CROWDSIM: A framework to estimate safety of egress performance in real life scenarios

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ABSTRACT

In this thesis we discuss the use of crowd simulation to reproduce and evaluate egress performance in specific scenarios. We present *CrowdSim*: a crowd simulation framework designed to automatically reproduce crowd behaviors during an egress process. A set of software validation tests has been conducted in order to ensure the accuracy of the simulations computed by *CrowdSim*. In addition, *CrowdSim* is able to generate a set of plausible egress plans to be performed in a specific environment and also to rank them. Several case studies were performed in order to evaluate the work[1].

Keywords: Egress performance, crowd simulation, safety.

1 INTRODUCTION

Enthusiasts from different areas have observed people behavior for many years, decades, or even centuries. Such observation can produce valuable data to be considered as object of study in different fields, from engineering to psychology for example. In nineteenth century, Le Bon [10] observed that when part of a group, an individual can abandon his/her own mental identity and assumes the identity of the group.

Emergent collective behaviors, often unpredictable, can occur when people is part of a crowd, and they can share ideas, feelings and have the same or a similar goal. In addition, recent scientific studies have considered crowds as an entity able to think [11]. In this thesis, we adopted the definition made by Sighele [14], who considers crowd as **a *heterogeneous* and *inorganic* aggregation of people**. He considers as *heterogeneous* because, usually, a crowd is composed by individuals from all ages, gender and different social and cultural realities. In addition, a crowd is considered *inorganic* because its capability to emerge in a sudden way without a formal control and organization.

We know that some places can be propitious to crowd formation. Such places can include, not exclusively, airports and public areas for example. Knowing the existence of places propitious for crowd formation, government, managers, researchers, designers and other professionals are interested in the development of different technologies to improve the evolution of those places, in a smarter and mainly safer way.

Crowd Simulation can be related with entertainment (games and movies) and safety industries. Thinking about entertainment, we can easily apply crowd simulation e.g. in order to populate scenes of a game or movie with bigger, more realistic and dynamic crowds. On the other hand, in the safety engineering, we can observe some open research problems. In this thesis we are going to deal with the problem related to understand the way people leave an environment during an egress process. The possibility of evaluating safety of venues is certainly important in real life crowded environments or events (e.g. Olympic Games at stadiums, train stations, etc.). Such understanding allows engineers to design better places and also to figure out the best way to orient people when choosing a evacuation route.

Different approaches have been proposed in the literature motivating the development of different scientific models along the last decades. Such approaches are concerned with computationally simulate the motion behavior of people, groups of them and even crowds. They were designed based on different goals and were built in different complexity levels. The first known model is a local rules based system [13] able to simulate the behavior of flocks, herds, and schools. Nowadays, complex and different techniques, since navigation fields [12] to different steering algorithms [3, 4], are applied when simulating crowds in order to achieve results coherently with reality.

One specific type of crowd literature is interested in crowd evacuation. When simulating crowds, specially during egress, a set of parameters can be considered in order to reproduce coherent behaviors. Such parameters aim to represent, *e.g* textitEnvironment physical structure, *functionality*,*Population data* and *Environment condition in events*. The variety of people behaviors based on these and other factors makes complex and challenging the reproduction and virtual simulation of an evacuation process. In order to collaborate with the design of safe environments, the research detailed in this thesis is focused on the study of crowd behavior, specially when in egress.

The main goal of this thesis is to present an entire pipeline able to simulate and analyze crowd behaviors when in egress process. In order to accomplish this goal we developed *CrowdSim*, a crowd simulation framework designed to reproduce people's motion behavior paying attention to aspects such human comfort and safety when in large groups.

2 *CrowdSim*: A CROWD SIMULATION TOOL

CrowdSim is a rules based crowd simulation software developed in order to simulate coherent behaviors in an evacuation process [6], [5]. Its main goal is to computationally reproduce crowd motion and behaviors during the process of occupation as well as evacuation and also to present some data that are used to estimate people's comfort and safety in a specific environment.

Two key components are considered in *CrowdSim*, which are organized in distinct modules: *Configuration* and *Simulation*.

2.1 Configuration Module

The configuration module requests, as a first input, the 3D representation of the environment in which a virtual crowd will be simulated. Such 3D model will be considered in order to allow the user to specify the walkable regions according to the building structure as well as physical restrictions and obstacles. Such walkable areas are called *contexts* and they are also able to store information regarding population data. Currently, we can work with three different types of contexts: *birth*, *motion* and *goal* contexts. Also the user defines the following information based on the total number of agents to be created:

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[1]Full thesis text available at: http://bit.ly/2uKn5eC

- *Groups Size*: The agents can be created in different groups until the total number of agents in the context is reached.
- *Creation Time*: Time when the groups of agents start to be created after the beginning of the simulation.
- *Time among groups*: Time interval to be taken into account when creating different groups.
- *Goal:* The context (or set of possible contexts) to be considered as goal to be reached by an agent.

When the environment is coherently mapped as well as the user have defined all the information regarding to *population data*, it is possible to specify how agents should behave when moving. The behaviors able to be performed are:

- *Goal Seeking*: The agents should seek their goals immediately or vague, performing random motion;
- *Keep waiting*: The agents can spend some time on specific regions of the environment before seeking for another goal;
- *Perform random motion*: The agents can chose random destinations during a specific time, before trying to identify the best path to achieve the main goal.

2.2 Simulation Module

The simulation module of *CrowdSim* is responsible to compute the **navigation** of virtual agents in a specific environment. The navigation must be computed coherently, taking into account several aspects such as agents' motion, collision control and other pedestrians' **behaviors**. Also, the simulation module is responsible to detect and start specific **events** during agents' motion. Such events can be the start of an evacuation process, speed variation by some agents located in a specific region of the simulated environment or even other behaviors.

A simulation setup is requested as input in order to define the simulation parameters and must be previously set in the configuration module. Considering such setup information, this module is able to compute the routes for each agent to achieve a specific goal. Routes can be computed based on user specification (i.e. a graph determined by the information defined in the contexts) or the best paths are determined considering only the distance criteria. In addition, during the motion simulation, *CrowdSim* is able to provide collision avoidance among agents and/or obstacles, using a simple local geometry method. Indeed, *CrowdSim* uses A* [8] in order to compute shorter paths.

The output of each simulation contains the following information:

- agents trajectories during the simulation;
- speed variation for each agent;
- agents' simulation time;
- local density along the time, we computed the local density by counting the number of agents per square meter;

The output data is stored and can be used to produce different statistical analyzes. On the other hand, the agents' trajectories can be easily visualized with 3D humans in a virtual environment in order to provide a qualitative validation of the simulation performed by visual inspection.

3 SOFTWARE VALIDATION

Validation & Verification are some of the most important software development activities [2], [1]. The purpose is to guarantee that the software was correctly built. In this section we present how the validation process was performed in *CrowdSim*. We assume as *validation*, for this work, the systematic comparison of *CrowdSim* predictions with reliable information (usually from real data analyzes) The work of Galea [7] presents a set of different validations to be performed. According to the author, there are different forms of validation/testing that evacuation models should undergo. We focus in three of them: *Component Testing*, *Qualitative and Quantitative Validation*. Such tests are already recognized and considered on the field of safety engineering in order to validate evacuation systems[2]. In London, the International Maritime Organization (IMO) developed *guidelines for evacuation analysis for new and existing passengers ships* IMO [9] based on Galea's work. Such guide aims to develop a methodology for conducting an advanced evacuation analysis in order to built systems coherently able to:

- identify and eliminate congestion regions which may arise during an abandonment, due to normal movement of passengers and crew along escape routes, taking into account the possibility that crew may need to move along these routes in a direction opposite to the movement of passengers;
- demonstrate that escape arrangements are sufficiently flexible to provide the possibility that certain escape routes, assembly stations, embarkation stations or survival craft may be unavailable as a result of a casualty.

In this section we relate a set of case tests suggested by IMO in order to validate *CrowdSim* in each category. In addition we detail how we particularly validate the software in a qualitative way.

3.1 Component Testing

Component testing is part of the normal development cycle and involves checking if the various components of the software perform as intended. This involves running the software through a battery of elementary test scenarios.

3.2 Qualitative and Quantitative Validation

Qualitative Validation concerns the nature of predicted human behavior with informed expectations from observed situations. While this is only a qualitative form of verification, it is nevertheless important, as it demonstrates that the capabilities built into the model are able to produce realistic behaviors.

Quantitative verification involves comparing model predictions with reliable data generated from evacuation demonstrations. Galea's work highlights[7] two kinds of quantitative validation: *historic* and *prediction* based validation. In the first case, the user knows the results from previous simulations and real exercises. On the other hand, the second case refers to the usage of the model to perform predictive simulations prior to having sight of experimental results.

To the best of our knowledge, current IMO's guidelines do not have evaluated any experimental data in order to allow a thorough quantitative verification of egress models. Therefore, in this work, we propose method to quantitatively validate *CrowdSim*.

It is important to mention that the quantitative validation should take into account other information besides the total evacuation time. Such information is based on the simulation model outputs and should include data as exit selection, behavior in different conditions, bottlenecks regions, exit and finish times, among others.

[2]This procedure has been highlighted in ISO document ISO/TR 13387-8:1999.

Thus, the level and quality of quantitative validation is dependent on the completeness and quality of the simulators reported data.

Wherever possible, the simulations performed by *CrowdSim* have been quantitatively evaluated. Several analysis have been undertaken in order to validate simulation results. For the purposes of the *CrowdSim* validation, we present the following results of performed comparisons:

- *CrowdSim* was used to simulate the evacuation of a night club. The results were compared against data collected from a real egress exercise [5]. In this project, we were able to record data from real life in order to contrast with *CrowdSim* predictions. Such recorded data includes local and global times, local and global densities and velocities. The analysis of simulated data allowed us to verify some attention points validated during the real egress exercise: *i)* region of highest density (stairs); *ii)* we have estimated a greater density of 5.4 people by sqm while, in the real exercise, the max value was 4.5 people by sqm. *iii)*the greater density was observed at second 40 of simulation, whilst that occurred in second 50 during egress exercise; *iv)* the observed times of simulation and real life were coherent.
- we also applied *CrowdSim* to reproduce crowd behavior when evacuating a college building. An analyzes of the extracted data from real and simulation scenarios allows us to observe that: *i)* times observed in simulated and real scenarios, besides different, are coherent (rel life evacuation takes 15% more time than simulation). We believe that the difference between simulated and real life time occurs because all the simulation agents were created and started to move in the exact same time, while in the real life people had different response time to events. Also real people do not feel panic voluntarily, since they know that an egress exercise is not a real fact of panic. The simulation assumes that all agents are supposed to go immediately towards the exists. *ii* The analyzes of the simulation results allows us to compute the density of the place during the simulated evacuation process and address attention points.

We are aware that this process for quantitative validation is yet simple due to the lack of rich information captured during an egress event (real life or simulation). However the qualitative validation were used by the managers of the night club and college building in order to improve their evacuation process.

4 Evacuation Plans Generation and Validation

Evacuation Plans are not useful just for fire situations. These plans can be easily employed in other occasions that can require evacuation. Such occasions can include severe weather problems, medical emergencies, bomb threats among others. Usually, when analyzing a specific environment, it is possible to identify different ways to leave a specific place. Normally, public places that can receive more than a certain number of people simultaneously must present an egress plan, which is defined based on safety rules and in general, not based on simulations. This section presents our approach to generate and evaluate automatically evacuation plans.

Actually, it is a challenge to identify, among many possible evacuation plans, the one which can better serve the purpose of guiding people to the exit in a safe and comfortable way. There is no warranty that a short path can be the best one to be followed during an egress process or still that the plan with lower evacuation time is the best one. In order to evaluate different evacuation plans for a specific building, we develop a module in *CrowdSim* able to evaluate a set of simulated evacuation plans.

Since an environment is mapped into a 3D world by the user, it is possible to generate the environmental graph meaning all connections among the environment areas. Follow, after the set of N evacuation plans is generated, it is necessary to simulate and collect results from all of them. It is important to note that all evacuation plans that must be compared in the same environment should include the same number of agents A, otherwise results are not comparable. Results of every simulated plan are computed and organized in a $4d$ vector for each one of evacuation plans $\vec{EP}_i$:

$$\vec{EP}_i(gt_i, at_i, ad_i, as_i) = (gt_i, \frac{\sum_{k=1}^{A} lt_k}{A}, \frac{\sum_{k=1}^{A} ld_k}{A}, \frac{\sum_{k=1}^{A} ms_k}{A}), \tag{1}$$

where gt_i is the total time of evacuation for evacuation plan i, i.e. the time that the last agent has left from the environment, while at_i is related with the average time needed for all agents to escape from the place (lt_k is the local time achieved by each agent k). ad_i is the average density occupied by all agents, while ld_k is the local density computed for each agent k. ld_k is computed considering agent k in the center of a $1m^2$ region where number of agents are counted. In addition the average speed as_i is also computed based on mean speed ms for each agent k. Other parameters could be also be used, however we empirically defined the most important to used in the automatic evaluation of evacuation plans.

In order to compute correctly the plan evaluation we propose to include someway the complexity of environment. So, we propose to use an agent reference in order to normalize some of evaluation parameters: $\vec{ar}(lt_{ar}, ms_{ar})$, where lt_{ar} and ms_{ar} are local time and mean speed, respectively, for a specific agent when it is simulated alone, in the environment. The proposed normalization is detailed in equations:

$$gt_i' = \frac{gt_i}{lt_{ar}}, \tag{2}$$

$$at_i' = \frac{at_i}{lt_{ar}}, \tag{3}$$

$$as_i' = \exp(\frac{1}{\frac{as_i}{ms_{ar}}}). \tag{4}$$

Then, evacuation plan i can be evaluated based on harmonic mean of evaluation parameters:

$$ep_i = \frac{4}{\frac{1}{gt_i'} + \frac{1}{at_i'} + \frac{1}{ad_i} + \frac{1}{as_i'}}. \tag{5}$$

Consequently, we are able to rank all the simulated plans and the best evaluated $\vec{EP}_j$ has $j = ARGMIN(ep_i)$ for $1 < i < N$. In order to see if this equation was coherent with real life, we contacted an expert on the domain of safety engineering. We showed him the data generated when 9 different evacuation plans were simulated and we asked him to order them. From 0 to 8, he should ordered from the worst to the best case. Figure 1 shows the ordered simulations from expert and based on our method. We can note a small difference what means a good compromise between numerical results and the quality assessment of results. Further investigations should bring new answers from experts.

5 Case Studies

When analyzing an egress process simulation, it is possible to extract data that can be used to provide a deeply analysis of scenarios. Before something goes wrong, a simulation project can identify attention points related to people comfort and safety when in egress.

The data obtained by crowd simulation can be very useful to safety analysis in order to estimate environment conditions and attention points (i.e. bottlenecks regions) as well as to map and understand people behavior during an evacuation process. Although the final evacuation time is commonly the only variable used in the analysis, other information are also important. According to

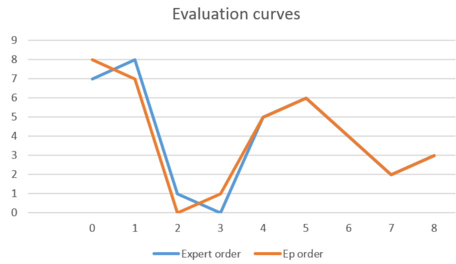

Figure 1: Ordered values for each evacuation plan define by the expert and computed by our method. X axis is related with id of simulated evacuation plan while Y axis specifies the order defined by expert and the method.

Galea [7], in addition to total time of evacuation, important information can be considered, including bottleneck regions, exit details and agents behaviors.

With the *thinking of safety* in mind we have applied *CrowdSim* in a set of projects which the main goal is to demonstrate its potentiality in real-world application. Each project contains a different setup, but all of them are concerned with evacuation behaviors. In each project we were able to analyze different populations and also different ways to people leave the specific building. To this, in each project we ran different simulations setups, aiming to analyze different situations. Moreover, comparing the obtained results from different simulations in the same environment, we can evaluate the efficacy of alternative evacuation strategies and also the building structure.

Despite that each case study considers different buildings and population details, all of the projects followed the same execution pipeline. In this theses, a set of case studies have been performed as previous presented pipeline. This case include: Olympic Stadium, Technological Park, College Building, School, Night Club.

6 Final Remarks

The problem addressed in this thesis was concerned with simulating the egress process in order to investigate the best way to a crowd leave an environment. In order to attend this issue, we presented *CrowdSim*, a framework to simulate crowds in different situations during an evacuation process.

We know that it is very important the coherency on data computed by crowd simulators. Since we want to use simulation results to improve aspects in real life, this validation is an important issue. We evaluate our framework according to international guidelines [9] and recognized scientific approaches [7]. A set of tests have been performed in different categories aiming to check the accuracy of results computed by *CrowdSim*. Our framework have shown acceptable results in all the tested categories. Considering *CrowdSim* as a validated tool, we have applied it on a set of case studies.

In addition, our *ep* metric is an aggregation of different factors and obtained results show its coherency. This is a very important contribution of our work.

As far as we know, our research is very original in Brazil. *CrowdSim* is recognized as the first Brazilian Crowd Simulation Software. Such fact has motivated the insertion of *CrowdSim* in Brazilian Press many times, including the website of Brazilian Federal Government.

7 Awards and Software Registration

- *CrowdSim* is already registered on National Institute of Intellectual Property (INPI - Brazil). The register was published on *Revista da Propriedade Industrial (RPI) n. 2306* in March 17$^{\text{th}}$, 2014 and is valid until December 20$^{\text{th}}$, 2023.
- The project received the first prize from *Santander Prize of Science and Innovation* regarding to *Information Technology and Communication*[3].
- The author of the thesis was one of ten researchers (among 200 submissions) selected to participate on Academy-Industry Training in Rio de Janeiro and Switzerland[4].

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