an agent is key to simulating the evacuation behavior of people. The psychological factors affect human actions that include selfish

Table 2 Responses to "In which direction would you evacuate?" (Abe 1986)

	Selected actions	All (%)	Sex	
			Male (%)	Female (%)
1	Follow instructions from clerks or announcements	48.7	38	54.7
2	Hide from smoke	26.3	30.7	22
3	Go to the nearest staircase or emergency exit	16.7	20.7	12.7
4	Follow other individuals' movements	3	1.3	4.7
5	Go in the direction that has fewer people	3	2.7	3.3
6	Go to bright windows	2.3	2.7	2
7	Retrace his/her path	1.7	2.7	0.7
8	Other	0.3	0.7	–

movements, altruistic movements, and others. The following cases demonstrate some properties of human behavior. These actions also change the behavior of crowd evacuations:

- People swerve when they come close to colliding with each other. When people see responders approaching, they make way to pass them automatically. The two behaviors are similar; however, they are different at the conscious level of an agent. Agents categorize the agents around them into normal or high-priority groups depending on common beliefs in the agent's community. For example, the agent gives consideration to the rescuers and disabled, both of whom are categorized as agents with high priority.
- Families evacuate together. When parents are separated from their children during emergencies, they become anxious and go to their children at the risk of their own safety. For instance, the child might be in a toy section in a department store and have no ability to ask others about his/her parents.

Pedestrian Dynamics Model and the Mentality of Individuals

The belief-desire-intention (BDI) model is one method for representing how agents select actions according to the situation during the sense-reason-act cycle (Weiss 2000). Belief represents the information that the agent obtains from the environment and other agents. Desire represents the objectives or situations that the agent would like to accomplish or bring about, and their actions, which are selected after deliberation, are represented by intention. In the case of evacuation in emergency situations, the desires are to move quickly to a safe place, know what happened, or join families. The associated actions are to move to specific places. These actions are represented as a sequence of target points. The target points are the places where people go to satisfy their desires.

Movements, including bidirectional movements in a crowd, can be micro-simulated in one step using pedestrian dynamics models (Helbing et al. 2000). The models are composed of geometrical information and a force model that resembles the behaviors of real people. The behaviors of individuals may block others who are hurrying to refuges and hence cause pedestrian jams in evacuation (Pelechano et al. 2008; Okaya and Takahashi 2014).

Guidance to Agents and Communication During Evacuation

The NIST report showed differences in evacuation behaviors between the two buildings, WTC1 and WTC2. The buildings were similar in size and layout, and similar numbers of individuals were present in the buildings during the attacks. Individuals in both buildings began to evacuate when WTC1 was attacked, and WTC2 was attacked 17 min later. At that time, about 83 % of survivors from WTC1 remained inside the tower, and about 60 % of survivors remained inside WTC2. The difference in evacuation rates between two buildings given similar conditions indicates that there are other interactive and social issues that should be taken into consideration to simulate crowd evacuation behavior.

A PA gives evacuation guidance to people. According to the GEJE report, only 56 % of evacuees heard the emergency alert warning from a loudspeaker. Of these, 77 % recognized the urgent need for evacuation, and the remaining 23 % did not understand the announcement because of noisy and confused situations. Nowadays, people communicate with others in public using cellar phones. This behavior is assumed to happen during emergencies. Indeed, in GEJE, 2011, it was reported that people knew and shared information using SNS and personal communications (Okumura 2014). In a case of family's evacuation, the following communications between parents and their children often occurs when they are apart:

> Where are you?
> I am at location X.
> All right, I will be there soon, stay there.

Information regarding the situation and personal circumstances play an important role when determining actions. The information affects both the premovement and travel times of evacuation behaviors. With respect to the information or knowledge of people, whether broadcast or communicated personally, the evacuation process has the following phases:

- When emergencies occur, people either perceive the occurrence themselves or authorities make announcements. The alarm contains urgent messages conveying that an emergency situation has occurred and gives evacuation instructions.
- People confirm and share the information that they obtain by communicating with people nearby. After that, people perform actions according to their personal reasons: some evacuate to a safe place, others hurry to their families, and still others join rescue operations.
- People who are unfamiliar with the building follow guidance from authorities or employees who act according to prescribed rules or manuals of the buildings. The information that authorities and employees have may vary with time.

The information transfer and sharing model enables the announcement of proper guidance to people or information sharing during evacuation (Okaya et al. 2013). The difference in agents' information and style of communication causes the diversity of human behavior and affects the behavior of evacuations (Niwa et al. 2015).

Future Directions

An ABSS is expected to simulate the behaviors of agents in unusual scenarios that are difficult to test in the real world. We learn how people behave and evacuate during disasters from media stories and reports published by those in authority.

Table 3 Evacuation simulation parameters

Subsystem	Parameters	
Agent	Physical	Age
		Sex
		Impaired/unimpaired
	Mental/social	State of mind
		Human relationships (family, office member, etc.)
		Role (teacher, leader, rescue responder, etc.)
	Perception	Visual data
		Auditory data
	Action	Evacuate (walk/run)
		Communicate (hear, talk, share information among agents)
		Others (altruistic behavior, rescue operation)
	Preference	Culture
		Nationality
Environment	Map/buildings	2D/3D
		Elevator
	Subsystem	Pedestrian dynamics
		Disasters effects (fire, smoke, etc.)
Interaction	Communication	Announcement (guidance from PA)
		Information sharing
	Human	Personal
	Relationship	Community

These reports cover evacuation from airplanes, ships, theaters, sport stadiums, stations, underground transport systems, and others (Wanger and Agrawal 2014; Peacock et al. 2011; Weidmann et al. 2014). Behavior models have been formulated to meet the innate human features that were described in the reports and are key features of these evacuation simulations. Table 3 shows the parameters of the evacuation models in which human behaviors are taken into account. The parameters represent the features of the agents, environment, and interactions among agents or others during the scenarios. In addition, the parameters specify the evacuation scenarios. Some of the parameters are related to each other; for example, parameters related to pedestrian dynamics are personal spaces, speed, and avoidance sides, and others are dependent on countries (Natalie Fridman and Kaminka 2013).

In scientific and engineering fields, the following principle, hypothesis → compute consequence → compare results, has been used to make models and to increase the fidelity of simulations (Feynman 1967). Fundamentally, this principle is applied to the crowd evacuation simulation. The following points are assumed when modeling crowd evacuation behaviors:

- Whole-part relations assumption. A crowd evacuation simulation system is composed of subsystems: an agent's action planning, pedestrian dynamics, and disaster situations. A model for evacuation behavior is implemented in each agent, and the pedestrian dynamics models calculate the positions of the agents. The movements of agents are integrated into crowd behaviors.

- Subsystem causality assumption. The agent's behavior is simulated by formulas or rules in each agent at every simulation step. In each step, the status of the system is changed to a new status according to the parameters, models, and formulas. They may be refined to cover more phenomena or make the results of subsystem simulations more consistent with experimental data or empirical rules.
- Total system validity assumption. The simulation results of the subsystems and the positions of all agents are integrated into the results of the crowd evacuation simulation. The results of the simulation are checked with empirical rules or previous data.

At the second assumption, the model of the subsystem is verified with respect to real data, and the parameters are tuned to the conditions of the scenarios (Peacock et al. 2011; Weidmann et al. 2014; Ronchi et al. 2013). The Tokyo fire department publishes a guide for building fire safety certificates based on simulation results (Tokyo Fire Department). The results predict the evacuation time at fire under their specified method and can be used to certify the likelihood of a safe evacuation. The simulations are in Case 1 of Table 1, which is equivalent to evacuation drills in everyday conditions. At the third assumption, people evaluate the results of simulation from their personal and organizational perspectives. Using an ABSS with the functions mentioned in section "Introduction" can simulate more realistic conditions such as those in Cases 2 to 4.When the integrated simulation results are likely to be reasonable in unexpected situations, there is no evidence to endorse whether or not the results can be used in real applications.

In a case in which the results do not fit the empirical rule, even though it may involve a significant predictor, it is difficult to adopt the simulation results in a prevention plan according to scientific and engineering principles because we do not have enough real data and cannot perform experiments in real situations, as in the case of evacuation simulation. It is important and required to verify the results of evacuation simulations for emergency situations that have not occurred and affirm that the planning based on the simulation results will work well in a possible emergency situation.

Verification and validation (V&V) of the simulation tools and results has been one of the most important issues in crowd evacuation simulations. V & V problems are represented using the following questions:

- How do we judge if a tool is accurate enough?
- How many and which tests should be performed to assess the accuracy of the model predictions?
- Who should perform the test, i.e., the model developers, the model users, or a third party?
- Does the model accurately represent the source system?
- Does the model accommodate the experimental frame?
- Is the simulator correct?

The questions are essential to ABSS. Questions 1 to 3 are from the test methods that are suggested from quantitative/qualitative points for behavioral uncertainty (Ronchi et al. 2013). Questions 4 to 6 are from a study of validation on evacuation drills from a ten-story building (Isenhour and Löhner 2014).

A method of comparing simulation results to real scenarios as macroscopic patterns in a quantitative manner has been proposed as a validation method (Banerjee and Kraemer 2010). Interactions among agents and dynamically changing environments also affect the behavior of crowd evacuations. A verification test is suggested in order to check evacuation plans under the dynamic availability of exits (Ronchi et al. 2013). The following qualitative standards are proposed for application in simulations without real-world data that involve real evacuation data and experimental data (Takahashi 2015):

- Consistency with data. The simulation results or its variations after changing parameters or modifying subsystems are compatible with past anecdotal reports.
- Generation of new findings. The results involve something that was not recognized as important before the simulations, which is reasonable given empirical rules.
- Accountability of results. The cause of the changes can be explainable from the simulation data systematically.

While we do not have answers to these questions, ABSS has been applied to more realistic situations. For example, an evacuation from a building with fire shutters is a realistic case (Takahashi et al. 2015). The fire shutters are installed in buildings by law to prevent fire and smoke from spreading inside. Some agents evacuate instantly and others evacuate after finishing their jobs. Operators at the prevention center close the fire shutters at time t_1 to prevent fire spreading. If there is no announcement regarding the shutter closing, the agents don’t know the changes of environments. They evacuate according to their own cognitive map, which might not be updated until they notice the fire shutter closing at t_2. As a result, the evacuation time from t_1 to t_2 is wasted, even though the agent starts evacuation instantly. This simulation demonstrates that evacuation times change for various scenarios in dynamically changing environments corresponding to Case 3, 4 and 5 and proves the potential of evacuation simulation for future applications.

In this chapter, we presented some features of crowd evacuation simulations: the role of human mental conditions during emergencies, the presentation of agent mental states, and information on evacuations. We also showed that the combination of an agent’s physical and mental status and pedestrian dynamics is the key to simulating crowd evacuation and replicating various human behaviors. Simulating crowd evacuation more realistically introduces additional human-related factors. This makes it difficult to systematically analyze the simulation results and compare them with data from the real world. At present, the simulation results are not so much objectively measured as subjectively interpreted by humans. Future research and model development will focus on the study of agent interactions, human mental models, and verification and validation problems.

Cross-References

- ▶ Crowd Formation Generation and Control
- ▶ Functional Crowds

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