

Automatic Optimization of Wayfinding Design

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Abstract—Wayfinding signs play an important role in guiding users to navigate in a virtual environment and in helping pedestrians to find their ways in a real-world architectural site. Conventionally, the wayfinding design of a virtual environment is created manually, so as the wayfinding design of a real-world architectural site. The many possible navigation scenarios, as well as the interplay between signs and human navigation, can make the manual design process overwhelming and non-trivial. As a result, creating a wayfinding design for a typical layout can take months to several years. In this paper, we introduce the Way to Go! approach for automatically generating a wayfinding design for a given layout. The designer simply has to specify some navigation scenarios; our approach will automatically generate an optimized wayfinding design with signs properly placed considering human agents' visibility and possibility of making mistakes during a navigation. We demonstrate the effectiveness of our approach in generating wayfinding designs for different layouts such as a train station, a downtown and a canyon. We evaluate our results by comparing different wayfinding designs and show that our optimized wayfinding design can guide pedestrians to their destinations effectively and efficiently. Our approach can also help the designer visualize the accessibility of a destination from different locations, and correct any “blind zone” with additional signs.

Index Terms—wayfinding, navigation, procedural modeling, level design, spatial orientation

1 INTRODUCTION

IMAGINE walking in a subway station with no wayfinding signs. How could you walk to the right platform after you buy your ticket? After some random trials, you might finally find your way to the platform, but this probably would not be a pleasant experience. You would have saved much time and energy if wayfinding signs had been placed properly in the environment to guide you through. A layout with no wayfinding signs is as confusing as a maze.

In “The VR Book” [1], Jerald points out that wayfinding aids are especially important in virtual environments because it is very easy to get disoriented throughout a navigation in a virtual space. A well-constructed environment should include environmental wayfinding aids thoughtfully put by the level designers, considering the possible navigation and the navigation goals of the user. Recently, interesting experiments by Darken and Peterson [2] verify that most users would feel rather uncomfortable being in a largely void virtual environment, and that it is important to regularly reassure the users that they are not lost throughout a navigation.

Conventionally, level designers mainly rely on experience or a “common sense approach” [3] in creating a wayfinding design. Given an environment, they think of all likely navigation scenarios that the user will go through and then place wayfinding signs or other aids to guide the user accordingly. For example, for a train station, one common scenario is to walk from the ticket machine, through the gate, and then to the right platform. Another common scenario is to walk from the platform to the exit. Directional signs are then placed along the routes. While this design approach is straightforward, the efforts required will quickly become daunting when the number of scenarios scales up as in a real-world situation. For example, a real-world train station typically involves tens or more navigation scenarios. Moreover, when placing the signs, it is necessary to consider the user's visibility and the fact that the user may miss a sign or make mistakes throughout the navigation. Designing a

wayfinding scheme that jointly considers all these factors is highly non-trivial and challenging, while a sub-optimal wayfinding scheme may easily result in a confusing and frustrating navigation experience of the users.

To tackle these problems, in this work we introduce a novel computational approach to automatically generate a wayfinding design for a given environment. To use our approach, the designer simply specifies all the navigation scenarios likely to be taken by the users. Our approach will then generate a wayfinding design to accommodate the needs of all the scenarios while considering a number of desirable factors relevant to the navigation experience and management convenience. Through agent-based simulations, our approach further refines the locations of the wayfinding signs by considering visibility and robustness with respect to the possible mistakes made by the users throughout their navigation. After generating a wayfinding design, the designer can gain further insights of the design by visualizing the accessibility of a destination from any other locations in the environment, and remove any blind zones (if necessary) by adding more signs and re-triggering the optimization.

In a real-world architectural site, typical wayfinding aids include signs, landmarks and GPS-based mobile navigation system. In a virtual environment, additional virtual wayfinding aids such as compasses [1] and mini-maps [4] can also be used to facilitate wayfinding. In this work, we focus on generating signs to guide the user because: 1) signs are a very common and universal mean for wayfinding; 2) signs as wayfinding aids are direct yet subtle—the user usually does not need to stop walking while reassuring his direction with a sign he sees on his way, in contrast to using other wayfinding aids such as a map which requires the user to stop his locomotion; 3) signs integrate naturally with most indoor and outdoor environments.

The major contributions of our work include:

- introducing a novel optimization and agent-based approach for automatically generating wayfinding designs.
- demonstrating the capability of our approach for generating wayfinding designs for different layouts.
- showing how our approach can be further applied for

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visualizing and editing a generated wayfinding design.

- evaluating the effectiveness of our automatically generated wayfinding designs in guiding the navigation of users by comparing with other wayfinding designs.

Additionally, we implement our approach as a handy plugin of the Unity game engine, which can be used by game level designers to automatically and quickly generate wayfinding schemes for their virtual worlds, hence saving their time and manual efforts spent on determining users' paths and placing wayfinding signs. We will release the plugin for public use.

2 RELATED WORK

To the best of our knowledge, there is no existing work on automatically generating wayfinding designs for a given layout. We review some relevant work in wayfinding design for real-world and virtual environments. We also review some work in sign perception, navigation and path planning which bring useful insights about the human factors to consider in a wayfinding design.

2.1 Conventional Wayfinding Design

We give a succinct overview of the real-world wayfinding design process, which inspires our computational approach for generating wayfinding design.

In architectural design, wayfinding refers to the user experience of orientation and choosing paths within a built environment, which usually relates to the user's needs or the attractiveness of the places and streets in the environment [5], [6]. In the book *The Image of the City* [7], Lynch defined wayfinding as the "consistent use and organization of definite sensory cues from the external environment". Environmental psychologists later extended the definition of wayfinding to include also the use of signage and other graphical and visual clues that aid orientation and navigation in built environments [8].

The process of wayfinding—how humans walk to their destinations in an unfamiliar environment—involves four major steps [9]: *orientation*, *path decision*, *path monitoring* and *destination recognition*. *Orientation* refers to determining one's current location. *Path decision* refers to selecting paths to navigate to the destination. *Path monitoring* refers to continuously verifying that the path indeed leads to the destination. Finally, *destination recognition* refers to confirming that the destination has been reached. Our goal in this work is to automatically generate a wayfinding design for a given environment to facilitate the above wayfinding steps.

Today almost all public spaces and private premises require a wayfinding scheme [10] to ensure that they are universally accessible for all users [11]. To achieve this goal, after a layout is designed by architects, a wayfinding design team [12] will decide about the wayfinding signs to put in the environment. In current practice, the design team manually creates a wayfinding scheme following a "Common Sense Approach" mainly based on experience [3], [13]. Given a new premises such as a train station, designers create a wayfinding scheme following these major steps:

- 1) *Identifying Major Paths*: The design team first identifies the major paths likely to be taken by pedestrians, by experience or surveys with the property managers. The team examines the site's floor plan or make an on-site inspection to estimate people flows [12]. The goal is to gain a comprehensive understanding of the site.
- 2) *Devising a Wayfinding Scheme*: Considering all the major paths, the design team determines the types

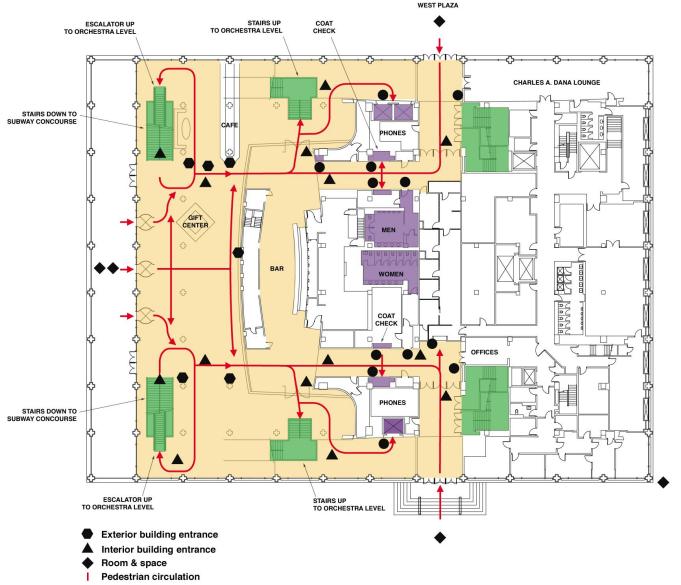


Fig. 1: Circulation analysis and wayfinding scheme of a concert hall manually created by a wayfinding designer, including projected circulation paths and sign types. Courtesy of ArchitectureWeek.

and locations of the wayfinding signs, which should be placed at an appropriate height and angle clearly visible to pedestrians. Additional signs should be placed to eliminate any possible confusion caused by the architecture itself. As an example, Figure 1 shows the circulation analysis and a wayfinding scheme manually created for a concert hall.

- 3) *Designing, Fabricating and Placing Signs*: After devising the sign placement, the designers design the appearance of the signs to be manufactured and placed in the real environment.

- 4) *Evaluation, Maintenance and Update*: The team maintains the wayfinding signs in a database and reviews the sign placement periodically to replace any outdated signs.

Interested readers may refer to the literature [10], [12], [14] for more detail of the design process. Similar to the real-world wayfinding design process, our computational approach focuses on automatically identifying locations for placing signs in an environment according to the designer-specified navigation goals of the pedestrians.

2.2 Wayfinding Design for Virtual Environments

Wayfinding aids are crucial in virtual environments because they help users form cognitive maps, maintain a sense of position and direction of travel, and find their ways to their destinations [1]. Common wayfinding aids in virtual environments include signs, maps, landmarks, light, and paths [1], [15]. In designing a highly immersive and steerable virtual environment, it is important for level designers to make use of wayfinding aids effectively to enhance spatial understanding of the environment so that users can comprehend and operate smoothly [1], [16]. This principle also applies to game level design. In his book, game designer Michael Salmond emphasizes the use of a road sign system in games as an important wayfinding tool to provide players with a highly immersive navigation experience [17]. Figure 2 shows some example road signs used in the popular video games Fallout 4 and the Elder Scrolls IV: Oblivion.

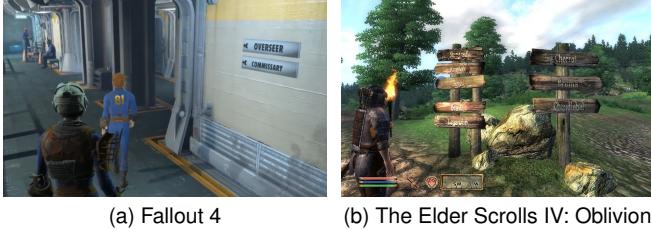


Fig. 2: Example road signs used in video games.

In current practice, wayfinding aids are manually added to a virtual environment by level designers and then empirically tested for effectiveness, which depends on the quantity and quality of wayfinding aids provided to users, yet research found that it could be overwhelming to users if exposed to too many wayfinding aids [18].

Darken and Sibert conducted an important study [19] about the wayfinding strategies and behaviors of human users in large virtual worlds. Their experiments verified that human wayfinding strategies and behaviors in large virtual worlds are strongly influenced by environmental cues. Their experiments asserted that *humans generally adopt physical world wayfinding strategies in large virtual worlds, hence common wayfinding aids in the physical world can be effectively applied to facilitate wayfinding in virtual worlds*. Based on the insights, Cliburn and Rilea [20] conducted a further study to compare human performance in searching for an object in a virtual environment with no aid present, with maps and with signs. The results show that subjects who navigated the virtual environment with the aid of signs achieve superior performance than under other conditions. These findings motivate us to investigate the automatic propagation of directional signs in virtual environments to enhance wayfinding.

Wayfinding Map Generation. In computer graphics, there are interesting approaches for automatically generating tourist brochures [21] and destination maps [22]. Though these maps are intended for real-world navigation use, they could potentially be used to assist navigation in virtual environments. Given a map and some desired destinations, these approaches select a subset of roads to reach the destinations, and visualize the important routing instructions on a generated map which is intuitive to use. Our approach is inspired by these approaches, but focuses on optimizing the placement of wayfinding signs in the layout so as to guide pedestrians to reach their destinations easily. Combining automatically generated maps with the wayfinding signs generated by our approach can potentially provide users with effective wayfinding aids to navigate smoothly in virtual environments.

2.3 Perception, Path Planning and Navigation

Our wayfinding design approach is also inspired by how humans perceive and navigate in everyday environments.

Perception. In everyday environments, humans continually shift their gaze to retrieve wayfinding cues for making navigation decisions [23], [24], [25]. Human visual attention is known to be attracted by low-level features such as changes in color, intensity, orientation and contrast [26], and by high-level scene context [25]. Some particular categories of objects, such as signs and texts [27], [28], [29], are known to strongly attract eye fixations regardless of their low-level visual saliency. Therefore, we focus on optimizing the placement of wayfinding signs in our approach.

Path Planning and Navigation. Given a layout, there are usually multiple paths a pedestrian can take to navigate

from a starting point to a destination. For instance, suppose a hiker wants to walk from the bottom to the top of a hill. He may walk a path which is mostly straight, or a shortcut with sharp turns. A common strategy for path planning is to design a cost function to evaluate each path, and then search for a path that corresponds to a low cost [30], [31], [32], [33]. For a low-dimensional configuration space, a grid-based search such as A* [34] or D* [35] can be applied to find an optimal path. For a high-dimensional configuration space, sampling-based approaches [36], [37] are commonly applied to find an optimal or near-optimal solution.

For path planning, common navigation factors to consider in the cost function involve: 1) path length (one wants to choose a short path to reduce the travel time needed to reach the destination); 2) number of turns (one wants to minimize the number of turns to reduce the complexity of the route [22], [38]); 3) number of decision points (each intersection is a decision point where the pedestrian will need to decide which road to follow next; one wants to minimize the number of decision points to reduce the chance of making mistakes). Arthur and Passini [39] noted that the number of decision points has an important influence on the difficulty of performing wayfinding. Casakin et al. conducted empirical studies [40] which further verify these observations. We consider these criteria in the generation of our wayfinding designs, after which we will place the wayfinding signs and refine the placement based on agent's properties. Moreover, the designer can control the importance of each criterion by adjusting its associated weight. Our approach will generate a wayfinding design accordingly.

Navigation Mistakes. Humans occasionally make mistakes in navigation. For example, it is common for pedestrians to miss a sign due to occlusion by other pedestrians; distractions such as advertisements or events happening in the environment [41], [42]; or a wrongly recognized sign or landmark [43]. It is also common for pedestrians to make wrong turns in navigation [42]. A well-thought-through wayfinding design should tolerate these kinds of human mistakes [19], [39]—a pedestrian should still be able to reach to his destination even if he makes mistakes occasionally.

Agent-based Evaluation. Martin Raubal [44] used agent-based simulation to evaluate human wayfinding in unfamiliar environments, yet the simulation used does not consider the mistakes that can be made by the agents; further, it is unsure how such evaluations can be used to enable automatic sign placement. In contrast, our agent-based simulations consider navigation mistakes and we also show how such simulations can be used to create a robust wayfinding design. Our approach is also motivated by autonomous agents [45] and crowd simulations [46], [47], [48]. However, instead of generating realistic agent simulations, we focus on applying agent-based simulations for optimizing wayfinding designs.

To achieve a robust wayfinding design, our approach conducts agent-based simulations in placing the signs to evaluate how well the design can tolerate occasional mistakes made by agents. Using our approach, the designer can control how robust the generated wayfinding design needs to be by changing the agent parameters. For example, in creating the wayfinding design for a subway station where the pedestrians (many of whom are first-time visitors) are generally expected to be unfamiliar with the environment, the designer can adjust the agents to have a higher chance in making mistakes. Our approach will generate a more robust wayfinding design by placing signs in important locations so that pedestrians can still find their ways despite the mistakes.

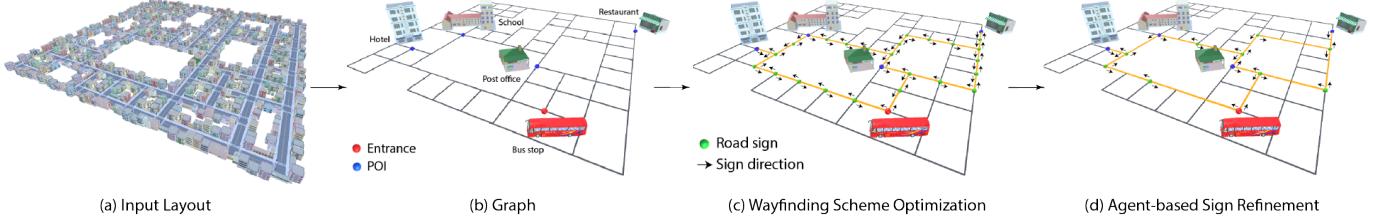


Fig. 3: Overview of our approach. (a–b) An input layout is first converted into a graph representation. (c) A wayfinding scheme optimization is then performed to find the optimized paths from the entrance to the points of interests, considering wayfinding criteria such as path lengths, angles and number of decision points. (d) An agent-based sign refinement subsequently takes place, which employs agent-based simulations to evaluate and refine the sign placement according to the navigation properties of agents mimicking human pedestrians.

2.4 Computational Layout Design

Layout design is an important problem in computer graphics. A layout typically consists of a number of sites connected by paths, with each site serving a different purpose. Computer-generated layouts can be used for creating virtual environments where virtual agents and human users can navigate for simulation and entertainment purposes. Galin et al. proposed to generate roads procedurally given a natural landscape with river and hills [32]. Computationally generated layouts can also be used for architectural design [49], [50], [51] and urban planning [52], [53], [54], [55]. Refer to the survey [56] by Smelik et al. for a comprehensive review of the state-of-the-art procedural modeling techniques for generating layout designs for virtual environments.

An important consideration in designing a layout is the navigation experience of the pedestrians. Recently, Feng et al. proposed an approach [57] which uses crowd simulation to generate mid-scale layouts optimal with respect to human navigation properties such as mobility, accessibility and coziness. However, concerning navigation, one important consideration is missing: the wayfinding experience of the pedestrians in the generated environments. We argue that their generated layouts are navigation-aware only if wayfinding signs are properly placed in the layouts.

In this regard, we consider our automatic wayfinding design approach as complementary to automatic layout design or road network generation approaches. The wayfinding signs automatically generated by our approach can enhance the navigation experience of users in virtual environments, as we show in our experiments.

3 OVERVIEW

Figure 3 shows an overview of our approach. We use a layout called *City* as our illustrative example to describe our approach. Our approach works on a graph representing an input layout. It consists of two major steps: *Wayfinding Scheme Optimization* and *Agent-based Sign Refinement*. In the *Wayfinding Scheme Optimization* step, our approach determines the paths for pedestrians to walk from the starting points to the destinations under different navigation scenarios specified by the user. Different human-centered navigation criteria such as turning angles and walking distances are jointly considered through an optimization to determine the paths to take. In the *Agent-based Sign Refinement* step, our approach places wayfinding signs strategically at appropriate locations along the paths. By using agent-based simulations to evaluate sign placement, our approach takes into account different human properties such as visibility and the possibility of making navigation mistakes. Depending on the requirements of the navigation scenarios, the designer can easily generate a wayfinding design that satisfies the domain-specific requirements, by changing the weights of

different criteria in the wayfinding scheme optimization and the parameters of the agent-based simulations.

4 PROBLEM FORMULATION

4.1 Representation

Graph Construction. To apply our approach, the user first creates a graph $G = \{V, E\}$ to represent the input layout, where V is the set of nodes representing the intersections, entrances and points-of-interest (POIs), and E is the set of edges representing the connecting paths between adjacent nodes. The creation process is simple and is similar to specifying a waypoint system in typical game level design. The user places nodes at the intersections, entrances and POIs of the layout. For example, in the illustrative example, *City*, the POIs include the school, the post office and so forth. The user also adds an edge between two adjacent nodes if the places represented by the nodes are connected by a road.

Source-Destination Pairs. A source-destination pair encodes a navigation scenario to be considered by our approach, e.g., going from a bus stop to a restaurant, akin to an input pair a wayfinding designer creates to specify a navigation scenario in conventional wayfinding design [12]. Each pair $z_i = (s_i, d_i)$ consists of a source (starting point) s_i and a destination d_i .

To facilitate the creation of source-destination pairs, by default our approach automatically generates a source-destination pair between every node representing an entrance and every node representing a POI, with the former being the source and the latter being the destination. Additionally, the user can specify any extra pair if needed. For instance, in the *City* example, he may want to create a pair connecting the hotel and the restaurant.

Importance Values. We also allow the user to assign an importance value $\kappa_i \in [0, 1]$ to each source-destination pair. For instance, in the *City* example, the (*Hotel*, *Restaurant*) pair can be given a higher importance value if many pedestrians are expected to walk from the *Hotel* to the *Restaurant*, whereas the (*School*, *Restaurant*) pair can be given a lower importance value if fewer pedestrians are expected to walk from the *School* to the *Restaurant*. In the optimization, the path connecting the *Hotel* with the *Restaurant* should be given a higher priority, compared to the path connecting the *School* to the *Restaurant*. If a trade-off exists, it is important to make sure that pedestrians can walk conveniently from the *Hotel* to the *Restaurant*, while it may not matter as much for pedestrians to walk a somewhat inconvenient path from the *School* to the *Restaurant*.

5 WAYFINDING SCHEME OPTIMIZATION

Given a source-destination pair $z_i = (s_i, d_i)$, there could exist multiple possible paths from s_i to d_i . Let P_{z_i} denote

the set of all such paths. Our goal in this step is to generate a wayfinding scheme that takes all source-destination pairs $\{z_i\}$ into account and selects a path for each pair. In other words, we select a path $p_i \in P_{z_i}$ for each pair z_i , such that the set of all selected paths $P = \{p_i\}$ satisfies some local and global criteria defined by our cost terms. We formulate our problem as an optimization of a total cost function:

$$C_{\text{all}}^P(P) = w_{\text{local}}^L C_{\text{local}}^L + w_{\text{local}}^N C_{\text{local}}^N + w_{\text{local}}^A C_{\text{local}}^A + w_{\text{global}}^L C_{\text{global}}^L + w_{\text{global}}^N C_{\text{global}}^N \quad (1)$$

The total cost function $C_{\text{all}}^P(P)$ refers to a weighted sum of cost terms encoding the length, number of decision points and the amount of turns of each path, as well as the length and number of decision points of the overall wayfinding scheme. The user can adjust the importance of different design criteria by changing the weights of the corresponding cost terms, to accommodate the domain-specific needs of the layout for which the wayfinding scheme is designed. We describe each cost term in detail as follows.

5.1 Wayfinding Cost Terms

Local Path Length. In general, pedestrians prefer to walk a short distance [12], [19], [58]. Hence, for each source-destination pair, a shorter path is preferred. We define a cost to penalize the length of the selected path of each source-destination pair:

$$C_{\text{local}}^L(P) = \frac{1}{|P|L_E} \sum_{p \in P} \kappa_p L(p), \quad (2)$$

where $|P|L_E$ is the normalization factor with $|P|$ being the number of source-destination pairs and L_E being the total length of all edges in graph G . $L(p)$ returns the length of path p . $\kappa_p \in [0, 1]$ is the importance value assigned to the source-destination pair that path p belongs to.

Local Path Node. The nodes in our formulation correspond to *decision points* in the wayfinding literature [12]. Decision points are locations where pedestrians need to make a decision about which direction to go, such as an intersection between paths (e.g., a lobby in a subway station); or where pedestrians need to confirm the identity of the current location, such as a place of interest (e.g., a platform in a subway station). Directional or identification signs need to be placed at decision points to guide pedestrians to find their directions [12], [14] or identify their current locations. Paths with lots of decision points should be avoided [39] as making each navigation decision induces stresses to the pedestrians for the fear of making a wrong decision that may lead to a wrong place [39], [59]. Therefore we define a cost to penalize the number of decision points of each path:

$$C_{\text{local}}^N(P) = \frac{1}{|P||V|} \sum_{p \in P} \kappa_p N(p), \quad (3)$$

where $|P||V|$ is the normalization factor with $|P|$ being the number of source-destination pairs and $|V|$ being the total number of nodes in graph G . $N(p)$ returns the total number of nodes along path p .

Local Path Angle. Research in spatial orientation [43] suggests that paths with varying orientation tend to confuse pedestrians in wayfinding, causing disorientation, anxiety and discomfort [2]. A wayfinding scheme composed of straight paths is more intuitive for navigation [33]. We therefore include a cost term to penalize the selection of paths with varying orientation:

$$C_{\text{local}}^A(P) = \frac{1}{|P||V|\pi} \sum_{p \in P} \kappa_p A(p), \quad (4)$$

where $|P||V|\pi$ is the normalization factor with $|P|$ being the number of source-destination pairs and $|V|$ being the total number of nodes in graph G . The maximum absolute turning angle between two adjacent edges is π . $A(p)$ returns the sum of absolute turning angles between all adjacent edges along path p .

Global Path Length. Our approach encourages paths to overlap with each other so as to minimize the total length of roads (edges) that are part of a path. This property could be useful from the management's perspective [8], [12], because by directing the flow of human movement to fewer roads, fewer roads will need to be maintained, patrolled and lightened up. We define a cost to encourage overlapping paths accordingly:

$$C_{\text{global}}^L(P) = \frac{L(P)}{L_E}, \quad (5)$$

where L_E is the total length of all edges in graph G as the normalization factor. $L(P)$ returns the total length of the edges that belong to any path in P .

Global Path Node. Our approach also encourages different paths to share nodes. Similar designs can be observed in the wayfinding schemes of different real-world premises, such as subway stations, shopping malls and concert halls, where people are directed to a lobby or an information desk that can lead to multiple destinations (see Figure 1 for an example). From the management's perspective, it could be easier to maintain signs centralized at certain locations in the environment [10], [14]. Also, centralizing signs could save space, which could be reserved for other better uses [58]. We define a cost to encourage node sharing accordingly:

$$C_{\text{global}}^N(P) = \frac{N(P)}{|V|}, \quad (6)$$

where $|V|$ is the total number of nodes in graph G as the normalization factor. $N(P)$ returns the total number of nodes that belong to any path in P .

5.2 Optimization

For each source-destination pair z_i , there exist a lot of possible paths going from the source to the destination. For instance, pair (*Bus Stop*, *School*) in the illustrative example (Figure 3) has more than 1,000 possible paths. Given the many combinations of possible paths of all pairs, the solution space could be huge as it grows exponentially with the number of pairs being considered.

To reduce the search space for a solution, we devise a sampling-based, stochastic search algorithm to solve the optimization problem as follows. For each pair, we only consider the first loopless k shortest paths, which can be found by Yen's algorithm [60] in $O(|E| + |V| \log(|V|))$ time using a Fibonacci heap, where $|E|$ is the number of edges and $|V|$ is the number of nodes. Deviation algorithms [61] and alternative implementations [62] exist that could further enhance computational efficiency, yet we adopt the classical implementation for simplicity.

Given the k shortest paths for each source-destination pair, we find a combination of paths of all source-destination pairs which corresponds to a low cost value. Even though we reduce the size of the solution space this way, an exhaustive search for the global optimum would still require

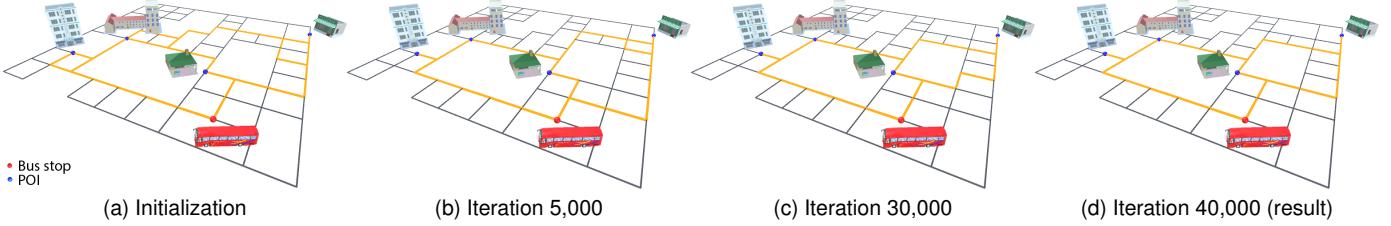


Fig. 4: Wayfinding schemes generated over the iterations of an optimization of the illustrative example, *City*. (a) Initialization. The source-destination pairs include walking from the bus stop to each POI, and walking between every pair of POIs. The path of each pair is randomly chosen from its k shortest paths. (b) Iteration 5,000. The selected paths start to overlap. (c) Iteration 30,000. The result is still sub-optimal. For example, the path connecting the bus stop to the restaurant at the upper right still shows large turning angles. (d) Optimized result.

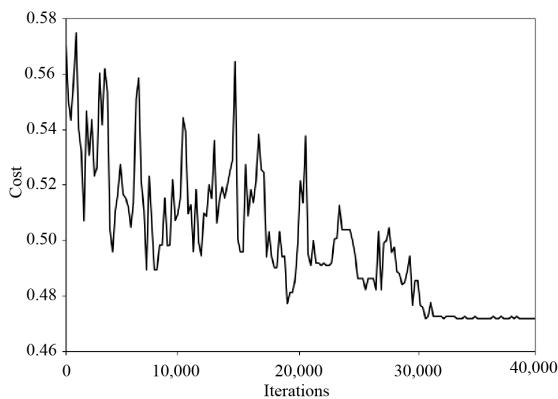


Fig. 5: Cost throughout the optimization of the *City* example.

heavy computation exponential to the number of pairs being considered.

Instead, our approach finds a local optimum as an approximate solution. We apply the simulated annealing technique [63] with a Metropolis Hasting [64] state-searching step to explore the complex optimization landscape. The optimization proceeds iteratively. In each iteration, the current solution P is altered by a proposed move to another solution P' , which may or may not be accepted depending on the acceptance probability of the proposed solution. More specifically, the acceptance probability is calculated by the Metropolis criterion:

$$\Pr(P'|P) = \min(1, e^{\frac{1}{T}(C_{\text{all}}^P - C_{\text{all}}^{P'})}), \quad (7)$$

where T is the temperature of the annealing process. T is high at the beginning of the optimization, allowing the optimizer to explore the solution space more aggressively; T is low towards the end of the optimization, allowing the optimizer to refine the solution. Essentially, the optimizer accepts any solution with a lower cost, while it accepts a solution with a higher cost at a probability: the higher the cost, the lower the acceptance probability. The optimization terminates if the absolute change in cost is less than 1% over 1,000 iterations.

Figure 4 shows the wayfinding schemes generated over the iterations of the optimization process of the illustrative example. Figure 5 shows the decay in cost over the optimization process. We also experimented with changing the importance values of the source-destination pairs; the resulting wayfinding schemes are depicted in Figure 6.

Proposed Moves. Our proposed moves follow a simple design. Depending on the number of source-destination pairs $|P|$, our optimizer changes the selected paths of up to $|P|$ source-destination pairs in a single move. The probability \Pr_x of drawing a move to change the selected paths of x

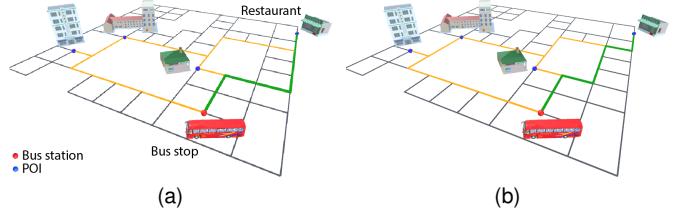


Fig. 6: Experimenting with different importance values. (a) Wayfinding scheme generated with all source-destination pairs having the same importance value of 0.5. The path from the *Bus Stop* to the *Restaurant* is shown in green. (b) Wayfinding scheme generated with the (*Bus Stop*, *Restaurant*) pair having a lower importance value of 0.25. In this case, the global path length is improved (i.e., the global path length is shorter) while the local path angle of the path from the *Bus Stop* to the *Restaurant* becomes worse (i.e., the path has more orientation changes).

pairs is inversely proportional to x , i.e., $\Pr_x = \frac{|P|-x+1}{X}$, where $X = \sum_{i=1}^{|P|} i$. A selected path is randomly changed to another path from the set of k shortest paths of its corresponding source-destination pair.

Parameter Settings. In our experiments, we initialize P by randomly selecting a path from one of the k shortest paths for each source-destination pair. By default we adaptively set k such that the length of the k -th shortest path is just within 16% of the length of the first shortest path, as research in spatial cognition finds that humans typically choose a path with a length within 16% of that of the shortest path [33]. Unless otherwise specified, each pair is assigned the same importance value $\kappa_i = \frac{1}{|P|}$, and we empirically set the weights w_{local}^L and w_{local}^N to 1, w_{global}^L and w_{global}^N to 5, and w_{local}^A to 10. These parameters and weights can be adjusted via the interface of our tool according to domain-specific design needs—a flexibility provided by our optimization-based design framework.

6 AGENT-BASED SIGN REFINEMENT

The wayfinding scheme optimization in the previous step produces a wayfinding scheme which comprises paths from the sources to the destinations. In this section, we discuss how our approach automatically places signs for each path to facilitate wayfinding.

6.1 Overview

Each node along a path corresponds to a decision point where a sign may be placed [12]. In our experiment design, a sign shows an arrow pointing to the next node and the destination's name or symbol. Two or more signs placed at the same node are combined into a single sign showing multiple pieces of wayfinding information. Figure 7 shows an example sign placed at a street corner in the *City* scene.

A trivial yet unrealistic solution is to place a sign showing the direction to the destination at every node along a path, so that a pedestrian walking along the path will keep reassured that he is heading to his destination. However, this solution will involve placing many redundant signs occupying a lot of space, and is generally not adopted.

Instead, our approach places signs at strategic locations according to human vision and navigation properties which are evaluated via agent-based simulations. The sign placement process is performed as an optimization against a number of cost terms reflecting the quality of the wayfinding experience brought about by the signs. The optimization starts with the trivial solution of placing a sign at each node along a path, then iteratively alters the sign placement to optimize the costs.

One advantage of this approach compared to the alternative approach of iteratively adding signs from scratch is that the optimization process of this approach is much more tractable, because the initial solution and each intermediate solution represent a feasible wayfinding solution even though they may contain redundant signs and the sign distribution may not be ideal. As we experienced in our experiments, this approach allows the optimizer to progress stably and conservatively to achieve a refined sign placement solution effectively.

6.2 Representation

A sign placement solution refers to placing signs at certain nodes of the input layout. Given the path of each source-destination pair (computed from Section 5), a good sign placement solution guides each pedestrian to walk from the source to the destination through the path effectively. Note that there could exist multiple reasonable sign placement solutions. The goal of this step is to locate one of such solutions through an optimization.

In case a road connecting two adjacent nodes is long, we may want to place signs at some intermediate locations along the road to reassure the pedestrian about his walking direction. Therefore, for roads longer than a distance threshold d_r , our approach adds extra nodes between the two end nodes of the road in a pre-processing step, such that the distance between any two adjacent nodes is shorter than d_r . These extra nodes serve as additional potential locations for placing signs. d_r can be empirically set by the designer depending on how frequently a pedestrian should be reassured about his direction. For example, for a subway station, the designer can use a smaller d_r such that more signs will be generated along a long road to reassure pedestrians that they are walking towards a desired destination (e.g., a platform). For our illustration example, City, we set d_r to be 50 meter.

More specifically, given the graph $G = \{V, E\}$ representing the input layout, we extend V to V' to include the extra nodes added. A sign placement solution is represented by $S = \{(v_i, \phi_i)\}$, where $v_i \in V'$ is the node at which sign ϕ_i is placed. ϕ_i contains the sign's attributes such as its arrow direction and the name of the destination it is referring to. Our optimization searches for a desirable sign placement solution S^* by minimizing a total cost function $C_{\text{all}}^S(S)$:

$$C_{\text{all}}^S(S) = w_{\text{sign}}^N C_{\text{sign}}^N + w_{\text{sign}}^D C_{\text{sign}}^D + w_{\text{sign}}^F C_{\text{sign}}^F, \quad (8)$$

where C_{sign}^N and C_{sign}^D are regularization costs; C_{sign}^F is the agent-based simulation cost for estimating the wayfinding



Fig. 7: Example sign.

failure induced by the sign placement solution S . w_{sign}^N , w_{sign}^D and w_{sign}^F are the weights of the cost terms, which are respectively set as 1, 1 and 10 by default.

6.3 Sign Placement Cost Terms

Number Of Signs. We include a cost term to regularize the number of signs in the sign placement solution, to penalize the existence of redundant signs:

$$C_{\text{sign}}^N(S) = \frac{N(S)}{|V'|}, \quad (9)$$

where $N(S)$ is the number of placed signs; $|V'|$ being the total number of nodes (i.e., potential locations for placing signs) is a normalization constant.

Distribution of Signs. In a real world design, signs are often evenly distributed along a path, which serve the purpose of regularly reassuring a pedestrian about his direction towards the destination. Accordingly, we include a cost term to regularize the distribution of signs:

$$C_{\text{sign}}^D(S) = \frac{1}{|P|} \sum_{p \in P} \frac{\sigma(p)}{L(p)}, \quad (10)$$

where $|P|$ is the number of source-destination pairs; $\sigma(p)$ is the standard deviation of the distances between any two adjacency signs on path p , and $L(p)$ is the length of path p .

Wayfinding Failure. The placed signs should effectively guide the pedestrians from the sources to the destinations. We include a cost term to penalize wayfinding failure:

$$C_{\text{sign}}^F(S) = \begin{cases} F(S) & \text{if } F(S) \leq \mu, \\ +\infty & \text{otherwise,} \end{cases} \quad (11)$$

where $F(S)$ is the percentage of agents who fail to reach their destinations under the current sign placement S . $F(S)$ is obtained by performing an agent-based simulation with sign placement S . μ is a failure tolerance level specified by the designer, which is set as 20% by default.

6.4 Agent-based Evaluation

In each iteration of the optimization, we employ an agent-based simulation to evaluate the wayfinding experience under the current sign placement S , to obtain $F(S)$ used for computing the wayfinding failure cost.

Agent Model. Each agent mimics a pedestrian walking from a source to a destination. We model each agent with wayfinding behavior according to Montello and Sas [65]. The agent starts from the source. It can see any unoccluded sign within visible distance d_v . Whenever it sees a sign pointing to its destination, it will follow the sign to choose a direction to walk. If it arrives at an intersection but is unsure about which road to take out of several roads connected to that intersection, it will randomly choose a road to walk with equal probability. To more realistically model mistakes that humans can make throughout a navigation, each agent has a probability Pr_{miss} of missing a sign even within sight.

Simulation. For each source-destination pair, 100 agents are employed to walk from the source to the destination using the agent model described. At the end of the simulation, we count the number of agents that can successfully reach their destinations, and hence compute $F(S)$.

A “success” is defined as follows: let d_b be the “baseline” walking distance from the source to the destination if no mistake is made (i.e., $\text{Pr}_{\text{miss}} = 0$) under full sign placement (i.e., a sign is placed at every node along a path). If an

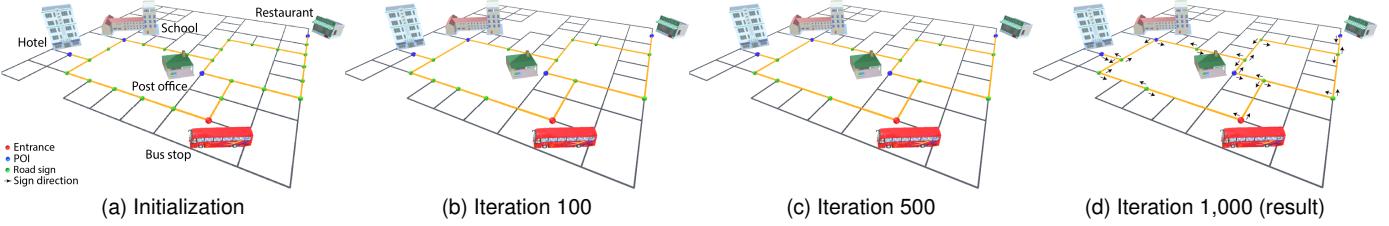


Fig. 8: Sign placement generated over the iterations of the optimization in the agent-based sign refinement step. (a) Initialization. Road signs are placed at every intersection along the paths generated in the wayfinding scheme optimization step. (b) Iteration 100. Some redundant road signs have been removed. (c) Iteration 500. Redundant road signs along the bottom path have been further removed. (d) Result. The signs on the bottom path are combined into a single sign placed near the middle of the path. The redundant sign on the upper path has been removed.

agent, given the chances of making mistakes and under the current sign placement S , can walk from the source to the destination by a distance no longer than λd_b , the navigation is considered as a success. The navigation is counted as a failure otherwise. We use $\lambda = 1.5$ in our experiments.

6.5 Sign Refinement by Optimization

Initialization. Our optimization is initialized with the full sign placement solution, i.e., a sign is placed at every node along the path from the source to the destination of each source-destination pair. Although this sign placement can lead the pedestrians to their destinations, it consists of a lot of redundant signs that could be removed without affecting the pedestrians' ability to find their ways. We apply a stochastic, agent-based optimization to search for a reasonable sign placement solution.

Iterative Refinement. Our optimization proceeds iteratively. At each iteration, a move is randomly proposed to alter the sign placement solution whose quality is evaluated using the total cost function $C_{\text{all}}^S(S)$. The moves include:

- Adding 1 or 2 signs to 1 or 2 source-destination pairs.
- Removing 1 or 2 signs from 1 or 2 pairs.
- Moving a sign from one node to another node of a source-destination pair.

The proposed solution is accepted with an acceptance probability determined by the Metropolis criterion as described by Equation 7, using $C_{\text{all}}^S(S)$ as the cost function. The optimization terminates if the absolute change in cost is less than 1% over 50 iterations.

Figure 8 shows the sign placement over iterations for the illustrative example. In this example, the source-destination pairs include walking from the *Bus Stop* to each POI, and walking between every pair of POIs. Each iteration of the optimization takes about 0.01 second to finish in our experiments. It takes about 1,000 iterations (about 10 seconds) to finish the sign placement optimization for this example.

7 EXPERIMENTS AND RESULTS

We implemented our approach as a plugin for the Unity 5 game engine using C#, which level designers can use to create a wayfinding scheme of a given layout. We run our experiments using a Macintosh machine equipped with a 2.3 GHz Intel Core i7 processor and 8GB of RAM. Generating a wayfinding scheme for a layout similar to the illustrative example, *City*, takes about 40 seconds using our current implementation.

7.1 Different Layouts

We used our approach to generate wayfinding designs for different layouts: *Amusement Park*, *Downtown* and *Penn*

Station. Figure 9 shows the maps from which the layouts are extracted following the procedure in Section 4.1. Figure 10 shows the wayfinding designs generated by our approach. We describe the details of each generation in the following. Please also refer to the supplementary material for details of the generated wayfinding schemes of the layouts, and also for the results of two more layouts: *City* and *Canyon*, which demonstrate how our approach could be applied to generate wayfinding designs for 3D virtual environments and with robustness as a key consideration.

Amusement Park. We use the layout of an amusement park, Six Flags New England, as input (see Figure 10). The POIs, which in this case are the Entrance, Sky Screamer, Bonsai, Batman and Picnic Grove, represent the popular spots the visitors would like to visit. The source-destination pairs involve all pairs of entrances and popular spots, and all pairs of popular spots. In addition to the popular spots, we expect there are street performances and stalls in the park, which might distract visitors from navigating to their destinations. To model such distractions, we set the missing chance \Pr_{miss} in the agent simulation of the sign placement optimization step to a relatively high level of 0.2. Besides, we assume that visitors highly prefer to walk shorter and more direct paths to their destinations if possible, therefore we use larger values of 5 for the weights w_{local}^L and w_{local}^N of the local path length and local path node costs.

Figure 10 shows the generated design. Our approach generates a path for each source-destination pair. It places road signs densely at each intersection along the paths to ensure the robustness of the wayfinding system. The left-hand side of the layout shows a shortcut generated which is part of the paths from the popular spot at the lower left to the popular spots on the right. The shortcut allows visitors to walk shorter paths to their destinations, and is also more direct for the visitors as it passes through fewer intersections (2 instead of 3) compared to the alternative path above.

Downtown. This example uses the layout of Downtown Boston as input. The goal is to place road signs that guide drivers to an available parking lot nearby. The entrances refer to the major roads through which most cars enter the Downtown area. The POIs are the parking lots, which are placed at the same locations as the real parking lots found on Google map. We suppose that all the parking lots are run by the same company, hence there are signs showing the way from one parking lot to a nearby parking lot within 0.2 mile, such that if a parking lot is full the driver can follow the signs to a nearby parking lot. Accordingly, we define the source-destination pairs to connect each entrance to its nearest parking lot, as well as to connect each parking lot to its nearby parking lot. The latter type of pairs are given a relatively larger importance value ($\kappa_p = 0.8$ instead of 0.5 given to other pairs), so that our system will prefer to find shorter paths passing through fewer intersections for

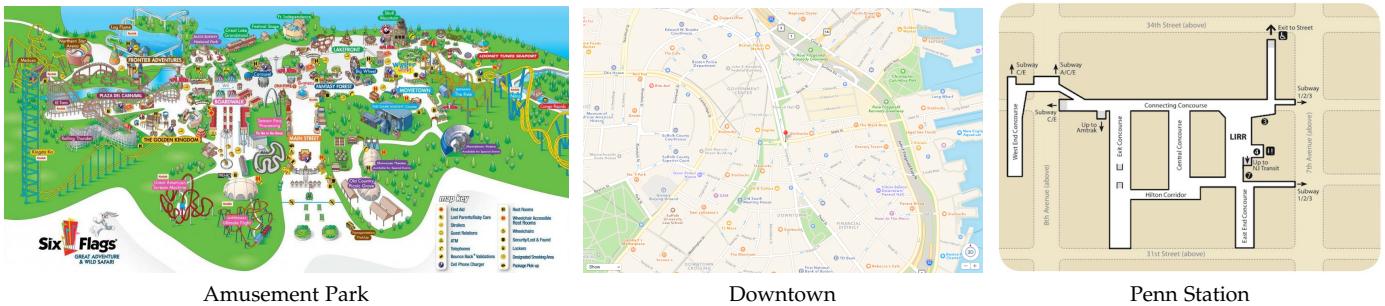


Fig. 9: Maps and 3D models from which the layouts are extracted.

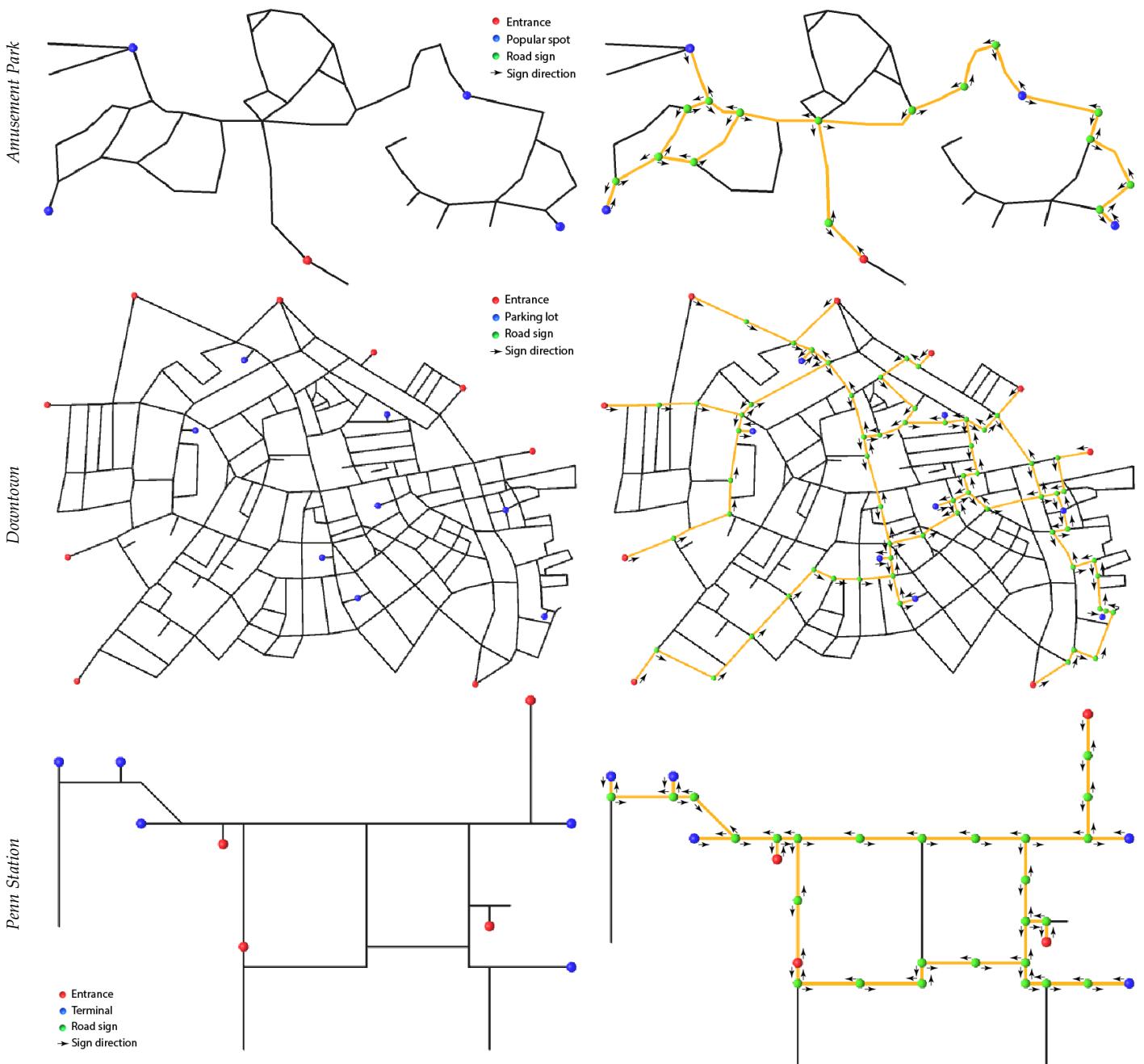


Fig. 10: Wayfinding designs generated for Amusement Park, Downtown and Penn Station.

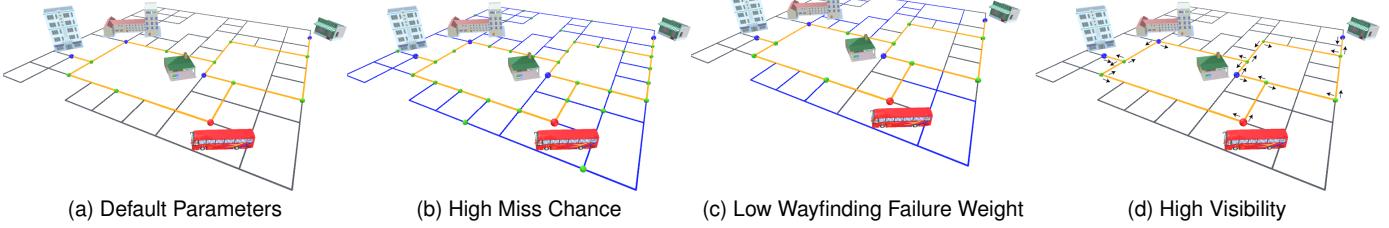


Fig. 11: Effects of changing the parameters of the agent-based sign placement step. (a) Default parameters. Roads that belong to a path of the wayfinding scheme are shown in yellow. (b) High miss chance. The blue lines indicate the roads that the pedestrians have walked but do not belong to any path. The generated wayfinding design is more robust against navigation mistakes. Signs are placed densely, and are also placed on some roads not belonging to any path to guide the pedestrians back to the correct paths in case they get lost. (c) Low wayfinding failure weight. Fewer signs are placed as wayfinding failure is more tolerable. (d) High visibility. Fewer signs are placed as the pedestrians can see signs far away.

the paths that connect one parking lot to a nearby parking lot, to help drivers to get to an alternative parking lot more easily in case a parking lot is full.

Figure 10 shows the generated design. A path is generated to connect each entrance to its nearest parking lot. Short and direct paths are also generated to connect parking lots to nearby parking lots. While there are many possible paths that can be chosen as the layout comprises a network of many streets, our approach chooses paths which are straight and consists of few turns, as the local path node cost penalizes the inclusion of intersections and the local path angle cost discourages orientation changes.

Penn Station. This example uses the lower level of the Penn Station as input. In this example, the entrances refer to the gates and the stairs from the upper level. The POIs refer to the terminals. The source-destination pairs include every pair of entrance and terminal, and every pair of terminals (for modeling the situations where a passenger wants to transfer from one terminal to another terminal). As the station is expected to be crowded, the visibility d_v of the agents is set to a relatively low value of 10 meters to account for the occlusion by human crowd, and the miss chance Pr_{miss} is set to a relatively high level of 0.2. Figure 10 shows the generated wayfinding design. The road signs are placed densely and are also placed at non-intersection nodes, to counteract the higher miss chance by reassuring pedestrians about their directions.

7.2 Changing Agent Parameters

We further experimented with changing the parameters of the agent-based sign placement process using the *City* layout. In the default settings, the missing chance Pr_{miss} is set to 0%, the weight w_{sign}^F of the wayfinding failure cost term is set to 10 and the visibility distance d_d is set to 125 meters. Figure 11(a) shows the resulting sign placement generated with the default parameters.

We experimented with increasing the missing chance Pr_{miss} to 10%. Figure 11(b) shows the resulting sign placement. Our system places more signs so as to increase the robustness of the wayfinding design against navigation mistakes. In addition, some signs are placed on the roads not belonging to any path for guiding the agents back to the correct paths.

Next, we experimented with lowering the weight of the wayfinding failure cost term to 0.01. Figure 11(c) shows the resulting sign placement. Our system keeps fewer signs, because it is acceptable even if some agents make mistakes and do not walk to the destination within a desired period of walking. The pedestrians walk along some roads (shown

in blue) not belonging to any path. This setting maybe useful for some situation where it is not critical for the agents to reach the destination, and when space is better preserved for other uses. For example, in a flea market, it may not be critical for the pedestrians to visit each stall as they are expected to wander around in the market.

Finally, we experimented with increasing the visibility to 250 meters. Figure 11(d) shows the result. Our system keeps only a few signs because the pedestrians are capable of seeing signs at a farther distance. This setting is useful for modeling situations where the signs are big (such as those shown in billboards) and can be seen far away.

7.3 Visualization

Destination Accessibility. Our approach also allows the designer to visualize the accessibility of a destination under the generated wayfinding design. This is a very useful functionality that can help the designer to create a wayfinding design that guides pedestrians from different locations to walk to a destination as desired. Figure 12(a) depicts this functionality. The accessibility of a destination (the *Post Office*) is visualized as a heatmap. Agents in the blue region can travel to the *Post Office* successfully by following the wayfinding signs under the current wayfinding design; while those in the red region have a low chance of success.

To compute the accessibility heatmap with respect to a destination specified by the designer, our system sample points at regular intervals along all the edges of the input layout (whether the edges are part of the paths of the generated wayfinding design or not). Agents are employed to walk from each sample point to the destination, in a similar fashion as in the agent-based sign placement step (Section 6), to compute the rate of success of reaching the specified destination from each of the sample points. The rates of success are used to set the heatmap colors at the corresponding sample points; the heatmap color values between two sample points are interpolated.

Note that a destination typically does not need to be accessible from every region, because enforcing such full accessibility will likely involve placing a lot of signs even at some “unimportant” regions. For example, it may not be important to place signs to guide pedestrians how to walk from a post office to a restaurant. By visualizing the accessibility to a destination using a heatmap, the designer can intuitively tell what regions are covered by the current wayfinding design and if any improvement is needed.

Removing Blind Zones. If the designer wants to remove a “blind zone” (i.e., a region shown in red indicating low accessibility to the destination), he can easily do so by

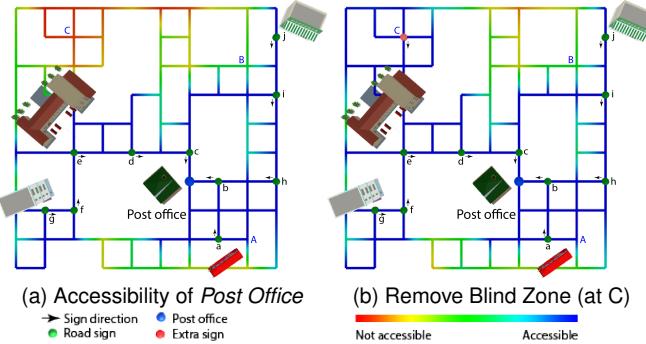


Fig. 12: (a) Accessibility of the *Post Office* visualized as a heatmap. The accessibility from location A is good as depicted by the blue color, because a pedestrian can easily see and follow a sign on the west to walk to the *Post Office*. The accessibility from location B is fair as depicted by the green color. A pedestrian starting at B has a 50% chance to walk to the street towards the north or the east and get lost. The accessibility from location C is poor as depicted by the red color. Without any sign nearby, a pedestrian starting at C has a very low chance to reach the *Post Office*. (b) Removing the blind zone at C. The user triggers our system to place a road sign at C showing the direction to the *Post Office*. The accessibility around C is improved, as depicted by the change in color from red to blue on the updated heatmap.

clicking on the red region via our user interface. Our system will automatically place signs which guide pedestrians to walk from the clicked point to the path leading to the destination. This is achieved by re-running the wayfinding scheme optimization and the agent-based sign refinement steps taking the existing solution as the initialization. Note that these additional optimization steps only change the paths and signs related to the newly-added POI; the locations of the signs and paths in the existing solution are fixed. After the optimization steps, agent-based evaluations will be re-run at each sample point to update the heatmap accordingly, which takes about 1 second for the *City* example. Figure 12(b) shows an example of removing a blind zone.

8 EVALUATION

8.1 User Study

Conditions. We conducted a user study to evaluate the effectiveness of the wayfinding designs generated by our approach. Our user study was conducted in the *City* layout used as the illustrative example. Participants were asked to navigate from a starting point to a destination under 4 different wayfinding conditions:

- 1) No sign.
- 2) Mini-map. A mini-map that functions like a mini-map in a common first-person 3D video game is shown;
- 3) Full signs. In this case, we only run the wayfinding scheme optimization step to generate the paths for the source-destination pairs. Signs are placed at every node along each path.
- 4) Refined signs. In this case, we run the wayfinding scheme optimization step to generate the paths, and then the agent-based sign refinement step to refine the sign placement. Signs are placed strategically at some of the nodes along each path.

Figure 13 shows two screenshots of the user study tests under the mini-map and refined sign conditions. There are 2 different scenarios. In the first scenario, the participant was asked to walk from the *Bus Stop* to the *Restaurant*. In the second scenario, the participant was asked to walk

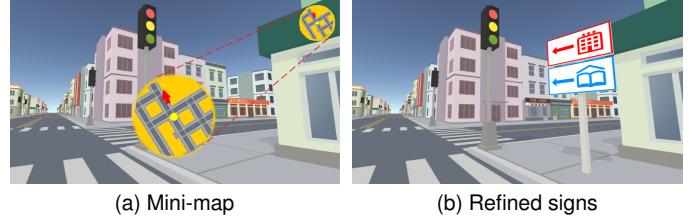


Fig. 13: Screenshots of the user study tests under the (a) mini-map and (b) refined signs conditions.

from the *Bus Stop* to the *School*. Each scenario was tested by 80 participants under the 4 different wayfinding conditions (i.e., 20 participants for each condition).

Participants. In total, we recruited 160 participants through social networks. The participants are university students. All of them have experience with 3D video games and are familiar with the movement control of common first-person-shooting games, which our user study program similarly adopts. Before each test, a description of the task and the movement control is shown to the participant, and the participant is allowed to get familiar with the movement control in a warm-up session.

Test Sessions. The goal of the participant in each test is to walk to the destination (*School* or *Restaurant*) as fast as he can. To make sure he is clear about the destination, a screenshot of the destination is also shown to the participant before the user study begins. Our program records the path, the distance walked and the time taken by the participant. The test ends if the participant reaches the destination, or if the time taken exceeds the time limit, which is defined as three times the time needed to walk from the start to the destination without any stop following the path generated by the wayfinding scheme optimization step. The latter is considered as a failure case.

8.2 Results and Analysis

Path Taken. Figure 14 shows the results of the user study. The paths taken by the participants are visualized in a heatmap. The roads with high usage are shown in red, and those with low usage are shown in blue. There are some interesting observations. Under the no sign condition, the participants wandered around and could barely reach the destination. Under the mini-map condition, the participants walked towards their destinations along similar directions. However, there are considerable variations among the paths taken, as can be seen from the color dispersion on the heatmaps. For example, in scenario 2, near half of the participants took the bottom path while the other half took the upper path. Under the full signs and refined signs conditions, all participants walked to the destinations following the same path.

Distance Walked. Table 1 shows the statistics of the distances walked by the participant under different conditions. For the no sign condition, only the data of the participants who could reach their destinations within the time limit is used to calculate the statistics. For the other conditions, all participants can reach the destinations and all data is used to calculate the statistics.

Under the no sign condition, only 55% and 25% of the participants could reach their destinations in Scenario 1 and 2 respectively. For those who could reach the destinations, they generally needed to walk a very long way as shown by the large mean values.

Under the mini-map condition, all participants could reach their destinations. In Scenario 1, the participants

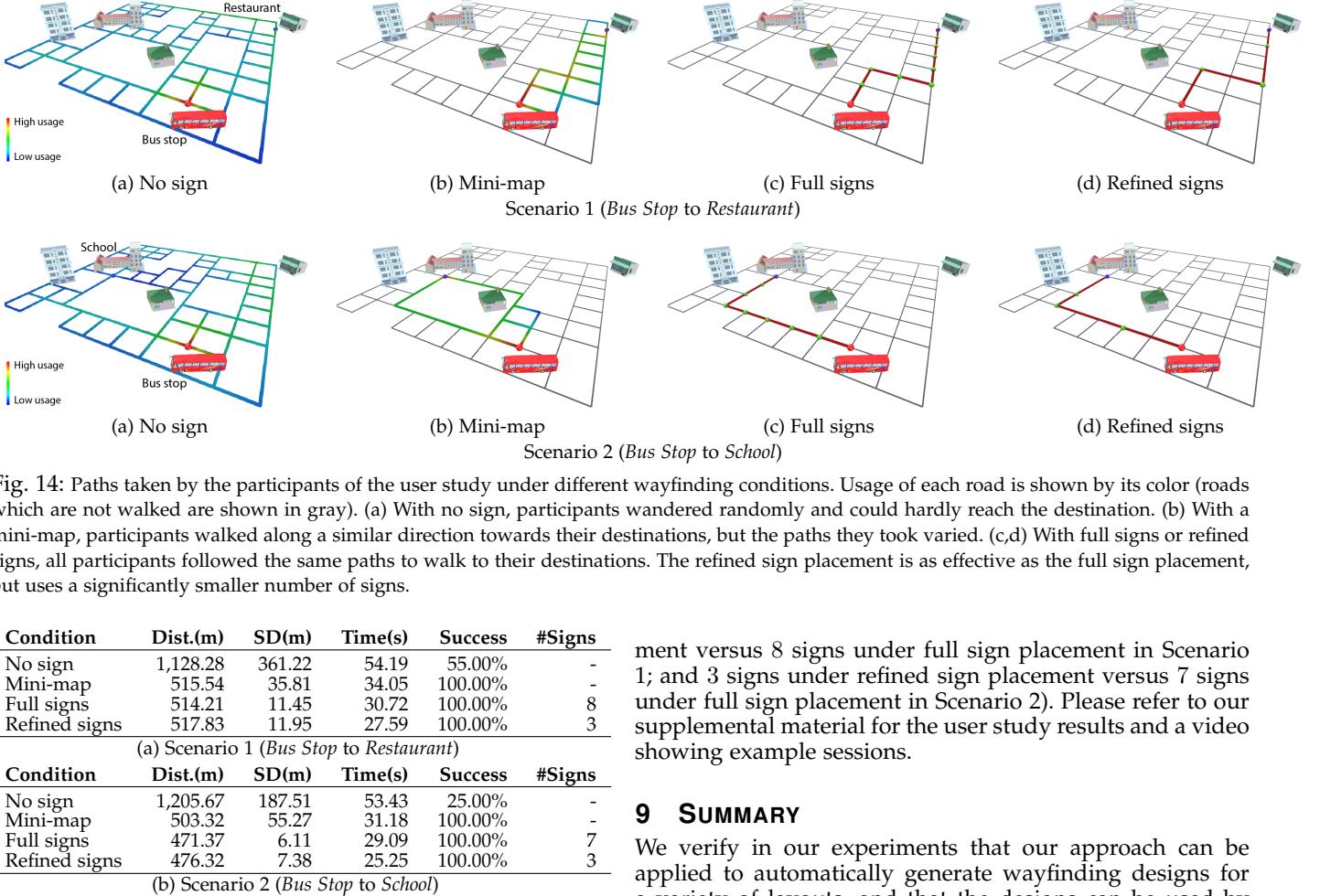


Fig. 14: Paths taken by the participants of the user study under different wayfinding conditions. Usage of each road is shown by its color (roads which are not walked are shown in gray). (a) With no sign, participants wandered randomly and could hardly reach the destination. (b) With a mini-map, participants walked along a similar direction towards their destinations, but the paths they took varied. (c,d) With full signs or refined signs, all participants followed the same paths to walk to their destinations. The refined sign placement is as effective as the full sign placement, but uses a significantly smaller number of signs.

Condition	Dist.(m)	SD(m)	Time(s)	Success	#Signs
No sign	1,128.28	361.22	54.19	55.00%	-
Mini-map	515.54	35.81	34.05	100.00%	-
Full signs	514.21	11.45	30.72	100.00%	8
Refined signs	517.83	11.95	27.59	100.00%	3

Condition	Dist.(m)	SD(m)	Time(s)	Success	#Signs
No sign	1,205.67	187.51	53.43	25.00%	-
Mini-map	503.32	55.27	31.18	100.00%	-
Full signs	471.37	6.11	29.09	100.00%	7
Refined signs	476.32	7.38	25.25	100.00%	3

TABLE 1: Average distances walked and average time taken by participants under different wayfinding conditions. For the no sign condition, only the data of the participants who successfully reached their destinations are used to compute the statistics. In general, it took the least amount of time for participants to reach their destinations under the “refined signs” condition. Compared to the “full signs” condition, users under the “refined signs” condition probably needed to spend less time looking for and reading signs. Compared to the “Mini-map” condition, users under the “refined signs” condition could probably determine the correct direction more intuitively and quickly.

could reach the destination *Restaurant* by walking a distance similar to that in other conditions. However, the standard deviation (35.81m) is higher than the standard deviations (11.45m and 11.95m) of the other conditions, showing that there are larger variations in performances, due to different paths chosen as shown in Figure 14. In Scenario 2, the relative difference in standard deviation is even more pronounced (55.27m under the mini-map condition, versus 6.11m and 7.38m under the other conditions), due to the larger differences in walking distances of the paths chosen. In average, the participants walked a shorter distance to reach the destination under the full signs or refined signs conditions (471.37m and 476.32m) than under the mini-map condition (503.32m).

Under the full signs and refined signs conditions, all participants can reach their destinations. The means and standard deviations of the walked distances are similar. This shows that the refined sign placement is as effective as the full sign placement in guiding the participants to their destinations. However the refined sign placement uses significantly fewer signs (3 signs under refined sign place-

ment versus 8 signs under full sign placement in Scenario 1; and 3 signs under refined sign placement versus 7 signs under full sign placement in Scenario 2). Please refer to our supplemental material for the user study results and a video showing example sessions.

9 SUMMARY

We verify in our experiments that our approach can be applied to automatically generate wayfinding designs for a variety of layouts, and that the designs can be used by human users to navigate to their destinations effectively in virtual worlds. Compared to the conventional approach of creating wayfinding designs manually, the novelty of our approach lies in formulating the problem as an optimization, which can be solved automatically and efficiently, hence overcoming the design challenge posed by the considerations of multiple paths and design criteria. Our optimization approach also allows the flexibility of considering additional constraints in wayfinding design and the designer can trade off between different criteria by controlling their corresponding weights. We adopt an agent-based approach to automatically place signs at strategic locations, considering human perception and navigation properties such as eyesight and the possibilities of making mistakes. The agent model makes it intuitive and flexible for designers to define agent properties and behaviors according to the specific requirements of their design projects on hand; signs will be automatically placed according to the specified agent properties.

9.1 Limitations and Future Work

Our approach only focuses on placing textual and arrow signs to facilitate wayfinding. While these are common wayfinding aids, in reality humans also make use of other wayfinding aids and cues such as maps (e.g., “You-are-here” maps [10], [12]), landmarks and flow of people movement to determine directions. In future extension it would be useful to consider all these alternative aids and cues in generating a wayfinding design.

Our agent-based simulation model only focuses on a few properties that are relevant to wayfinding. More realistic

virtual humans comprising of cognitive, perceptive, behavioral and kinematic modules, similar to the autonomous agents used for artificial life simulation [45], could be used to replace our agents. The perceptual data obtained from the simulations based on such agents could be used for more sophisticated wayfinding analysis to enhance the computationally-generated wayfinding design.

In our current approach, for simplicity we only consider one path for each source-destination pair. In fact, there could exist multiple paths (secondary paths) for each pair. This can be modeled by extending our framework to allow multiple paths for each pair, which will be considered jointly in the optimization.

In our approach, the source-destination pairs are manually specified rather than automatically generated. This is because our approach does not infer the layout context. An interesting future direction is to devise a data-driven approach to automatically identify the possible locations of interests given a layout based on prior statistics of human flows, and hence automatically suggest the source-destination pairs to consider. For example, given a subway station, a data-driven approach may automatically suggest that (*Entrance*, *Ticket Machine*) and (*Ticket Machine*, *Gate*) as likely source-destination pairs, based on the real-world statistics of human flows in subway stations.

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