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A MAT-based Granular Evacuation Modeling Framework.

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***Abstract*—In this paper we describe an evacuation modeling framework based on a graph representation of the scene which is derived from its geometric description. Typically such graphs (geometric networks) are constructed using Medial Axis Transform (MAT) or Straight Medial Axis Transform (S-MAT). In our work we use Voronoi tessellation of a set of points approximating the scene (a single floor plan) along with the dual graph – Delaunay triangulation. Using these two graphs we extract not only the information about paths in the building, but also information about path widths and areas assigned to vertices. Typically only path lengths from MAT or S-MAT based geometric networks are used in evacuation modeling. Our approach enables us to include flow analysis and e.g. locate bottlenecks. We discuss a typical density-based evacuation model coupled with a partial behavioral evacuation model within proposed framework.**

I. Introduction

ICRA project (http://icra-project.org/) aims to provide modern engineering tools to support fire commanders during firefighting and rescue operations.

As a module in this project, we aim to build a framework which would provide the basis for implementation of density-based (flow-based) evacuation models. While density-based models only represent one approach to evacuation modeling [1], we nevertheless stress that they are very similar to hand calculations carried out using methods described in [2], [3] and thus are the easiest for experts to understand and assess. Advantages and limitations of different methodological approaches have been discussed in [4].

While the assumptions of specific models, their degree of complexity as well as their specifics may differ, all of these models will operate on the same underlying representation of the scene. On one hand, the scene is represented by a building model which describes geometric properties, on the other hand, it is represented by a graph that describes the topology of connections in the building. Such a graph is called a *geometric network* [5].

Vertices in a geometric network correspond to so-called transition points, whereas edges correspond to paths. Geometric networks are widely used in geographic information systems [5], and indoor navigation systems [6]. A computational geometry tool that has been often used in construction of geometric networks from planar plans is *Medial Axis Transform* (MAT) or *Topological Skeleton*, introduced by Blum [7].

Indoor navigation models for the purpose of emergency movement were previously studied in [8], [9], [10]. Building representations that supplement each other seem to be a common trend in the literature, see e.g. [11], [12], [13].

In this paper we describe an approximate process of constructing a geometric network that is further enriched: Vertices are assigned to areas in the building and edges are enriched by information about path lengths, widths, and stairs parameters that affect maximum flows. We also discuss an implementation of a typical density-based model [2] coupled with a partial behavioral model based on PD 7974-6 norm [3] within the proposed framework.

The outline of our paper is as follows: First we briefly describe the process of evacuation and the role of evacuation modeling in ICRA project. Afterwards we introduce two evacuation models: one includes a behavioral component, the other one is strictly a (density based) movement model. In the following sections we briefly discuss Building Information Modeling (BIM) and the process of geometric network calculation in our model.

Granularity announced in the title will become apparent when we discuss the duality of vertices in the graph and areas in the geometric description of a building.

II. Evacuation process

Evacuation models are typically implemented in the context of building safety analysis. In this usage scenario, which needs to address the worst-case usage pattern of a building, one is usually interested in comparison of available safe egress time (ASET) and required safe egress time (RSET). ASET is the period of time which permits safe escape from a building. RSET, on the other hand, is the time between ignition of fire and the completion of evacuation. Methods of ASET estimation are outside of the scope of actual evacuation modeling, although some models (e.g. buildingEXODUS [14] and FDS+EVAC [15]) enable joint fire and evacuation calculations or inclusion of fire simulation results in evacuation

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calculations [1]. In what follows, we remind the typical [3], [2] model of RSET calculation. Following [2] and [3] (from which we borrow the notation) we define:

$$RSET = \Delta t_{\text{det}} + \Delta t_a + \Delta t_{\text{evac}}$$

where Δt_{det} denotes the time between fire ignition and detection, Δt_a is the time of alarming, and t_{evac} is the actual evacuation time. Δt_{evac} is further decomposed as:

$$\Delta t_{\text{evac}} = \Delta t_{\text{pre}} + \Delta t_{\text{trav}}$$

where Δt_{pre} is pre-movement time and Δt_{trav} is travel time. Pre-movement time consists of recognition time (the time it takes an alarm aware occupant to take action) and response time (additional time it takes the occupant before he starts walking towards exit).

III. Evacuation model as a decision support system

There are important differences between typical usage of evacuation models and the usage scenarios considered in ICRA project: In building safety analysis, one typically aims to analyse potential worst-case scenarios, whereas during a Fire Rescue Action the placement of occupants may be known, and the model is used to assess this specific situation.

In ICRA project, the end user is the fire commander. Two primary use cases that we consider are direct assistance in Search and Rescue operations and providing a rough estimate of egress time along with bottleneck analysis. Usage scenarios differ mainly in assumptions of occupant localization. We cover these from the least to the most specific:

- In most situations, rough occupant density assumptions can be made based on domain knowledge. For example, if a fire alarm is triggered at a school at 9am, we can expect the highest overall density, with most classrooms utilized. Further assumptions about typical class size (e.g. 20 pupils) can lead to accurate evacuation time estimates. A uniform density in all rooms may be assumed without further clues.

The following two points are still an area of research, but we nevertheless stress them now as the current roadmap of our research:

- If technology permits, we may infer vague hints as to density placement of people in different parts of a building based e.g. on cellular traffic or information from other sources. Thus, we may rule out certain bottlenecks that would not be apparent if we assumed an overall uniform density of people in the building.
- We also consider a very specific scenario where only few occupants are left in the building, and their locations are (approximately) known. The module could provide hints for navigation of fire fighters and directly support Search and Rescue operation rather than provide egress time estimation.

In this paper we only consider the first usage scenario: we assume that occupants are uniformly placed in the building. We wish to estimate total egress time and determine possible bottlenecks in building structure. The model should also provide a plausible forecast for a given timestamp.

IV. Implementation of PD 7974-6 norm

PD 7974-6 norm by British Standards Institute [3] describes an algorithm of RSET calculation that encompasses two scenarios: a sparsely populated and a densely populated building. If the building is densely populated, first occupants will usually have shorter pre-movement times than in the other scenario [3], but a queue may form quickly afterwards, limiting the outgoing flow. If the building is sparsely populated, the movement is unobstructed, but pre-movement times of last occupants may be longer (e.g. there may be nobody around to notify them). Thus, the overall evacuation time for the first scenario may be calculated as:

$$\Delta t^{\text{sparse}}_{\text{trav}} = \Delta t_{\text{pre}(99)} + \Delta t_{\text{trav(walking)}}$$

and for the second scenario as:

$$\Delta t^{\text{dense}}_{\text{trav}} = \Delta t_{\text{pre}(1)} + \Delta t_{\text{trav(walking)}} + \Delta t_{\text{trav(flow)}}$$

where:

- $\Delta t_{\text{pre}(99)}$ is the pre-movement time of the 99th percentile of occupants in a sparsely populated building,
- $\Delta t_{\text{pre}(1)}$ is the pre-movement time of the first percentile of occupants in a densely populated building,
- $\Delta t_{\text{trav(walking)}}$ is the unimpeded evacuation time of an occupant with the longest path to the exit.
- $\Delta t_{\text{trav(flow)}}$ is the queuing time of occupants at the exits.

Usually $\Delta t^{\text{sparse}}_{\text{trav}} < \Delta t^{\text{dense}}_{\text{trav}}$, although in some situations the opposite may hold true, hence both scenarios are usually considered.

PD 7974-6 also describes the calculation procedure of pre-movement times for several behavioral scenarios and building types (characterized by their complexity, management level and alarm system). For the rest of this paper we assume that parameters required for calculation of pre-movement times (according to the discussed model) can be provided by an operator of Fire Command Center.

It is worth stressing that in this setting, alarm times and pre-movement times for certain scenarios are intervals, thus the output of the discussed evacuation model is not a single number, but a 2×4 matrix that describes the sparsely-populated and densely-populated scenarios, e.g.:

scenario	Δt_a	Δt_{pre}	$t_{\text{trav(walk)}}$	$t_{\text{trav(flow)}}$
sparse	$2-5$	>20	10	0
dense	$2-5$	>10	10	15

Fig. 1. The output of the model consists of time (in minutes) of alarming-time, pre-movement time and evacuation time (walking and queuing) for different scenarios. Pre-movement time in the sparse scenario corresponds to the last occupants (99th percentile), whereas in the dense scenario it corresponds to the first occupants (1st percentile).

In this setting, Δt_{pre} corresponds to inter-percentile range of pre-movement times of all occupants in the building. Pre-movement time of a single occupant in the building typically follows approximately log-normal or normal distribution [3] (log-normal), [16] (log-normal or normal). It is worth stressing that other approaches to pre-movement time modeling are possible, see e.g. [16] for a discussion of a sampling-based approach, or overview of various other approaches in [1].

When hand calculations are used, $\Delta t_{trav(walk)}$ is usually approximated by the longest route to exit multiplied by a conservative estimate of human speed, whereas $\Delta t_{trav(flow)}$ is usually estimated by finding the dominating bottleneck in evacuation plan and performing calculations for this bottleneck alone.

V. Flow Model

The simplest model of $\Delta t_{\text{trav(flow)}}$ calculation hinted in the previous section requires determining the dominating bottleneck, which in turn requires analysis of the overall flow of people in the building. Since we are not hindered by time constraints that enforce simplicity (and approximations) of hand calculations, we describe a somewhat more general scheme. In what follows, we remind a flow model described in [2]. We begin by reminding an informal definition from the paper:

Consider a set of evacuation paths in a building. A *transition point* is any point where (i) a path becomes narrower or wider; or (ii) paths split, converge or join stairs.

From now on we consider a graph (V, E) such that vertices V represent transition points in a building and edges E represent evacuation paths. We will think of *flow* of people through edges $e \in E$, and thus for clarity we will assume that graph $G = (V, E)$ is directed. The unit of flow in this model is $\left[\frac{\text{persons}}{s \cdot m}\right]$ (flow denotes the number of people that pass through a corridor or a door of a given width in a time interval).

For each transition point $v \in V$:

$$\sum_{e=\langle v,w\rangle \in E} F_e W_e = 0$$

where F_e denotes flow departing (or arriving, if negative) from (or at) v through e and W_e is the minimum effective width of path $e \in E$. Furthermore, [2] defines maximum flow through e for horizontal travel and for stairs with different parameters (Riser and Tread) as a function of occupant density.

We remind that t_a, t_{pre} and $t_{\text{trav(walk)}}$ are calculated separately and the purpose of flow analysis is to determine $t_{\text{trav(flow)}}$ component only.

We may assume that queuing occurs and that a queue is already formed. For this reason, flow in this network can be approximated by optimization algorithms for flow networks ([17], [18]), by assuming fixed values of maximum flows through edges and iterating further calculations over vertices corresponding to consecutively depleted sources.

We stress that in the simple formulation above we make several gross simplifications, for example:

- we do not take into account the effects of fire or smoke,
- we assume that occupants act semi-rationally so as to reach (locally, at each moment) the maximum flow out of the building (in particular, no congestion points are formed at dominating bottlenecks),
- effective widths of corridors are estimated (using the floor plan) by actual corridor widths (i.e., we are ignoring potential obstacles not directly described on the floor plan),

However, all of these simplifications (and various other points) can be addressed within the same framework by extending the basic model.

VI. BIM and indoor navigation models

Afyouni et al. [11] presents a taxonomy of indoor spatial models proposed in the literature. The taxonomy is briefly summarized on Fig. 2. Authors of the paper further stress that hybrid spatial models that combine geometric and symbolic approaches may complement each other in various applications.

Building Information Modeling (BIM) is a general framework of representing, archiving and processing information about buildings in a structured digital format. One specific format which is widely used in practice is Industry Foundation Classes, and particularly IFC2x3 (IFC4 is published as ISO 16739, but IFC2x3 is still prevalent in practice today). Indoor navigation models for buildings represented in IFC were previously studied in e.g. [19], [20], [21]. IFC2x3 models combine the boundary-based geometric representation and an object-oriented (symbolic) model: typical objects in IFC2x3 files are storeys, walls or doors, along with information about their placement.

While IFC2x3 files may contain topological/graph-based representation of a building (described in terms of entities *IfcPath*, *IfcEdge* and other entities of supertype *IfcTopologicalRepresentationItem*), such graph-based representations are usually missing in IFC files exported by CAD tools.

Thus, in order to define the graph required for Flow Model calculations mentioned in the previous section, we transform the input BIM file to a geometric network, a structure that encompasses the geometric part defined in directly BIM and the topology which we infer from geometric representation. The topology is a graph whose vertices correspond to transition points.

From the perspective of evacuation modeling, a classification of the underlying grid or structure of the floor plan is discussed in [1] for various models. Authors discuss a fine network, a coarse network and a continuous network geometry. From the perspective of this ontology, the geometric network on which our model operates is a coarse network.

VII. Geometric Network Calculation

Usually Medial Axis Transform (MAT) or Straight-Medial Axis Transform (S-MAT) [5] is used to define a geometric network. See [6] for a discussion of other algorithms and [9] for an example of an alternative approach of indoor navigation that does not require topology construction. A Medial Axis of a set $F \subseteq V$ is the set of points $M \subseteq V$ that have at least two

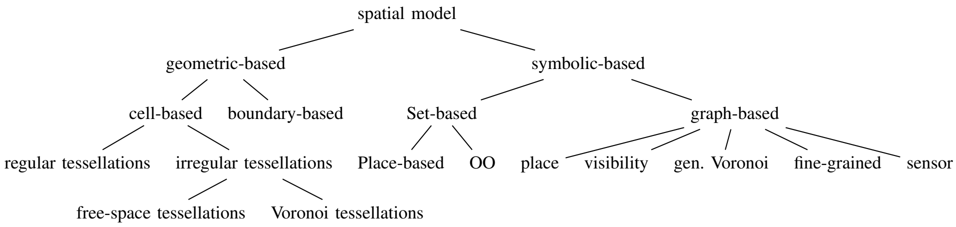

Fig. 2. Taxonomy of indoor spatial models presented by Afyouni et al. [11]

closest neighbours in F (see Fig. 3). If F is finite, Voronoi diagram [22] of F is the Medial Axis of F.

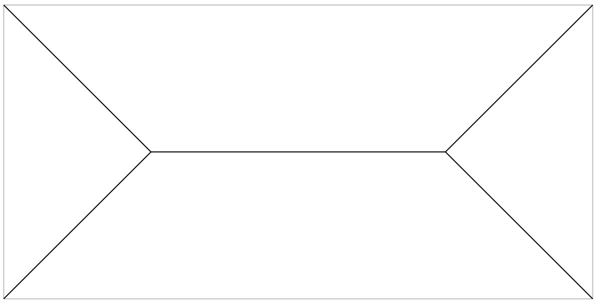

Fig. 3. Medial Axis Transform of the gray rectangle consists of five line segments shown on the picture.

Consider a plan of a floor in a building $F \subset R^2$ (Fig. 4). Instead of calculating MAT of F directly, we approximate F by a finite set of points S (Fig. 5) and calculate the Voronoi diagram of S, which consists of line segments. Denote by (V', E') the graph that consists of subset of line segments from Voronoi triangulation that do not intersect F (see Fig. 7). Edges in graph (V', E') describe permissible paths in our model.

Delaunay triangulation of S is the dual graph of the Voronoi diagram of S (Fig. 6). We utilize this triangulation in two ways: We use it to approximate the minimum width of a path ($e \in E$) by the shortest line segment in Delaunay triangulation that intersects e. Secondly, triangles in Delaunay triangulation are assigned to vertices $v \in V$ and provide a partitioning of the geometric view of the scene.

VIII. Conclusions and Future Work

In this paper we have discussed a framework for evacuation modeling based on building topology extraction from the building. We supplemented the typical graph representation of a floor plan derived from MAT by information obtained from Delaunay triangulation of the point set that approximates a single floor: path widths and areas assigned to vertices.

We have mentioned various areas of future research throughout our paper:

- Design of evacuation models based on different assumptions of occupant localization. Our current research focuses on localization of people within buildings.

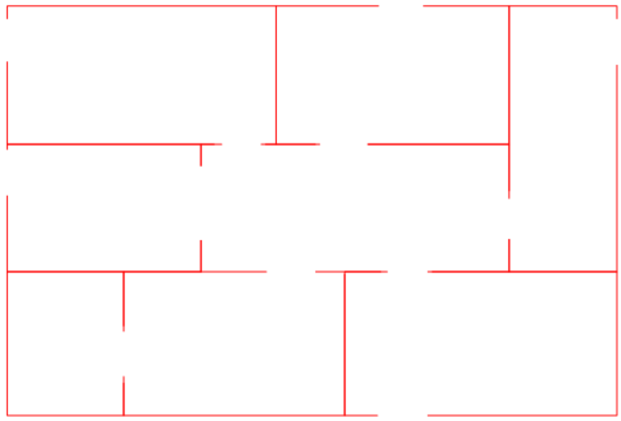

Fig. 4. A 2-dimensional slice of the building that represents a single floor (with doors removed).

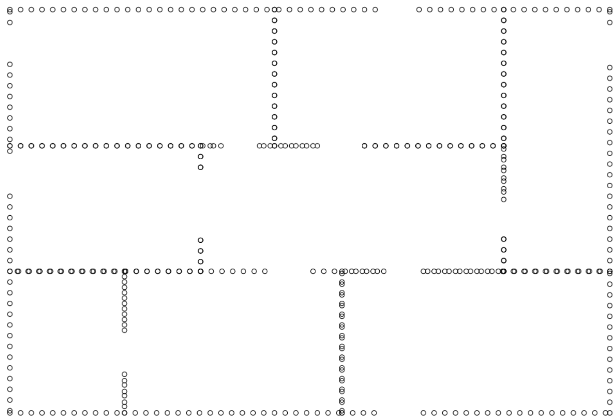

Fig. 5. Approximation of line segments by a set of points.

- More refined models, e.g. taking into account effects of fire or smoke.
- Staircases are often bottlenecks during evacuations, which suggests a more detailed modeling of the effect of different types of staircases and their parameters on movement speeds of crowds.

Other possible areas of future research are:

- Specification of evacuation scenarios in a dialogue with the user (during the ride to fire scene). The dialogue necessarily needs to be very limited, but it could aid

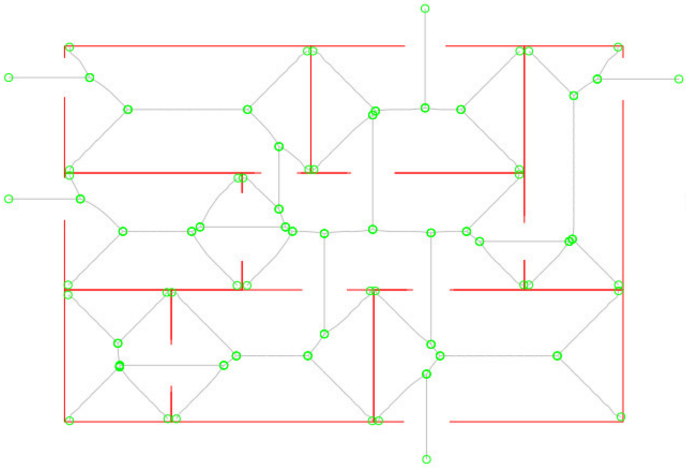

Fig. 8. A graph (V, E) resulting from contraction of edges of degree 2 in graph (V', E').

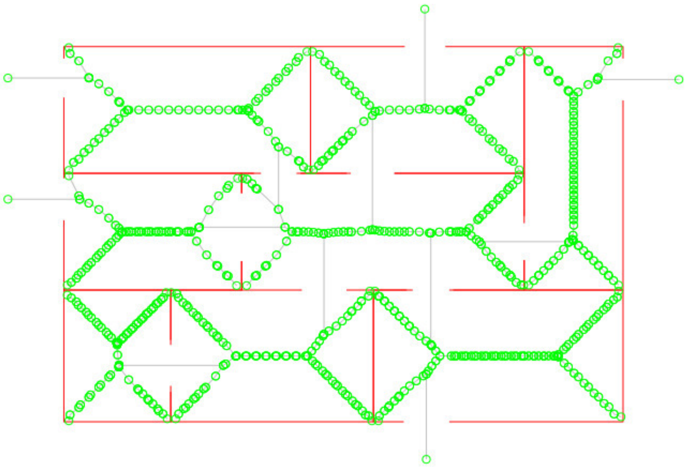

Fig. 7. A subset of line segments from Voronoi tessellation determines permissible paths. This is the initial graph (V', E').

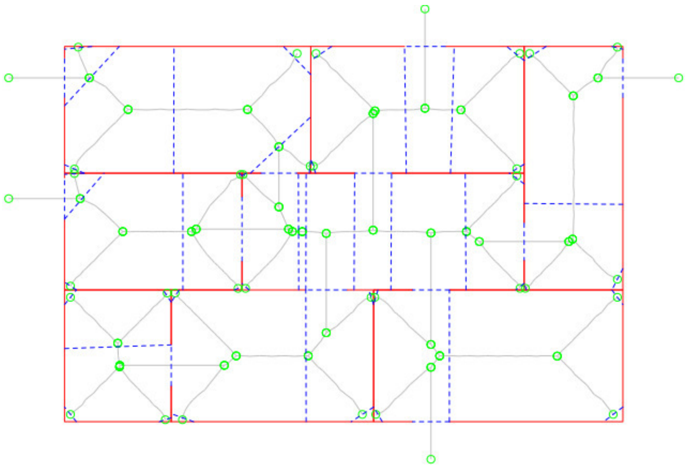

Fig. 9. Selected edges (dashed, blue) from Delaunay triangulation determine widths of paths described by edges in the graph. Delaunay triangulation also provides a mapping of points on the floor plan to corresponding vertices (though some triangles may contain a few vertices $v \in V$). Vertices in corners have very small areas assigned to them and the ratio of width to area size of such vertices is relatively high, thus they are not bottlenecks.

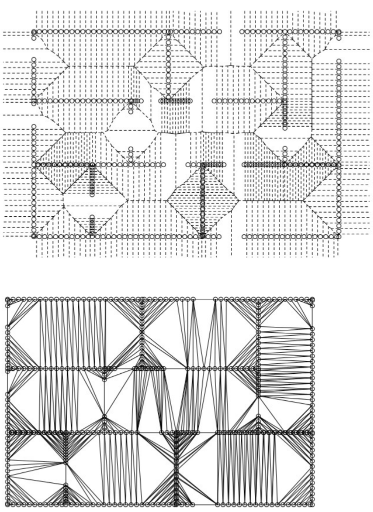

Fig. 6. Voronoi tessellation and Delaunay triangulation of a floor plan approximated by a set of points.

the commander in specifying initial plans of action better than passive information delivery. On rare occasions some hints may be also provided by the operator of Fire Command Center, e.g. unavailability of certain exits.

- We consider performing MAT or S-MAT calculations for floor plans consisting of line segments. In our preliminary experiments we have approximated the floor plan by a set of points so as to utilize the duality of Voronoi tessellation and Delaunay triangulation. The approximation by a discrete set may not be necessary.
- Addressing the problem of counter-flows, i.e. the interaction of fire-fighters getting into the building with the occupants trying to get out of the building.

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