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Conception, development, installation and evaluation of a real time evacuation assistant for complex buildings

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Abstract

In this contribution a pedestrian evacuation system for large buildings is presented. The aim of the system is to monitor and forecast pedestrian streams in complex facilities to assist decision makers and security services in case of emergency. Since the last decades the study of pedestrian dynamics has gained more attention due to continuously growing urban population and cities. This growth is accompanied by an increase not only in size but also in frequencies of large-scale events. The increase sets new challenges to architects, urban planners and organizers of such events. The growing interest in large-scale events additionally requires increased security measures and new security concepts that are tailored to the large amount of people. The hereby designed system is capable of performing real time forecasts of pedestrian traffic for the next 15 minutes starting from the current situation. The test venue for the system is a multi-functional arena in Düsseldorf, North Rhine-Westphalia, Germany. The emphasis in this contribution is set not only on the development and the deployment of the system but also on the validation of the results during the operational phase.

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Keywords: Evacuation system; route choice; pedestrian traffic; congestions; forecast

1. Introduction

In emergency situations, responders often have to rely on their experiences with past and similar situations to make decisions accordingly. In the case of situations involving pedestrians evacuation under imminent dangers, a fire or a technical incident for instance, decisions have to be taken as quick as possible. In large and complex buildings however, an arena for instance, where people are distributed in several different locations, the situation

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is often unclear and generally only incomplete information is available. For example, how many people are exactly in a specific location and what is the threat level in that location? Under these circumstances a complete overview of the situation, vital for right decision making, is often lacking. Decision support systems are welcome in this case. There is a wide range of evacuation simulation software and models to assist designers, architects, planners, for example in the preliminary phase of the construction of pedestrian facilities, in the preparation phase of an event where a huge number of attendees is waited or for offline emergency drills. A non-exhaustive list constantly updated is compiled at www.evacmod.net. Sometimes an online monitoring system is needed, which does not only capture and present the current situation, but is also able to make prognostics about its evolution based on the current data. There is to our best knowledge no pedestrians evacuation system that can be fed with data in real time and compute new prognostic based on the current situation.

The decision support system for building evacuation presented in this paper has two major goals. The first goal is the monitoring of the current situation in a large facility during a large scale event. The second goal is performing real time forecast of pedestrian streams using real time data such as the current distribution of pedestrians inside a building and the states of the escape routes. By implementing these solutions, the evacuation assistant for complex buildings assists decision makers and security services in case of emergency. The test venue for the system is a multi-functional arena in Düsseldorf. The challenge in the arena is to monitor and forecast the evacuation of 50 000 pedestrians for the next 15 minutes faster than real time. In the development phase of such a system, it is important to keep in mind, whom the system is designed for and to involve these stakeholders as early as possible. It has been done with the fire fighters and policemen who are the end users of the system. In addition other important topics such as data privacy have been addressed and no person related data are stored by the system. The system has been successfully tested during concerts and football games.

The second section of this contribution gives insight into the conception and the development of the assistant and explains the different steps involved. The third section describes the installation, the operation of the system and the validation of the simulation results. The aspect of route choice during an evacuation is addressed in the fourth section. Conclusive remarks are given in the last section.

2. Conception and development of the evacuation assistant

2.1. Conception

The architecture of the evacuation system features three main blocks: the first block matches all data and sensors input sources for the system. The data are used for monitoring and as initial states for the simulation. The processing of the data and the real time simulation are performed in the second block. The third block consists of the output devices. The assistant is steered from the communication module installed on the top of the three blocks. The communication module, which is a web-based application, collects all necessary information from the different input sources and merges them. It also launches a simulation if required and displays the results on a smart-board.

The input information for the evacuation assistant is divided in three streams. The first stream contains information related to the geometry. Depending on the type of event (concert, football) a different configuration for the geometry is needed. Different formats are needed as well to fulfill the requirements for the different pedestrian models used for the simulation. A non-trivial problem is transforming the original drawings (usually available as CAD-files) into files formats that can be understood by a simulation engine. It includes adding a semantic meaning to the drawing by specifying for instance that a particular line is an exit. The generation of the navigation mesh is also part of this process. The conversion work is done once and is usually a semi-automatic task.

The second stream of information comes from the safety and security management system installed in the arena. This is dynamic and changes with each run of the system. The information about the state of the escape routes, which is important in a hazardous situation, is made available. This information includes the states of the different doors and areas, for instance which doors are still usable (not blocked for instance) and which areas of the building are smoke-filled and thus not usable.

The third stream of information comes from an automatic persons counting system consisting of a camera grid. In a hazardous situation it is often required to know the distribution of the persons in the location. This is essential for choosing the best evacuation strategy and optimally assigning the resources available between the responders. The repartition of the persons is gained by analyzing video footages in real time. The system also provides data about spectators' route choice patterns for an empirical study. The cameras are positioned at all main entrances and passages of the building. The collected data are presented in terms of frequencies, i.e. the number of persons passing a counting line or exit per minute in the direction in and out of a section of the building. For that purpose the arena has previously been divided in different sections upon consultation with the stakeholders.

2.2. Development of models for pedestrian dynamics

Basically two classes of models are used to simulate pedestrian flows. Macroscopic models do not differentiate between individuals and share many concepts and techniques with fluid dynamics. In microscopic models, the simulated agents have different properties, for instance a preferred destination and velocity, or the belonging to a group. Microscopic models are further categorized in space discrete and space continuous models. More information about the different models including the advantages and drawbacks is presented by Schadschneider et al. (2009). In the system both microscopic and macroscopic models are tested. Microscopic models are used to calculate the forecast. But they are time consuming in calculation and for a simulation faster than real time a parallel computer is mandatory. Macroscopic models are less time consuming and allow calculating the optimal assignment of the attendees to the available exits by iterative reallocations thereby providing the best distribution of evacuees on the exit routes. Schomborg et al. (2011) gives more details on this approach.

Generally the framework used for describing pedestrian traffic in microscopic simulation is divided in a three-tier structure as presented by Hoogendoorn et al. (2002). One distinguishes between the strategic, the tactical and the operational level. The start and the end point for each pedestrian are usually known in advance. At the strategic level pedestrians choose their self-estimated best route, among a collection of different alternatives. This can be done based on experience. Examples could be the global shortest path or the familiar path to a given destination. Short-term decisions are taken at the tactical level, avoiding jams or switching to a faster route for instance. Basic rules for motions are defined at the tactical level; these include accelerating, decelerating, and stopping. The pedestrian model at the operational level is a force-based model described by Chraibi et al. (2011). In this model, pedestrians are described using ellipses with velocity dependent semi-axes. When the speed of pedestrians increases, the space needed in the direction of movement also increases. The model captures this effect. At the strategic level, the model used to route the pedestrians through the facility is given by Kemloh Wagoum et al. (2011). It is a quickest path model, where the pedestrians observe their environment and evaluate for instance the processing speed of queues at doors before taking individuals decisions. As already mentioned earlier, we are only simulating emergency clearings. This has two major impacts on the simulation. The first impact is that all pedestrians have the same goal, which is exiting from the facility. In a routine clearing, at the end of an event for instance, they may have a preferred destination, the parking lots or the train station for instance. The second impact is that the pedestrians will choose the quickest path to reach the outside. The quickest path thereby results in a unidirectional flow.

3. Installation, operation and validation of the assistant

3.1. Installation

The main components of the assistant are installed in the arena. This is the parallel computer for performing the real time computation, the safety and security management system and the cameras for the counting system. In order to avoid any possible interference with the installed automatic fire alarm which could be dangerous in a test phase, a clone of the already installed system has been used. The counting system consists of a grid of mono and stereo cameras installed in areas of interest. Each camera is merely responsible for one exit, which means that at each time the number of pedestrians passing through that exit is available. Also, the passing direction for each exit is identified, making it possible to calculate the number of pedestrians inside a specific section. The cameras are all connected to a server in a local area network. The server collects and aggregates the data in real-time and makes them available through web services. The data are presented in terms of frequencies, i.e. the number of persons passing the corresponding counting line or exit per minute in the direction "in" and "out" of a specific section. Using that information the proportional usages of the different exits are calculated. In order to comply with privacy regulations, no images are stored by the system. More information about the positions, the number and the data given by the cameras are presented in Kemloh Wagoum et al. (2012).

3.2. Operation period and feedback

The test period was conducted by choosing various games and concerts events which were systematically assessed by the stakeholders. The system is operated by firefighters, policemen and security services of the stadium. 9 football games and 4 concert events have been analyzed between July 2011 and November 2011. The geographical location of the test venue is presented in Fig. 1 (Left) showing the two main parking lots, the train station and the area of interest, which is drawn in red. Due to costs constraints on the test system, only the area of interest has been monitored and simulated in the pilot phase of the evacuation system. One point raised in the monitoring process is the efficient display of information during a crisis. Condensing the information to a minimum solves this, for instance no animations are displayed. The dynamic of the clearing however can be displayed in time slices. Five-minute time slices have proven to work well in this case. Simulation results like jams or congested areas are shown using different Level of Services (LOS) introduced by Fruin (1971), which displayed the usage of areas in three colors: red, yellow and green. Red stands for high density and green for low density. The LOS for a simulation is shown in Fig. 1 (Right).

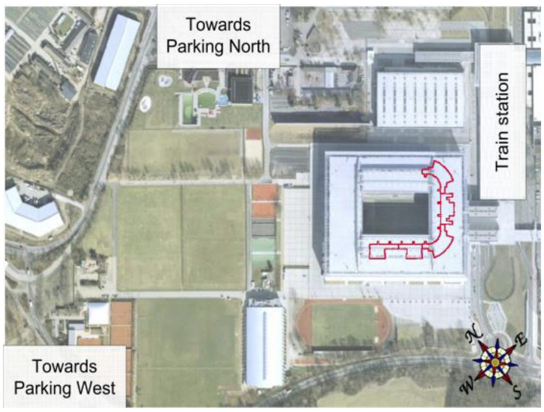

Fig. 1. (Left): Test venue of the evacuation system. The monitored and simulated area is drawn in red. (Right): Smart board displaying the Level of details of one simulation. Areas with low density during the evacuation simulation are green; areas with high densities are red.

3.3. Simulation and Validation of the results

Major challenges for the simulation part in the evacuation assistant include the development of microscopic models to accurately reproduce individual pedestrian motions, the development of a route choice model and the efficient implementation of these models with respect to the runtime. The key features of models are their capability of reproducing the real transport properties of the system, like flows, speeds, densities and the relations between these quantities. For that purpose, empirical data for calibration and verification are needed. In the field of pedestrian dynamics, such data are scarce and they often show disparities, see Schadschneider et al. (2009). Considering this aspect, one of the goals followed in the conceptual phase of the system was to compile a database of experimental data. For that purpose, more than 300 different configurations of experiments were performed over three days involving more than 400 test persons. The experiments were performed in the same venue where the system is installed. The experiments organized give insights movement of pedestrians in certain parts of the arena. One sample experiment in Fig. 2 (Left) shows three pedestrian streams merging at a gate of a tribune section. All pedestrians are walking on stairs. The streams from left and right (pedestrians in red and black shirts) are descending; the stream in the middle (pedestrians in grey shirts) is ascending the stairs. A qualitative validation of the simulation using this stair experiment is presented in Fig. 2 (Right). The velocity of the pedestrians is color-coded. Slow pedestrians are red and pedestrians moving at their desired free flow velocity are green. The desired velocities are Gaussian distributed with mean 1.34 ms-1 and standard deviation 0.26 ms-1. The congestions are present in the sitting rows and on stairs. But as pedestrians move towards the gate, the space is less confined and their speed increases. Zhang et al. (2011, 2012) presents an analysis of some of the experiments in corridors (uni- and bidirectional flows) and in T-junctions. The special case of stairs and different pedestrians streams merging into a gate (See Fig. 2) have been empirically investigated by Burghardt et al. (2013a, 2013b). The analyzed value is the relationship between density and velocity, and between density and flow otherwise known as the fundamental diagram. Detailed quantitative calibration and validation of the pedestrian model in corridors and corners using the data from the experiments are performed by Meunders (2011).

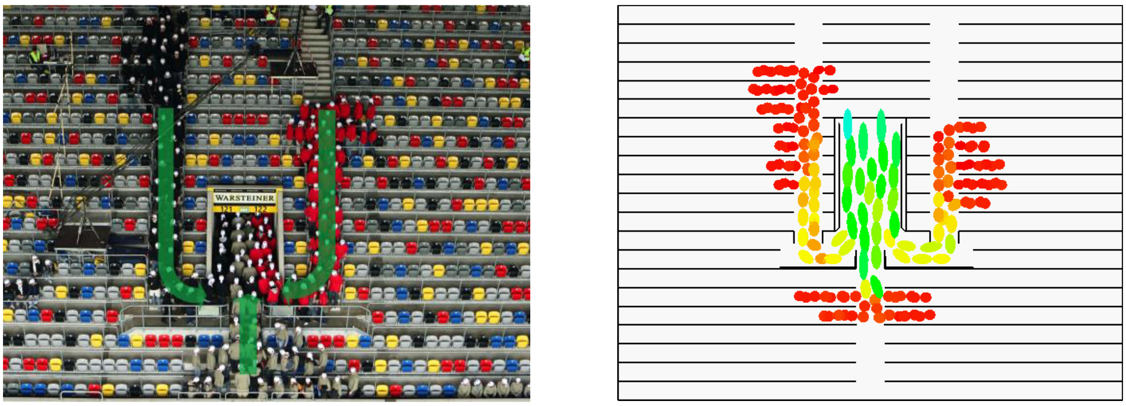

Fig. 2. Qualitative validation of a simulation using experimental data. (Left): Experiment showing the merging of three pedestrians streams in a tribune section of the arena. (Right): Simulation displaying pedestrians. The velocity is color-coded. Red stands for slow pedestrians and green for fast pedestrians.

4. Aspect of route choice during evacuation

For the right forecast of jams and congested areas, route choice modeling in pedestrian dynamics is essential. The problem statement is the following: given a set of possible routes, which criteria influence pedestrians' choice for a particular route? This is essential for reproducing route choice in computer models and is difficult due to the many underlying subjective influences on this choice. The manner in which pedestrians choose their way in a simulation has a direct influence not only on the predicted evacuation times but also on the average time they spend in a jam. Also, the route choice in general is often bounded to a certain history of the pedestrian. When entering a building, much information is subjectively recorded, for example the chosen way or a closed door along the path is remembered. This history is usually not available in simulation environments. However, when it comes to estimate evacuation times or to forecast congestion areas during an evacuation process, route choice and specially the history of the simulated agents may play an important role. In the case of an evacuation, it is generally assumed that the intrinsic behavior of the crowd is to follow the seemingly (self-estimated) quickest path. The quickest path in pedestrian dynamics describes the process of minimizing the travel time to a given a destination. This is indeed a subjective notion as it depends on some prerequisites, e.g. whether or not the pedestrian is familiar with the facility. Even cultural factors can affect this behavior. Chattaraj et al. (2009) showed the influence of different cultures on the fundamental diagram. It is clear that those influences can be extrapolated to the route choice behavior as well. He (Chattaraj, 2010) also investigates the route choice behavior of pedestrians in a hall with two exits of different widths. Obstacles of different sizes are positioned in the room and the influence on the evacuation time is assessed.

Preliminary investigations on the data captured by the person counting system presented by Kemloh Wagoum et al. (2012) suggested that even in the case of a routine clearing, there is a clear tendency of first leaving the building before aiming at the final destination, which implies the quickest path out of the building. The results were not affected by the time of the day as some of the investigated soccer games were played at midday and others during the evening. Therefore we can assume that this effect will be reinforced in the case of an emergency evacuation. The study did not provide the route choice patterns inside the promenade itself, for instance how many spectators move from one section to the other. Another restriction is that the type of the event has to be taken into account. The effect of using the quickest path to the outside is sketched in Fig. 3. When entering the arena, the main paths are described in Fig. 3 (Left). Most of the spectators come from the section connected to the train station and from there spread to the other sections. At the end of the event as presented in Fig. 3 (Right), the main paths is first to go outside and from there to look for the direction towards the final destination, which is the train station or a parking lot. In the implementation of the evacuation assistant, some restrictions must be considered. As we are simulating an evacuation scenario, we assume that all pedestrians have the same motivation, to leave the facility on the shortest past as fast as possible.

For the initial configuration of the simulation presented in Fig. 4, 2800 pedestrians are homogeneously distributed in the promenade and another 9000 pedestrians are homogeneously distributed in the tribune. The stage of the simulation after 5 seconds is presented in Fig. 4 (Left). All exits are well used at this stage due to the high density in the different sections of the promenade. There are still no congestions as can be inferred from the pedestrians' color which encodes the velocity. They are mostly green, meaning moving at their desired speed. After 2 minutes, the situation is completely different as displayed in Fig. 4 (Right). The congestions are only present in the tribune and pedestrians in the promenade only move towards the nearest exit. This is also the explication of the relatively high usage of some exits. In the absence of congestions, the quickest path is reduced to the shortest path, which is unique depending on the location. The evacuation time is determined by the outflow rate from the tribunes. All simulations are performed faster than real time. Evaluations of the times are presented in Kemloh Wagoum et al. (2013).

Generally speaking the quickest path is achieved by systematically avoiding congestions. The implementation proposed by Kemloh Wagoum et al. (2011) is based on an observation principle. It combines the classical shortest path with a quickest path. The idea behind the strategy is that in the case of emergency evacuation people will choose the quickest path to egress from the building. In order to detect the quickest path, pedestrians analyze their current situation. This has been modeled by observing the evolution of the different queues (if any) in the visible location and by systematically deciding for the fastest one. This choice takes into consideration the visibility range of the individual pedestrians and the efforts bounded to the change of a route expressed in terms of gain. The final decision whether or not to change the current route is regulated by a cost benefit analysis function, which takes as arguments the self-estimated travel times through alternative routes and a gain threshold. A good and plausible dynamics in the evacuation simulation process with reduced evacuation times have been the results of the modeling approach. Also, it is not sensitive to initial distribution of pedestrians or special topologies like symmetric exits, making it usable for any kind of geometry.

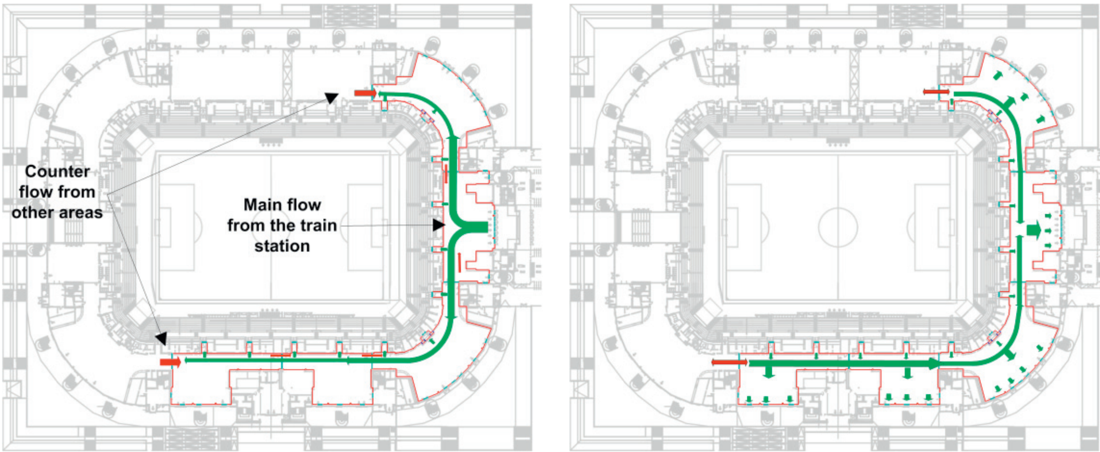

Fig. 3. Qualitative route choice description on entering the promenade at the beginning of the event (Left) and leaving the promenade at the end of the event (Right). The red arrows indicate pedestrians not following the main flow. The green arrows give the main direction.

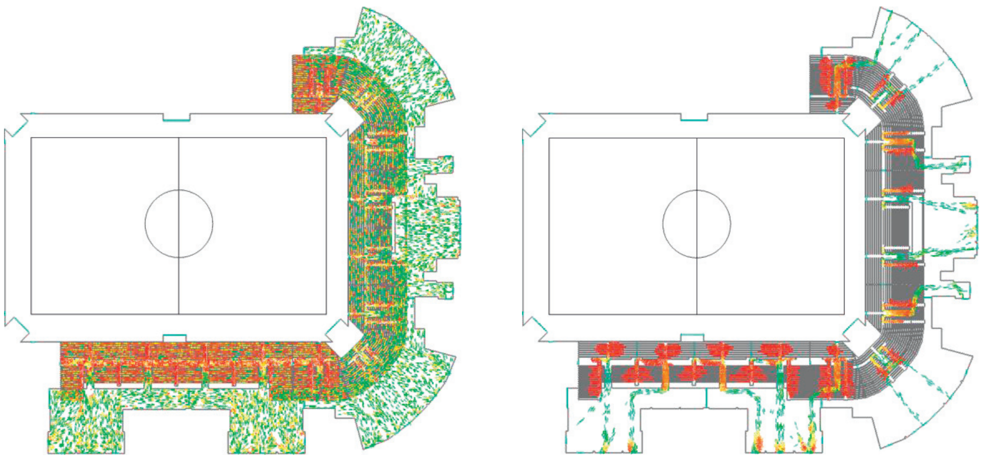

Fig. 4. Status of the simulation after 5 seconds. 9000 Pedestrians are distributed in the tribune. The exits are evenly used. (Left). Status of the simulation after 2 minutes (Right). The density is low in the promenade area and there is no congestion at all. The local nearest exits are preferred by the pedestrians. The evacuation time is determined by the outflow rate from the tribunes.

Fig. 5 shows 4 steps in the clearing of a specific section of the arena at different time steps. The different steps represent different densities and degrees of congestions. By applying the quickest path, all exits are evenly used, which is the expected behavior. As pedestrians go out of the tribune, they are faced with the different queues at exits and make their decision depending on what they perceive. On Fig. 5 (Upper left) all exits are jammed and number of pedestrians is high. Pedestrians coming from the tribune prefer exit where the queue is processing faster. On Fig. 5 (Upper right) one exit is almost free and is in the visibility range of many other pedestrians. The congestions avoidance process is clearer on Fig. 5 (Lower left) where two queues are left and they are avoided by other pedestrians as there are more free exits now. On the last Fig. 5 (Lower right) there are no more jams and the pedestrians simply proceed to the nearest exit.

Fig. 5. Qualitative validation of the exit choosing behaviour at different time steps in the simulation. (Upper left): after 10 seconds. (Upper right): After 40 seconds. (Lower left): After 60 seconds. (Lower right): After 100 seconds.

5. Conclusion

In this contribution, the steps involved in the development and operation of a real time evacuation assistant are presented. The designed system is capable of performing real time forecasts of pedestrian traffic and has been tested in real case scenarios and shows some limitations. For instance it is designed for evacuation cases but will most of the time be tested on routine clearings only. The output, which is mainly steered by the preferred route of the pedestrians, differs depending on whether a normal clearing or an evacuation is simulated. The different models developed and implemented in the system have been calibrated and validated using experimental data collected in the facility where the system is operated. With exception to the automatic persons counting systems, the system is not tailored to a special venue and can be fast deployed and operated on a different site.

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