OPTIMAL EMERGENCY EVACUATION GUIDANCE FOR TRANSPORTATION FACILITIES

Chih-Yuan Chu (Assistant Professor, Department of Civil Engineering, National Central University, Taiwan, Email address: jameschu@ncu.edu.tw)

ABSTRACT

The paper proposes a method for designing optimal evacuation guidance systems in complex building spaces. A visibility graph is used to analyze the geometry of the building in a manner consistent with actual human behavior. An algorithm for generating a simplified visibility graph and finding candidate sign locations is designed assuming polygonal obstacles. After a shortest path algorithm is executed on the graph, the optimal evacuation sign installation locations and the associated evacuation direction information can then be found by calculating the best routes from all origins to the exit. The guidance systems designed by the proposed method have three features. First, all pedestrians are covered by the guidance system. Second, after a pedestrian finds the first sign, the evacuation direction information is provided unambiguously without requiring any judgment on the part of the pedestrian. Third, the guidance allows a pedestrian to evacuate to the closest exit via the shortest path. After the optimal guidance system is determined, a cellular automata pedestrian model is used to evaluate the performance of the guidance system and identify the bottlenecks of the current geometry and evacuation guidance design. A by-product of this research is an improved method of calculating static fields in cellular automata simulations. Finally, an example based on a transportation terminal is presented to validate the methodology.

Keywords: cellular automata, emergency sign, evacuation guidance, pedestrian simulation, static field, visibility graph.

INTRODUCTION

The evacuation time of a building is one of the most critical measures of performance in its emergency design. In addition to building geometry, the design of the emergency guidance system is another key component that determines the time required for pedestrians to leave hazardous areas. The laws and regulations related to evacuation guidance, e.g., exit and evacuation direction signs, usually provide only general guidelines due to the great variety of building functions and designs that exist. For example, two types of evacuation guidance exist in the standards for fire safety equipment in Taiwan: exit signs are installed at the exits and evacuation direction signs are located at corridors and stairs. The standards stipulate that the distance between any location in a building and the nearest evacuation guidance must less than a certain value (10–60 m, depending on the building type). The standards also recommend that evacuation guidance be located at intersections in buildings. However, the standards provide no further guidance and thus the evacuation design could be ineffective in practice, particularly in large and complex buildings. Many decisions are crucial to the evacuation time but are not regulated by standards. For instance, nothing requires the evacuation guidance to be directly visible. Thus, there might not be any signs for a pedestrian to follow at some locations when an emergency situation arises. The standards also do not take into account the shortest evacuation routes. When multiple routes are available for pedestrians, these options are usually presented without any indication of which is the best. These issues are likely to increase the evacuation times in emergency situations.

The goal of this research is to develop an approach to designing optimal evacuation guidance systems, the performance of which can be evaluated quantitatively. The “optimal system” in this paper is defined as a system in which each pedestrian is provided the shortest path to the closest exit. Note that minimizing the evacuation time is not feasible because the evacuation time depends on the distribution and number of pedestrians, and a single optimal guidance system for all situations is unlikely to exist. Three components are required to achieve this research goal: a visibility graph, a design tool, and a pedestrian model, all of which are explained in detail in the following sections. Figure 1 illustrates the relationships between the major components of this paper. The visibility graph analyzes the building geometry and provides critical information to the design tool and the simulation model. More specifically, the graph generates the candidate locations for the signs and the shortest paths from these candidate locations to the exit to support the design of the evacuation guidance system. The graph also generates the static field for the cellular automata (CA) pedestrian simulation; this is difficult to calculate for complex geometries. Furthermore, the design tool for evacuation guidance systems and the simulation model are considered together because the performance of the design tool can be evaluated by the simulation model. That is, the design tool provides the evacuation guidance that drives the movement of the pedestrians in the simulation model while the simulation evaluates the performance of the guidance system and determines the bottlenecks in both the design geometry and the evacuation guidance system.

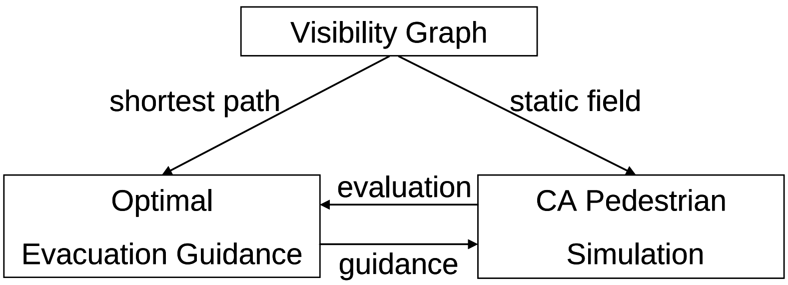

Figure 1 - Relationship between model components

The remainder of the paper is organized as follows. Section 2 describes related work in emergency evacuation guidance, computer simulation of pedestrian movement, path finding, and visibility graphs. Section 3 explains the methodology for designing optimal evacuation guidance systems and Section 4 presents the example of a transportation terminal used to validate the methodology. Finally, Section 5 provides the conclusion and recommendations for future research.

LITERATURE REVIEW

This section discusses previous studies of evacuation guidance, and then summarizes the major types of pedestrian simulation and the methods for path finding in complex geometries. The section also reviews visibility graphs, which are useful for searching for the shortest paths in such geometries.

Evacuation Guidance

Studies of evacuation guidance have focused on the relationship between the design of evacuation signs (e.g., shape, text, pattern, and height) and pedestrians' ability to see them. Tang et al. (2009) studied the impact of evacuation guidance on route selection for pedestrians using virtual reality. One of their findings was that people tended to move toward doors regardless of the doors' purpose; this is a problem if the doors do not provide a way out. Therefore, evacuation guidance that provides clear and correct information is very important. Wong and Lo (2007) conducted experiments to study the effects on sign visibility of sign height, pattern, color, and brightness as well as the age of pedestrians. Jin (2002) considered the visibility of guidance systems under smoky conditions during a fire. Studies have also addressed guidance system design; most of these examined how pedestrian behavior is influenced by the design of guidance systems (Lo et al., 2006; Johnson and Feinberg, 1997; O'Neill, 1991). However, studies of the optimal design of guidance systems are rare. Among the few that do exist, Chen et al. (2009) used the maximum covering approach to determine the optimal locations of exit signs. That study also used CA models, and pedestrians were assumed to be attracted by signs as well as by exits and other pedestrians. Note that by the definition of the maximum covering problem, there is no guarantee that all pedestrians will be covered by a sign, which is one of the key issues of evacuation guidance systems highlighted earlier. Therefore, the research into optimal evacuation guidance is still incomplete and requires further attention.

Computer Simulation of Pedestrian Movement

A complete review of pedestrian simulation can be found in Schadschneider et al. (2008). The most popular computer simulation models for pedestrian movement include agent-based models (Batty et al., 1998; Batty, 2003), social force models (Helbing, 2001; Helbing and Johansson, 2007; Helbing et al., 2000; Helbing et al., 2002), and floor field CA models (Burstedde et al., 2001; Burstedde et al., 2002; Kirchner et al., 2003; Kirchner et al., 2004; Nishinari et al., 2004). In essence, CA models are discrete-time and discrete-space approximations of the actual phenomena. They consist of a *static field* representing the attractiveness of locations and a *dynamic field* recording the trails of the pedestrians. The movement of a pedestrian depends on the static field, the dynamic field, and the availability of the adjacent cells. Chu (2009) proposed a CA implementation with a complexity linearly proportional to the number of pedestrians, while others (i.e., agent-based and social force models) are quadratically proportional to the number of pedestrians.[1] One of the major advantages of the model is its speed. It has been reported in Schadschneider et al. (2008) that the model can be simulated faster than real time for a large-scale crowd.

Impressed by the simplicity and efficiency of CA, Burstedde et al. (2001) reported that they contain all the important features of pedestrian dynamics including jamming, lane formation, oscillations, patterns at intersections, and trail formation. In the cases of emergency evacuation on which this paper focuses, examining the capability of CA to reproduce the behavior in panic situations is more important. A comprehensive discussion of behavior under panic conditions can be found in Helbing et al. (2000). The important characteristics of the pedestrian movement in such situations are summarized in Helbing et al. (2000), including:

1. Herding behavior. People tend to follow each other.
2. Movement speed greater than normal.
3. Uncoordinated passing at bottlenecks.
4. Arc-shaped jamming and clogging at exits.
5. Increased congestion.
6. Pedestrians overlooking closer exits.
7. Fallen or injured people as obstacles.
8. Individuals pushing each other.
9. Physical interactions in the crowd causing dangerous pressure. Extreme high pressure could bend steel bars or collapse walls.

CA models are sufficiently flexible to describe the first six behaviors in the list without difficulty and the majority of them have been implemented in the research mentioned earlier. Of these, the herding behavior is regarded as one of the key features of panic behavior in computer simulation models. For example, the well-known social-force pedestrian models proposed in Helbing et al. (2000) use this herding behavior as an indicator of panic. Under normal conditions, pedestrians move according to their own judgment. However, in a panic situation, pedestrians follow nearby pedestrians and move as a group. This herding is more obvious as the degree of panic increases. This formulation adopted by social force models is consistent with the dynamic field in CA models, which means that CA models are capable of capturing behavior under panic conditions in a way that is widely accepted. However, CA models are discrete space approximations of actual pedestrian behavior and are unable to

[1]In practice, the interactions among pedestrians are limited within a certain range for agent-based and social force models so their actual complexity can be reduced.

model the rest of the panic behaviors in the list, including physical pedestrian–pedestrian and pedestrian–building interaction.[2] Finally, although CA models use a cell structure, they are still capable of capturing differences between pedestrians' size and speed by discretizing the floor on a finer scale to allow pedestrians to move more than one cell per time step and to occupy more than one cell at a time (Kirchner et al., 2004). Therefore, based this discussion, CA models simulate pedestrian behaviors adequately and are highly efficient for the large-scale simulation of human movement in complex environments. Thus, CA models were chosen for this research to evaluate the performance of evacuation guidance systems.

Path Finding for Individuals

Studies have been conducted to understand the path-finding behaviors of individual agents such as pedestrians and insects (Golledge, 1999). Many methods of path finding have been developed to reproduce this behavior for pedestrians (Millington and Funge, 2009) and to plan robot trajectories (de Berg et al., 2008). Note that most of these studies focused on behavior at the individual level and are too computationally demanding for application to large-scale pedestrian evacuations in complex geometries. Therefore, more efficient approaches such as potential field methods have been adopted by many studies for large-scale pedestrian evacuations. The concept of potential field methods is that destinations have higher values of potential while obstacles have the lowest values, and the movement of the pedestrians is driven by this potential field. In the case of emergency evacuation, exits are the destinations, and exits and obstacles are common to all pedestrians. If these common factors affecting pedestrian movement are considered in advance, the remaining efforts at the individual level can be minimized. Marinova et al. (2003) used the potential field method to find paths for pedestrians. The routes from representative locations to the exits were connected through the turning points in a building (e.g., doors, intersections, and stairs) to form a network before the simulation began. After the network was constructed, the pedestrians simply followed the paths during the simulation to reduce the simulation time. Korhonen and Hostikka (2009) considered social-force models in the National Institute of Standards and Technology's FDS-Evac model (McGrattan et al., 2009). That model used a field that emulates the flow of incompressible fluid for path finding. Similarly, to improve obstacle bypassing behavior, Nishinari et al. (2004) proposed a visibility graph approach to calculate the static field in CA and generate a more reasonable path-finding behavior. The contribution of these studies is that reasonable moving behavior can be reproduced very efficiently for large-scale simulation.

These methods have several issues. The first is that they assume that the pedestrians have knowledge of the building space, at least the locations of the exits. This is not true in most emergency situations. In reality, when pedestrians have poor knowledge of the building, they may follow indirect or incorrect routes. The second issue is that due to the complex geometry of the building, the potential field may have traps if it is not calculated carefully and may result in an erroneous and dangerous evacuation design. The third issue is that these

[2]Although falling due to pushing cannot be modeled in CA, it is still possible that people stop moving for some reason and become obstacles to other people. Note that examination of the probability and effect of this behavior requires more research and is not considered here.

methods borrow techniques from other fields such as fluids, robotics, and imaginary potential, which are not realistic for human movement. The final issue is that these approaches only generate a feasible path from one point to another with no guarantee that the paths are optimal.

Visibility Graph and Shortest Path

Finding shortest paths in the presence of obstacles is a classic problem in computational geometry. The following theorem states the property of a shortest path from an origin to a destination in such space.

> **Theorem 1.** The shortest path from one point to another point among a set of disjoint polygonal obstacles is a polygonal path whose vertices (except for the origin and destination) are vertices of the obstacles.

The proof of the theorem can be found in de Berg et al. (2008). This theorem is very intuitive and can be illustrated with the following example. Consider a rope passing through two points with several obstacles between them. By assuming that the rope represents the correct path, the length of the path can be reduced by pulling on the rope from either end. When the rope cannot be pulled any further, the shortest path must be a polygonal line and its vertices are the vertices of the obstacles.

A *visibility graph* is a network whose vertices are the vertices of obstacles and whose arcs connect all vertex pairs that are visible to each other. The rule for determining if two vertices are visible to each other is that a straight arc can be constructed between them without intersecting any obstacles. Based on Theorem 1, a visibility graph always contains the shortest paths from one vertex to another in complex building spaces. To find the shortest path between an origin–destination pair, new arcs are added to connect the origin and the vertices of the network visible to the origin. Similarly, new arcs are appended for the destination. When the graph is constructed, the shortest path between the origin and the destination can be found in the network using a shortest path algorithm such as Dijkstra's. See Ahuja et al. (1993) for examples of shortest path algorithms.

Note that the naive approach to constructing a visibility graph for a single origin–destination pair has $O(E^3)$ complexity, where E is the total number of the edges for all obstacles. This can be computed in quadratic time ($O(E^2)$) using approaches such as those of Welzl (1985); this constitutes the optimal worse-case complexity. When many origins are considered and/or the number of obstacles is large, which is usually the case for emergency evacuation in complex building geometries, the running time could be significant. Therefore, more attention is required to reduce the computational complexity for this study.

METHODOLOGY

The movement of a single pedestrian from one point to another can be simulated in the following two steps, provided that the pedestrians have complete knowledge of the space. The first is to transform the space into a network structure. The second is to determine the route to the destination in the transformed network using a shortest path algorithm. However, the assumption that pedestrians have complete knowledge of the space is rarely valid. A more realistic assumption would be that pedestrians have only incomplete information about the building. Therefore, the objective of the methodology is to design an evacuation guidance system so that when pedestrians follow the guidance, they evacuate as if they have perfect knowledge of the building. This can be achieved by installing evacuation signs at proper locations, each sign with appropriate evacuation direction information. The remainder of this section describes the method for selecting candidate locations for signs, determining their optimal locations, and deciding on the evacuation direction information each sign should display.

Evacuation Sign Locations

From a pedestrian's point of view, the shortest path toward the exit when obstacles are present would be moving either left or right of an obstacle directly ahead. Once the obstacle no longer blocks the pedestrian's line of sight, the pedestrian repeats the same process to bypass the next obstacle until the exit is reached. Therefore, identifying the turning points on the shortest paths is critical so that necessary guidance can be installed at those locations. Essentially, a visibility graph analyzes how an obstacle affects pedestrians' visibility and how a pedestrian would move to bypass the obstacle. This reproduces human behavior better than the other path-finding approaches described earlier. As a result, a visibility graph can be used to determine locations where guidance is required and what evacuation direction information is required at those locations. More importantly, this approach would be the most effective because it guarantees shortest paths, which is not possible using other approaches.

To facilitate the construction of the graph, we assume that obstacles are convex polygons. Note that other obstacle shapes (concave polygons or round objects) can be constituted or approximated using convex polygons. The advantage of considering only convex polygons is that the visibility graphs can be simplified. The term "vertex" is replaced by "corner" from this point forward as we move our discussion from computational geometry to actual buildings. The naive approach to constructing a visibility graph would be to connect any two corners that are directly visible to each other. However, a visibility graph constructed in this way would have many redundant arcs and vertices. We can reduce the number of arcs and vertices by analyzing the relative positions of the obstacle and the pedestrian. As shown in Fig. 2, the pedestrian (circle) is blocked by the obstacle (black rectangle) and cannot see the exit behind the obstacle. Guiding the pedestrian around the obstacle first requires guiding the pedestrian to corner d, or to corner b then a. Therefore, we install signs at corners a and b or d. On the other hand, installing a sign at corner c would be of no help in bypassing the obstacle. Intuitively, corner c is not a candidate sign location for the pedestrian because a shorter path via corner d can be found to bypass the obstacle. Corners e and f are not considered at all because they are not visible to the pedestrian. As a result, the arcs connecting the pedestrian and corners c, e, and f should not be included in the graph.

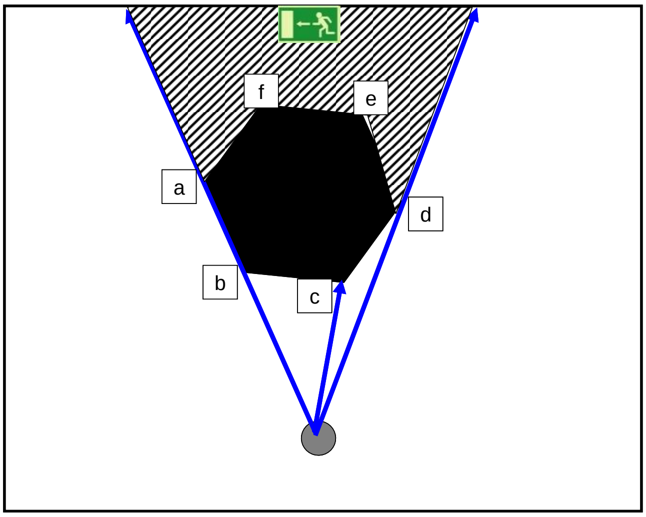

Figure 2 - Illustration of candidate sign locations

To generalize the above observation, we categorize the corners of an obstacle into three groups with respect to the observation point, which could be a corner or the location of a pedestrian. We consider the situation where the exit is invisible from the observation point. The *side corners* (a , b , and d in this example) of the obstacle are the rightmost and leftmost corners with respect to the observation point. A feature of these corners is that they might be able to see the exit directly due to their locations relative to the observation point. The *middle corners* (e.g., c) are the corners visible from the observation point that are between the side corners. The *invisible corners* (e.g., e and f) are the corners that are invisible to the pedestrian. Because the shortest path must be on the vertices of the obstacle, the first section of the shortest path must connect the observation point and a corner. The invisible corners are excluded because connecting to a corner that is not visible is impossible. Next, we consider the middle corners. When the path extends from the observation point to a middle corner, it can never be extended to the exit directly and will have to extend further to a second corner. It follows that we can reduce the length of the path by connecting the observation point to this second corner directly instead of via the middle point because the total length of two edges of a triangle is always greater than the length of the third edge. Therefore, only the side corners should be considered as candidate locations for signs. If a corner is not the candidate location, it can be excluded from the visibility graph and the graph can be simplified. An algorithm to construct the visibility graph can be found in Chu (2010). Figure 3 shows an example of a visibility graph. The black rectangles are the obstacles and the small squares are the candidate sign locations. The solid gray lines constitute the visibility graph and the green exit sign is the destination. The arcs are bidirectional except for arcs $\{e,b\}$ and $\{g,d\}$. That is, corner b could be a candidate for sign installation from the location of corner e; however, e is not a candidate from the position of corner b because e is not on the shortest path from b to the exit or any other corner. The explanation for corners d and g is the same.

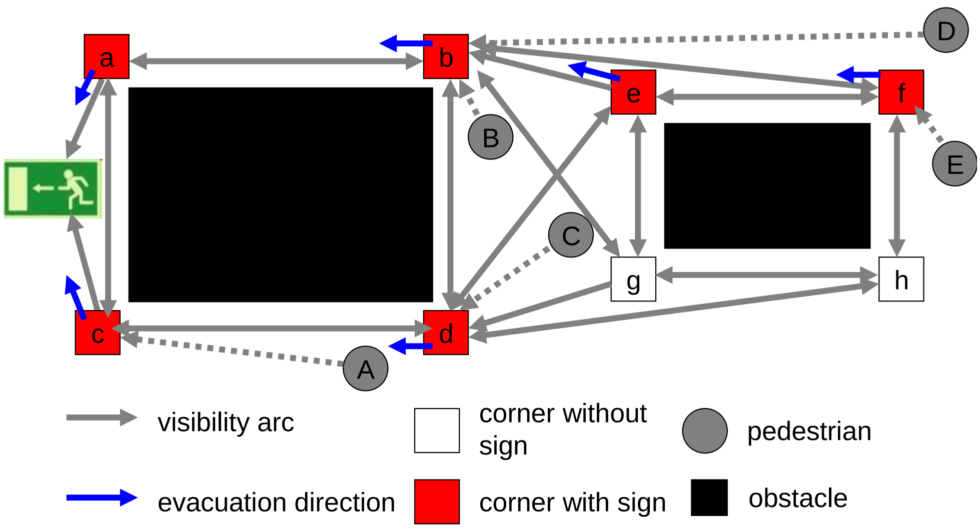

Figure 3 - Visibility graph and sign installation

Best Evacuation Guidance

After the visibility graph is constructed, the next task is to find the shortest paths from all corners to the exit and the corresponding sign installation locations, which should be done with a many-to-one shortest path algorithm. Note that the visibility is bidirectional; therefore, if one corner can be seen by another, the opposite is also true, and the distances for both directions would be identical. As a result, instead of running a many-to-one shortest path algorithm to find the shortest paths from all corners to the exit, a one-to-many shortest path algorithm is sufficient to find the shortest paths from the exit to all corners. The only required change is inverting the unidirectional arcs in the graph before running the shortest path algorithm and reversing the result of the shortest paths afterward. The shortest path from a corner to the exit can be easily traced.

Although signs could be installed at all vertices in the graph, only some of them would be useful for guiding pedestrians. We find the "best" corner for a pedestrian standing at a cell. The "best" corner and all the predecessor corners are marked until we reach the exit. The procedure is repeated for the complete building space (in the case of CA, all cells). After all cells are calculated, we remove all the corners that were never marked and their associated arcs. Finally, we install signs at all the remaining corners. To simplify the presentation, we assume that the range of visibility of a sign is unlimited. This assumption can easily be relaxed by adding relay signs between two distant signs. An algorithm that determines which corners require sign installation can be found in Chu (2010).

Finding the Best Sign Location

In the algorithm above, a "best" corner must be selected for the cell under consideration. It seems reasonable that pedestrians would select the signs closest to them. However, this criterion does not generate the shortest route to the exit. For example, in Fig. 3, if pedestrians B and E start the evacuation by following the signs closest to them (b and f, respectively), they end up following paths $b-a-exit$ and $f-b-a-exit$, respectively. On the other hand, pedestrians A, C, and D should not follow the signs that are closest to them. Instead, they should follow signs c, d, and b initially and evacuate via $c-exit$, $d-c-exit$, and $b-a-exit$ for their shortest paths. Thus, the correct criterion for selecting the "best" corner for a sign is to find the corner such that the distance from the corner to the exit plus the distance between the cell and the corner the smallest. In the figure, these "best" corners selected for installing signs are colored red and their evacuation direction information is represented by the short blue arrows. In practice, this criterion does not cause too much confusion when there is only one exit because all the visible signs for a pedestrian should be pointing in the same direction and the pedestrian can determine the correct direction to move. For example, it should be evident for pedestrian D that b is the sign to follow because signs b, e, and f are all pointing to the left and, moreover, e and f both point to b. The remaining problem is how to ensure that pedestrians follow the "best" signs, which may not be as obvious as the closest ones to them. Additional information can be provided by measures such as text, color, and special signs visible only from a certain position. The appropriate equipment and technology to achieve this will be the subject of future research.

Multiple Exits

So far, the search for the shortest path has been focused on a single exit. The methodology developed above can be easily extended to the case of multiple exits. The first situation we might encounter is that different groups are moving toward different destinations, e.g., firefighters and evacuees. In this case, each group uses the visibility graph corresponding to its destination and different guidance systems are calculated and provided to each group. Another possible situation is where multiple exits are available for a single group of pedestrians. In this case, pedestrians consider each exit separately and choose the shortest path to the exit that takes the least evacuation time. The approach is illustrated in Fig. 4. When the exit onthe left is available as the top of the figure shows, the signs are installed at a, b, c, and d. Pedestrian B takes route $b-a-exit$ and pedestrian C takes route $d-c-exit$. In the middle of the figure, the signs are installed at e, f, g, and h. Pedestrian B takes route $e-f-exit$ and pedestrian C takes route $g-h-exit$ for the exit on the right. When both exits are available as shown at the bottom of the figure, the pedestrians compare their best routes corresponding to each exit and pick the best one. That is, because pedestrian B is closer to the left exit, pedestrian B should take route $b-a-exit$ and signs are installed at a and b. Signs are also installed at g and h for pedestrian C.

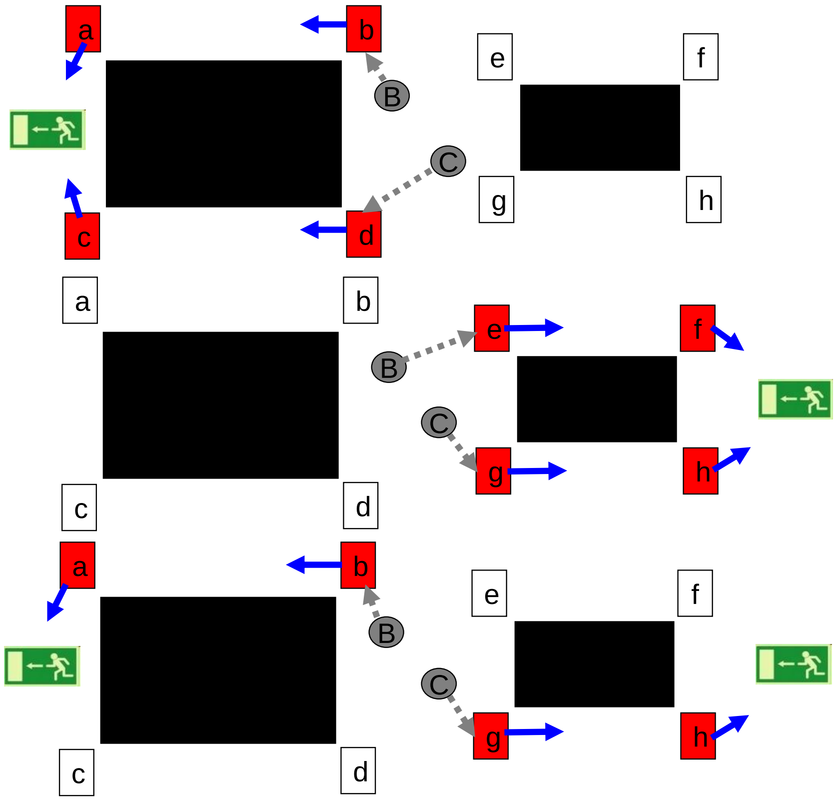

Figure 4 - Illustration of sign locations for multiple exits

NUMERICAL EXAMPLE

We used floor B1 of the Taipei Train Station, the largest transportation terminal in Taiwan, as an example to demonstrate the proposed methodology. Figure 5 shows the layout of floor B1 with a length of approximately 197 m and a width of 143 m. The floor provides space for ticket checking and passenger waiting areas. The north part is reserved for conventional rail and the south part is dedicated to high-speed rail. The four stairways connecting to the ground floor above serve as the exits in this example and are marked with exit signs. Other stairways connect to floor B2 below; however, because pedestrians would try to move upward during an evacuation, these stairways are not considered in this example. All the areas in the figure that constitute obstacles to pedestrians are black; these include walls, columns, and ticket gates. The geometry of the obstacles was extracted from standard CAD drawings that were used in the design and construction of the station. The use of CAD drawings to delineate the obstacles is beneficial because the result is highly accurate and can be produced quickly.

As shown in the figure, the design of the floor is rather complex. The floor is separated into several areas by ticket gates, which are indicated by red circles. The required separations between the office areas and the passenger areas as well as between conventional railway and high-speed railway further increase the complexity of the building geometry. Thus, evacuation without proper guidance would be difficult for pedestrians. As an example, the shortest evacuation path for pedestrian A is represented by the dashed blue line. A pedestrian must make many decisions just to evacuate the building without getting lost. It is unlikely that a pedestrian would take the shortest path without perfect knowledge of the floor or the appropriate guidance proposed in this research.

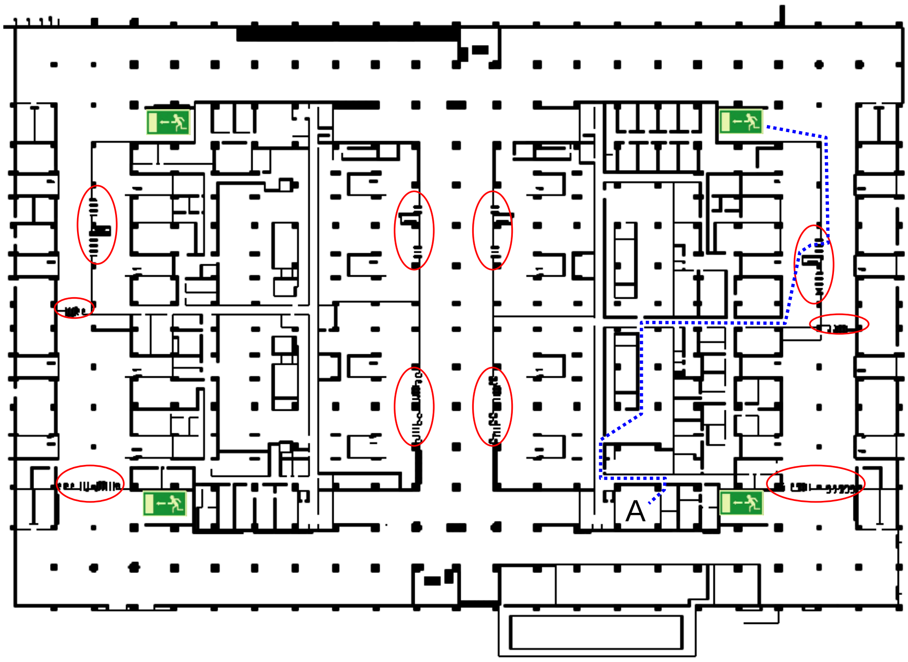

Figure 5 - Map of floor B1 in the Taipei Train Station

Optimal Evacuation Guidance

Figure 6 shows the optimal sign locations and the corresponding evacuation direction information determined using the proposed method. The black blocks are obstacles and the red dots are the signs. The total number of signs installed is 1216; that is, each sign covers approximately 23 m^2 of floor area. Note that a sign installed directly on an obstacle is less visible and also that pedestrians occupy space. As a result, the signs are installed within a certain distance from the corner of the obstacle instead of on the obstacle itself. The blue lines indicate the evacuation paths by connecting the corresponding signs. In this design, any location in the floor has at least one visible sign and pedestrians following the guidance always reach the exit(s) via the shortest paths.

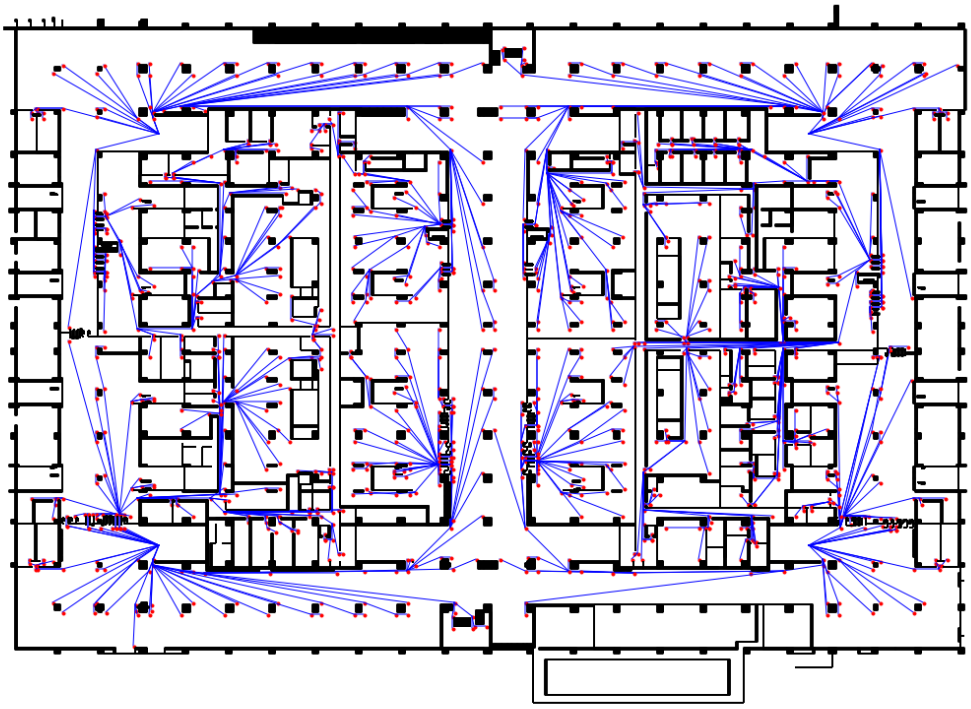

Figure 6 - Locations of optimal sign locations and evacuation paths

Next, we generate the static field that corresponds to the evacuation guidance system to evaluate its performance with CA simulation. One of the simplest forms of the static field in CA is the negative value of the Euclidean distance between the exit and the location under consideration; the static field of the exit is zero and the value decreases as the distance to the exit increases. This also means that the attraction of the exit to the pedestrian is the highest and the attraction is low when the location is far from the exit. This type of field works well in a simple geometry with no traps. Making walls and obstacles unattractive can further improve the models to reproduce more reasonable human behavior (Helbing et al., 2000; Nishinari et al., 2004). However pedestrians would easily be trapped in a complex geometry using this type of field. For example, if the Euclidean distance is used, the static field of the floor would be as shown in Fig. 7, where white indicates high attraction and black means no attraction. Each contour line represents 10 m in the figure. As expected, the static field value is the highest at the exits and decreases outwards. As a result, pedestrians move perpendicularly to the contours toward the center of the circles in the simulation. A pedestrian encountering an obstacle moves along the obstacle attempting to bypass it. However, pedestrians would easily become stuck in traps due to the complex geometry.

Figure 8 shows the static field corresponding to the optimal sign design. It is calculated by assuming that pedestrians select the "best" sign and follow the instructions to evacuate. The difference between the static field calculated with the simple method (Fig. 7) and the one based on the optimal guidance (Fig. 8) is significant. When a pedestrian attempts to move toward the exits, the static field based on the optimal guidance leads the pedestrian around obstacles and toward the exit via the shortest path. Therefore, this static field can be used to evaluate the performance of the optimal design quantitatively.

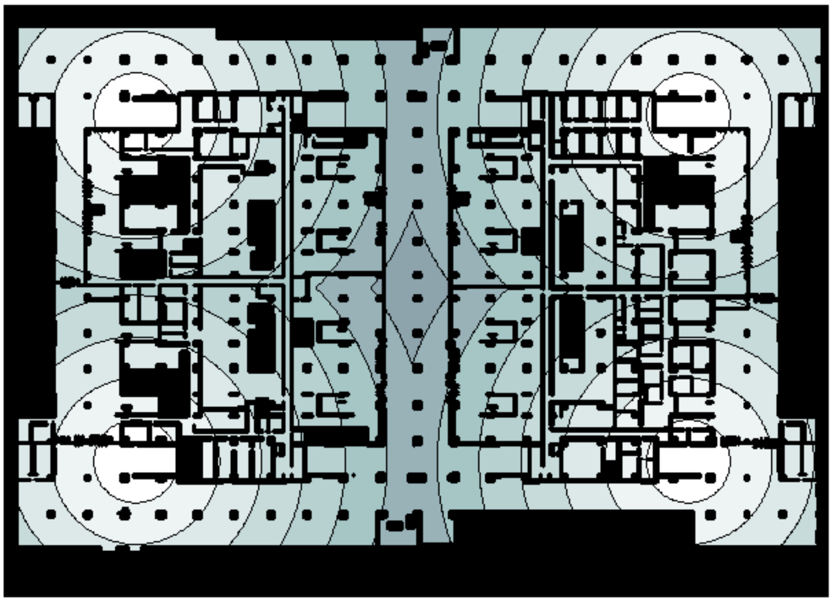

Figure 7 - Static field using Euclidean distance

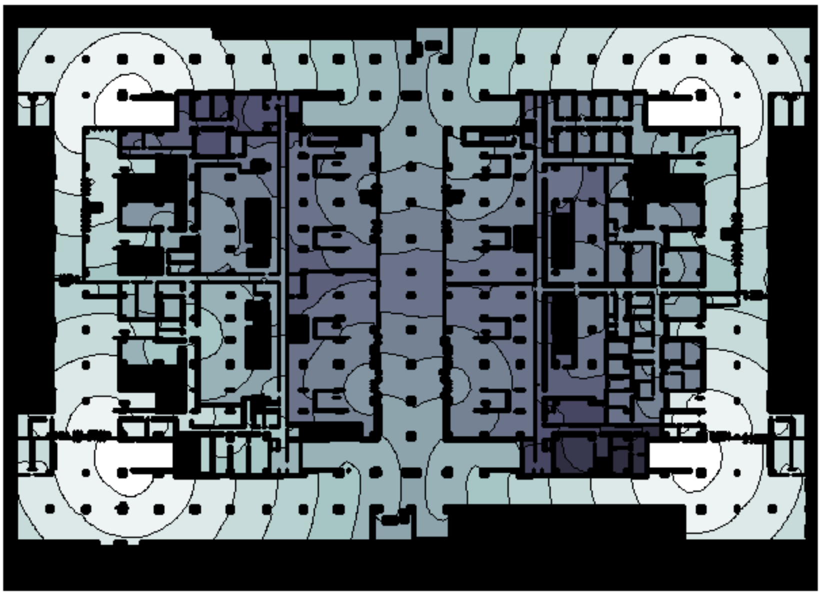

Figure 8 - Static field based on the optimal evacuation guidance design

CONCLUSION

This paper has examined the design of the optimal evacuation guidance system in complex building spaces. The guidance systems designed with the proposed methodology have the following properties. First, at least one sign is visible from any point in the building; that is, all pedestrians are covered by the system. Second, each sign indicates the direction to the next sign via the shortest path to an exit. Most importantly, the system guides pedestrians to their closest exits via the shortest paths.

A by-product of this research is a new method of calculating static fields for CA models. The static field simulates the movement of pedestrians with perfect knowledge of the geometry or pedestrians following the optimal evacuation guidance. As a result, the performance of the optimal design can be quantitatively evaluated with a CA model. Note that we cannot yet analyze the improvement achieved by adopting the optimal design because methods for evaluating the performance of the existing design are still immature. Although theories have been developed for path finding with partial knowledge of space or imperfect guidance (Golledge, 1999), adequate computer models that reproduce this behavior for large-scale evacuations in complex geometries are still unavailable. Thus, incorporating path finding given incomplete information in the simulation will be a topic for future study to estimate the benefit of implementing optimal evacuation guidance systems.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of Taiwan through research grant NSC 98-2221-E-008-078.

REFERENCES

Ahuja, R. K., Magnanti, T. L., and Orlin, J. B. (1993). Network Flow: Theory, Algorithms, and Applications. Prentice-Hall, Inc.

Batty, M. (2003). Agent-based pedestrian modeling. Advanced spatial analysis, P. A. Longley and M. Batty, eds., ESRI Press, Redlands, CA, USA, chapter 5, 81–106.

Batty, M., Jiang, B., and Thurstain-Goodwin, M. (1998). Local movement: Agent-based models of pedestrian flows. Centre for Advanced Spatial Analysis Working Paper Series 4, 1–62.

Burstedde, C., Kirchner, A., Klauck, K., Schadschneider, A., and Zittartz, J. (2002). Cellular automaton approach to pedestrian dynamics-applications. Pedestrian and Evacuation Dynamics, M. Schreckenberg and S. D. Sharma, eds., Springer, Berlin, Germany, 87–97.

Burstedde, C., Klauck, K., Schadschneider, A., and Zittartz, J. (2001). Simulation of pedestrian dynamics using two-dimensional cellular automation. Physica A, 295, 507–525.

Chen, C., Li, Q., Kaneko, S., Chen, J., and Cui, X. (2009). Location optimization algorithm for emergency signs in public facilities and its application to a single-floor supermarket. Fire Safety Journal, 44(1), 113–120.

Chu, C.-Y. (2009). A computer model for selecting facility evacuation design using cellular automata. Computer-Aided Civil and Infrastructure Engineering, 24(8), 608–622.

Chu, C.-Y. (2010). Optimal Emergency Evacuation Guidance Design for Complex Building Geometries. under review.

de Berg, M., Cheong, O., van Kreveld, M., and Overmars, M. (2008). Computational Geometry: Algorithms and Applications. Springer-Verlag, New York, NY, USA, 3 edition.

Golledge, R. (1999). Wayfinding behavior: Cognitive mapping and other spatial processes. Johns Hopkins University Press.

Helbing, D. (2001). Traffic and related self-driven many-particle systems. Reviews of Modern Physics, 73(4), 1067–1141.

Helbing, D., Farkas, I., Molnar, P., and Vicsek, T. (2002). Simulation of pedestrian crowds in normal and evacuation situations. Pedestrian and evacuation dynamics, M. Schreckenberg and S. Sharma, eds., Springer, Berlin, 21–58.

Helbing, D., Farkas, I., and Vicsek, T. (2000). Simulating dynamical features of escape panic. Nature, 407, 487–490.

Helbing, D. and Johansson, A. (2007). Dynamics of crowd disasers: An empirical study. Physical Review E, 75, 046109–1–046109–7.

Jin, T. (2002). Visibility and human behavior in fire smoke. SFPE Handbook of Fire Protection Engineering (P. J. DiNenno, ed.), National Fire Protection Association, Quincy, MA, USA, 3 edition, chapter 2-4, 2–42–2–53.

Johnson, N. and Feinberg, W. (1997). The impact of exit instructions and number of exits in fire emergencies: A computer simulation investigation. Journal of Environmental Psychology, 17(2), 123–133.

Kirchner, A., Kluepfel, H., Nishinari, K., Schadschneider, A., and Schreckenberg, M. (2004). Discretisation effects and the influence of walking speed in cellular automata models for pedestrian dynamics. Journal of Statistical Mechanics: Theory and Experiment, 2004(10), 1–21.

Kirchner, A., Nishinari, K., and Schadschneider, A. (2003). Friction effects and clogging in a cellular automation model for pedestrian dynamics. Physical Review E, 67, 056122–1–056122–10.

Korhonen, T. and Hostikka, S. (2009). Fire Dynamics Simulator with Evacuation: FDS+Evac, Technical Reference and User's Guide. VTT Technical Research Centre of Finland, Finland.

Lo, S., Huang, H., Wang, P., and Yuen, K. (2006). A game theory based exit selection model for evacuation. Fire Safety Journal, 41(5), 364–369.

Marinova, R., Ourdev, I., Stoilov, V., Brinkworth, L., and Gu, J. (2003). Pedestrian motion in realistic virtual reality environments: Application to high-rise building evacuation. Pedestrian and Evacuation Dynamics 2003, 283–293.

McGrattan, K., Hostikka, S., and Floyd, J. (2009). Fire Dynamics Simulator (Version 5), User's Guide. National Institute of Standards and Technology,Gaithersburg, MD, USA.

Millington, I. and Funge, J. (2009). Artificial Intelligence for Games. Morgan Kaufmann Publishers, Burlington, MA, USA, 2 edition.

Nishinari, K., Kirchner, A., Namazi, A., and Schadschneider, A. (2004). Extended floor field CA model for evacuation dynamics. IEICE Transactions on Information and Systems, E87-D(3), 726–732.

O'Neill, M. (1991). Effects of signage and floor plan configuration on wayfinding accuracy. Environment and Behavior, 23(5), 553–574.

Rohnert, H. (1986). Shortest paths in the plane with convex polygonal obstacles. Information Processing Letters, 23(2), 71–76.

Schadschneider, A., Klingsch, W., Klupfel, H., Kretz, T., Rogsch, C., and Seyfried, A. (2008). Evacuation dynamics: Empirical results, modeling and applications. Encyclopedia of Complexity and System Science (B. Meyers, ed.), Springer, Berlin, Germany.

Tang, C., Wu, W., and Lin, C. (2009). Using virtual reality to determine how emergency signs facilitate way-finding. Applied Ergonomics, 40(4), 722–730.

Welzl, E. (1985). Constructing the visibility graph for n-line segments in $O(n^2)$ time. Information Processing Letters, 20(4), 167–171.

Wong, L. T. and Lo, K. C. (2007). Experimental study on visibility of exit signs in buildings. Building and Environment, 42(4), 1836–1842.