Simulation of Congestion Management for Emergency Evacuation

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***Abstract*—This demonstration presents novel approaches in the field of evacuee assistance during emergency building evacuations. While much research has been done in this field and produced distributed and decentralized or robust platforms, most solutions are based on the assumption that the shortest-path is the safest one. We demonstrate that this approach is far from optimal, especially if evacuees are not evenly distributed across the building, or if they have special needs. The novelty of our work is in the introduction of path metrics which take flow- and capacity-constraints into account, and specific classes of users like disabled or children, for which criteria such as energy expenditure or route complexity are predominant. Our objective is to design a system which suggests routes tailored to the evacuee's needs, yet maximizes the flow of evacuees across each available path in the building. We also present the adaptation of a "self-aware" routing algorithm, inspired from computer network routing, to the evacuee routing problem. The Cognitive Packet Network (CPN) is a distributed routing algorithm able to discover and maintain a current knowledge of the network by intelligently allocating more overhead to the areas of the network where the best routes are found. The demonstration summarizes our efforts to model an area as a queuing network, in order to leverage the associated theory and apply some techniques originally designed for computer networks to routing people or objects.**

I. Introduction

Building controls have evolved into an ensemble of networked systems which collectively monitor and control most aspects of a building [1]. This evolution has been most visible for safety-related systems: uniquely addressed hazard detectors have become the norm for public buildings. Traditional static exit signs in shopping malls are being superseded by dynamic signs whose orientation can be controlled remotely. Despite these advances in sensing and control, decisions remain complex task in the presence of hazards [2], [3] and evacuation, where safety is tantamount. Indeed, while steering the evacuees clear from hazards is a difficult task in itself, doing so without creating unstable flows, congestion or stampedes is even more complex. While congestion is bound to occur when all building occupants simultaneously rush towards the building exits, this may nevertheless be alleviated by directing specific groups of evacuees towards less congested exits or paths. Additional problems can arise when networks that are used to direct evacuees also come under attack or are congested [4]. Most evacuee routing systems in the literature focus on finding and guiding evacuees along the shortest safe egress path. For instance, the concept of *artificial potential fields* [5], [6] supports distributed route-finding and can be embedded into resource-constrained wireless sensors. Opportunistic communications [7] provide a robust infrastructure-less method to exchange information on the location and intensity of hazards among evacuees, which lets them autonomously determine safe exit paths, though they are susceptibe to network attacks [4]. We have proved in recent work [8] that the shortest-path approach is valid for low occupancy rates where evacuee flows remain stable. However, the performance of such algorithms degrades sharply as the building user density increases. As the search is focussed on *the* best solution, users are inherently guided towards the same path. This often results in widespread congestion along this shortest route – while other less optimal (yet safe) paths may remain virtually unused throughout most of the evacuation process. Clearly, congestion management becomes a predominant success factor when the area to evacuate is densely-populated and offers several escape paths alternatives. Perhaps one of the simplest way to manage congestion is to incorporate it to the routing algorithm's path-cost metric. Instead of using distance alone, using the path traversal time – including queuing time – allows conventional shortest-path algorithms to solve the flow-optimization problem in emergency evacuations situations. We then calculate path traversal time by modeling the building as a network of queues [9]–[11] to determine queueing times based on current conditions. However, congestion is a routing-sensitive metric [12] which increases with the probability of routing traffic into the path. Given the presence of a time-delayed feedback loop between congestion and routing decisions, basic algorithms which only search for the lowest-cost route are expected to perform poorly, as they do not account for edge capacity constraints, nor the fact that routing evacuees through the best path inherently degrades it. In addition to this, most research in the field of evacuation assistance systems only considers a single *type* of evacuee, or merely randomize parameters like walking speed, health, etc. in an effort to portray the diversity in the evacuee population. Clearly, different classes of evacuees exist, and each have particular sets of evacuation constraints. While it may be required to send some evacuees down longer paths for the sake of easing congestion, this should be avoided for specific classes of evacuees – such as children, the disabled, etc. Instead, the system should recommend to the more vulnerable evacuees a path which is simple to follow, with less traffic and relatively short.

II. Concepts

This demonstration presents two congestion-aware metrics which can be fed to a routing algorithm, in order to optimize the evacuation in terms of evacuee flow. The first metric, referred to as "Reactive" simply measures current congestion levels across the building and increases the path cost by taking into account current queuing time. The second metric, referred to as "Proactive" requires the algorithm to determine the future time of passage at each node along the path assigned using queuing network techniques presented in [11]. Following this, the algorithm reserves capacity along each node at the expected time of passage. If the algorithm finds that all capacity has been reserved at the expected time of passage, the evacuee will have to queue until the edge becomes available once again, so the cost-metric for this route is increased accordingly. This effectively allows the routing algorithm to forecast congestion and take future congestion into account for each routing decision.

Because the objective of both metrics is to distribute the flow of evacuees evenly across each available path, the algorithm which performs the routing must be able to discover all viable evacuation paths: not only the shortest or optimal one. Performing a *full* search of all possible paths in a graph featuring hundreds of nodes and vertices is prohibitively expensive, from a computational point of view. To address this problem, we use a "self-aware" routing algorithm which was initially designed for computer networks: the Cognitive Packet Network. CPN uses "Smart Packets" to search the network for new routes, and update the cost metrics of known routes. Smart Packets are guided by Random Neural Networks (RNN) which are located in each node. Every time a Smart Packet reaches the exit, it backtracks and provides information to perform reinforcement learning on the RNNs which directed it. Combined with a certain degree of randomness in Smart Packet movement, CPN is able to quickly resolve a set of path in an otherwise unknown graph, and intelligently allocate the largest amount of overhead to the most promising path or areas of the network. The operation of CPN lends itself to decentralization: each node can be implemented by a device which can also perform a variety of tasks, such as sensing, communicating with users, and maintaining the RNN associated to the local node or issuing and forwarding Smart Packets.

CPN is also able to satisfy the needs of each *class* of evacuees while optimizing the overall evacuation problem. For this, a routing metric is tailored to represent the needs of each class of evacuees. Then, instead of using one RNN on each node, we set-up one RNN *per metric* which focusses on optimizing the routing for a specific class of users. In particular, we introduce an energy-consumption metric for motorised wheelchairs inspired from concepts developed in the fields of robotics and and Mobile Sensor Networks. An energy-efficient motion planning approach presented in [13] models the relationship between the motor's speed and the power consumption using polynomials, and accounts for acceleration and turns. In [14], the authors compute optimal paths for a mobile robot with the objective of minimizing energy consumption. This method assesses the suitability of the path in terms of risk of overturning the robot, impracticable grounds, excessively steep areas, which also happen to apply to wheelchair users. Different velocity schedules are also considered in [14] to minimize motion-related energy consumption in the presence of variable road conditions. Due to the typical "start-stop" motion of motorized wheelchairs, the method places a special emphasis on the effects of successive acceleration/deceleration phases. However, all algorithms previously mentioned only focus on a single individual and do not model interactions with other individuals in congested areas. Instead, the problem should be approached using an algorithm like CPN which takes a global approach to the problem to perhaps guarantee that wheelchair users are afforded sufficient space to move and set apart from the flow of "fit" evacuees.

III. Contributions

This demonstration features a complete simulation of a building evacuation, featuring sample runs of the evacuation simulator as in Figure 1. Using the results from [8] we demonstrate that using the Shortest-Path approach on its own to route building occupants during an emergency evacuation is inadequate. We also present results which confirm that CPN can be extended from packet network routing to the routing of physical evacuees across a graph representing a building or area. We then introduce some of the results from [15] and demonstrate how the two routing metrics – despite achieving similar evacuation times – result in a fundamentally different evacuation process in terms of routes offered to the evacuees, route oscillation, etc. This is presented in the form of route usage statistics, Fig. 2(a), and sample routes followed by evacuees, Fig. 2(b).

We also present results of our attempt to cater for different classes of evacuees, and show how the survival rate of slower evacuees can be maximised without greatly impacting the rest of the evacuee population.

IV. Demonstration Medium and Logistics

We intend to present a video during the demonstration session. Instead of showing simulations – which may be running slowly – the video format allows us to focus on the most relevant parts of the simulation, and provide an insightful view of the evolution of congestion in the building. The video medium will also help introducing the fundamental routing concepts in a dynamic and interactive manner.

In order to run our video, we require access to an electrical outlet to power a laptop and video projector. If a video projector can be arranged by the conference organisers, we will gladly use it, however we will be able to provide our own if required. We would also need some form of screen to project the video: this could be a suitable wall of the room, a divider, or a portable video screen.

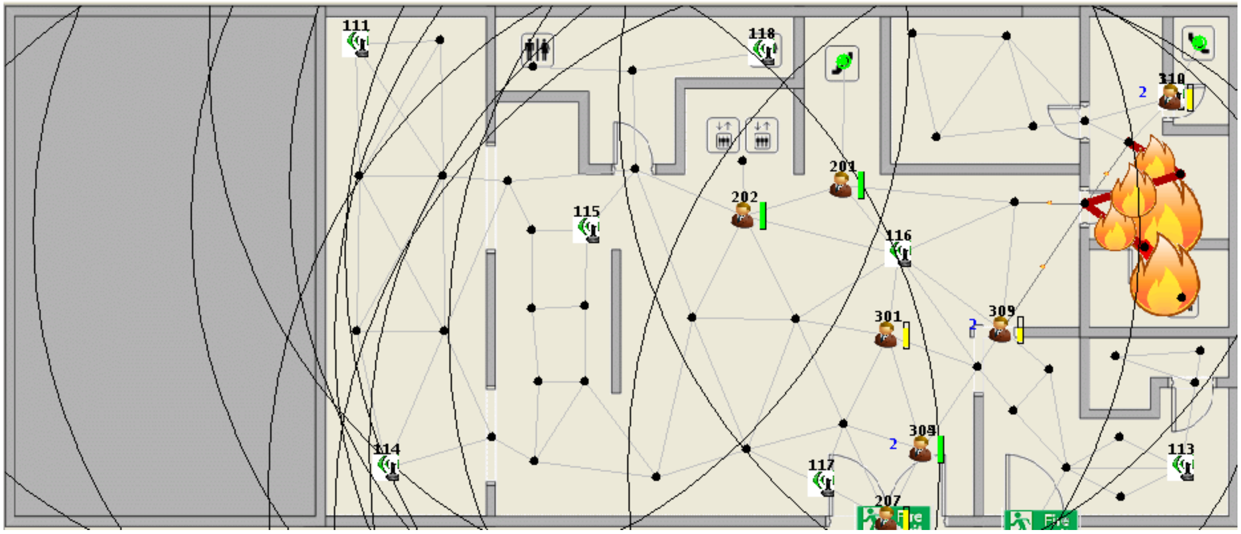

Fig. 1. Sample screen capture of the Building evacuation simulator

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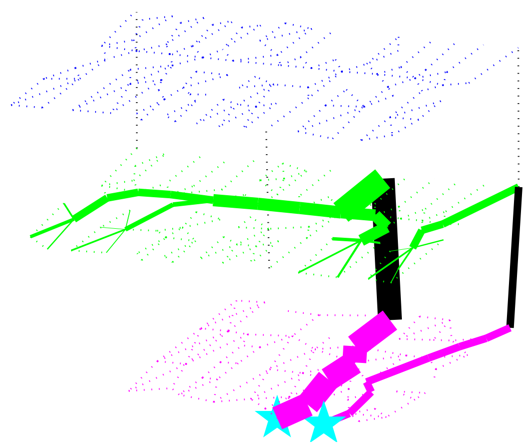
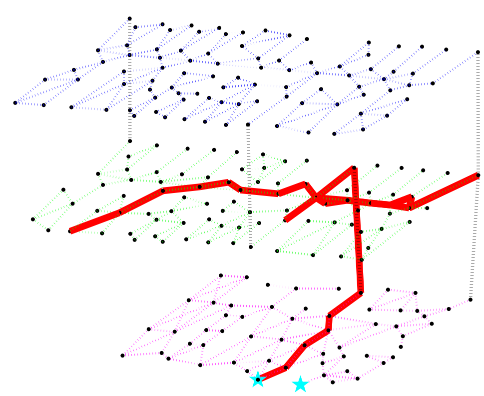


(a) Graphical representation of path usage statistics



(b) Graphical representation of a sample path followed by an evacuee

Fig. 2. Graphical representation of the simulator's results featured in the demonstration video