Automatic Generation of Indoor Navigation Instructions for Blind Users using a User-centric Graph

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Abstract—**The complexity and diversity of indoor environments brings significant challenges to automatic generation of navigation instructions for blind and visually impaired users. Unlike generation of navigation instructions for robots, we need to take into account the blind users wayfinding ability. In this paper we introduce a user-centric graph based solution for cane users that takes into account the blind users cognitive ability as well as the user's mobility patterns. We introduce the principles of generating the graph and the algorithm used to automatically generate the navigation instructions using this graph. We successfully tested the efficiency of the instruction generation algorithm, the correctness of the generated paths, and the quality of the navigation instructions. Blindfolded sighted users were successful in navigating through a three-story building.**

I. Introduction

The World Health Organization (2010) reported that 285 million people are visually impaired worldwide, of whom 39 million are blind and 246 million have low vision [1]. Based on data from the 2004 National Health Interview Survey, 61 million Americans are considered to be at high risk of serious vision loss if they have diabetes, or had a vision problem, or are over the age of 65 [2]. Since the eyes are the most important organs to sense the surroundings, their loss of vision can significantly reduce the visually impaired individual's orientation and mobility, especially in unfamiliar and complex indoor environments. Even with the help of a guide dog or cane, it is still a challenge for the visually impaired to independently navigate in such environments without help from sighted individuals. It is commonly accepted that the incapability of moving freely and independently can hinder the full integration of a visually impaired individual into society [3].

Currently, blind and visually impaired users mainly rely on training from Orientation and Mobility (O&M) instructors to acquire orientation and mobility skills. O&M instructors will guide their clients to the destination while taking into consideration the environment and client's mobility. While such instruction is very effective, navigating to unfamiliar environments requires the help of an O&M instructor or a sighted person limiting the independence of blind and visually impaired users.

Indoor navigation is a complex task, which can be divided into two problems: localization, and path planning using digital representation of the indoor environment.

Due to the inaccuracy of indoor GPS readings, people are trying to find other localization techniques, including 1) dead reckoning, which estimates the user location based on previous estimated location using accelerometers, magnetometers, compasses and gyroscopes [4,5], 2) direct sensing, which determines the user location by reading identifiers/tags using different technologies such Radio-Frequency Identification (RFID) [6,7], infrared (IR) tags [8,9], Ultrasound [10,11], Bluetooth [12] and Barcodes [13], and 3) pattern recognition, which uses computer vision [14] or signal fingerprinting [15,16].

Unlike vehicle navigation systems, path planning for indoor navigation for the blind needs to account for the user wayfinding ability. The REAL project [9], a resource-adaptive navigation system designed for users with cognitive limitations, prioritizes paths with minimum cognitive load rather than shortest distance or shortest time. Some projects for the blind and visually impaired [5,6,17] consider obstacle avoidance using different hardware sensors. Most of indoor navigation systems use Dijkstra's algorithm [19] or A* algorithm [20] to generate a path, given a graph that represents the indoor environment. Representation of indoor environments uses Blueprints [4], digital road maps [6], or subdivided indoor areas [14].

In this paper we introduce an algorithm that automatically generates indoor navigation instructions for the blind and visually impaired, while accounting for users' wayfinding ability. We assume that the localization is obtained by direct sensing using RFID tags deployed at specific landmarks in the environment.

The main contributions of this paper are 1) the introduction of a user-centric graph that takes into account the user mobility pattern, and 2) the generation of navigation instructions using this graph. The building structure is represented in a database that includes different elements such as corridors, recessed areas, doors, elevators, openings, rooms, walls, etc. The graph includes positions as vertices and actions as edges. After assigning a weight, which represents the cognitive load required to cross the specific edge, Dijkstra's algorithm computes the shortest path. Before we translate the shortest path into verbal sentences, we need to segment it into pieces properly, so that each segment fits into one instruction.

We successfully tested the efficiency of the instruction generation algorithm, the correctness of the generated paths, and the quality of the navigation instructions.

The paper is organized as follows. Section II introduces a method of simulating user's mobility. The generation of a graph based on user simulation and building structure follows in Section III. Section IV describes the instruction generation process. Testing results are provided in Section V and Section VI concludes the paper.

II. User Simulation

Our approach assumes that the blind persons use a white cane for their indoor wayfinding tasks. The white cane is generally longer than 1.2 m, which may vary depending on user's height and preference. As shown in Figure 1 (left), a user of an average height of 1.5-1.8 m can detect objects in a radius of about 0.8 m.

They can detect a wall or change of floor level in a sector area in front, back, left and right. In order to simplify the user simulation we select four directions, front, left, right, and back. As shown in Figure 1 (right), the user may stand in the black block, and detect an area of the upper semi-circle with a radius of 0.8 m.

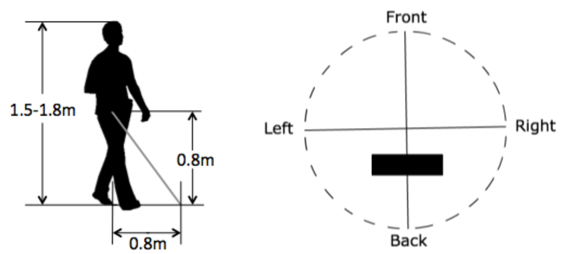

Figure 1. User Simulations – Measurement (left) and Model (right)

At each position the user can tell if there is an obstacle in these directions. This information determines the state of each position as a four-digit binary number [FRBL], standing for Front (F), Right (R), Back (B), and Left (L). At each position, the users can choose to take an action, which will lead them to the next position. There can be 9 possible actions as summarized in Table I. As these actions only depend on the state of current position, we call them primary actions.

TABLE I Primary Actions

Action #	Action	Description
1	Follow L	Follow the trace on left to end
2	Follow R	Follow the trace on right to end
3	Glide	Move forward without traces
4	Turn L	Simply turn left
5	Turn R	Simply turn right
6	Turn R N-F	Turn right when a wall appears in front
7	Turn L N-F	Turn left when a wall appears in front
8	Turn R L-F	Turn right at an inside corner on left
9	Turn L R-F	Turn left at an inside corner on right

A blind person using a white cane can recognize different types of landmarks, such as elevators, doors and openings. Therefore, some additional actions can be taken at these landmarks/positions. For example, users can follow an instruction like "turn right at the second door on left", which is not included in the primary actions. As these actions depend on the resulting position of primary actions, we call them secondary actions. Table II summarizes these secondary actions.

TABLE II Secondary Actions

Action #	Action	Description
10	Turn R R-N	Turn right at the opening on right
11	Turn L L-N	Turn left at the opening on left
12	Turn R L-N	Turn right at the opening on left
13	Turn L R-N	Turn left at the opening on right
14	Turn R L-L	Turn right when a landmark on left is found
15	Turn L R-R	Turn left when a landmark on right is found
16	Turn R N-R	Turn right at an outside corner on right
17	Turn L N-L	Turn left at an outside corner on left
18	Turn R N-L	Turn right at an outside corner on left
19	Turn L N-R	Turn left at an outside corner on right

Table III includes operation actions, which describe all possible interactions with landmarks, such as doors, elevators, stairs, etc. Primary, secondary and operation actions describe all possible movements of a user during indoor wayfinding tasks. In the next section we introduce the graph generation algorithm that uses the actions presented above and the building structure.

TABLE III Operation Actions

Action #	Operation Action	Description
20	Enter E F	Use elevator in front
21	Enter E L	Use elevator on immediate left
22	Enter E R	Use elevator on immediate right
23	Enter E B	Use elevator right behind
24	Enter S F	Use stairs in front
25	Enter S L	Use stairs on immediate left
26	Enter S R	Use stairs on immediate right
27	Enter S B	Use stairs right behind
28	Enter D F	Use door in front
29	Enter D L	Use door on immediate left
30	Enter D R	Use door on immediate right
31	Enter D B	Use door right behind

III. Graph Generation

The graph includes positions as vertices and actions as edges. Graph generation flowchart is shown in Figure 2.

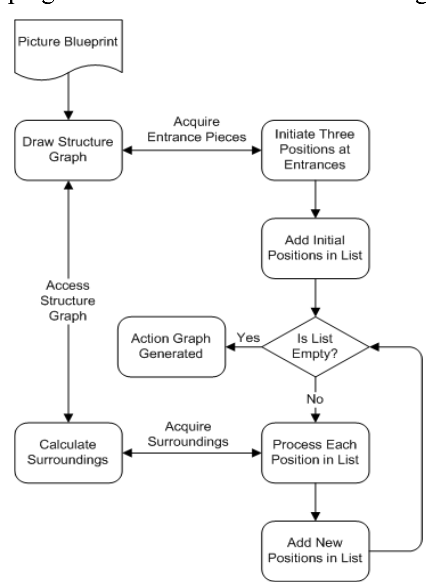

Figure 2. Graph Generation Flow Chart

IV. Instructions Generation

The graph generated in Section III describes all possible actions in the environment. We assign each action a weight, which represents the cognitive load required to cross the specific link. By incorporating the cognitive load for each action, we can use Dijkstra's algorithm while incorporating the special navigation requirements of blind users.

The path is represented by a linked list. Before we translate it into verbal sentences, we need to segment it into pieces properly, so that each segment fits into one instruction.

The translation method is simply to concatenate different prepared sentence patterns. The flow of segment translation is depicted in Figure 3. There are several parts in one instruction.

- The initial instruction after scanning the tag, may ask the user to turn around, such as "put your back to the door".
- The next part is "turn" action before any "proceed" action. For example, "turn left and follow the wall on your left".
- The generation of a main action is the part taking most time in an instruction. Obviously, a "turn" action takes much shorter time than a "follow" action.
- A "turn" may be attached to the end of a main action for reducing the complications of the next instruction. If there is no such action to add at this point, the instruction should include the ending condition for this main action. For example, "follow the wall on your left and stop at the next opening".
- The last instruction will point out the position of the chosen destination when the user reaches the expected position.

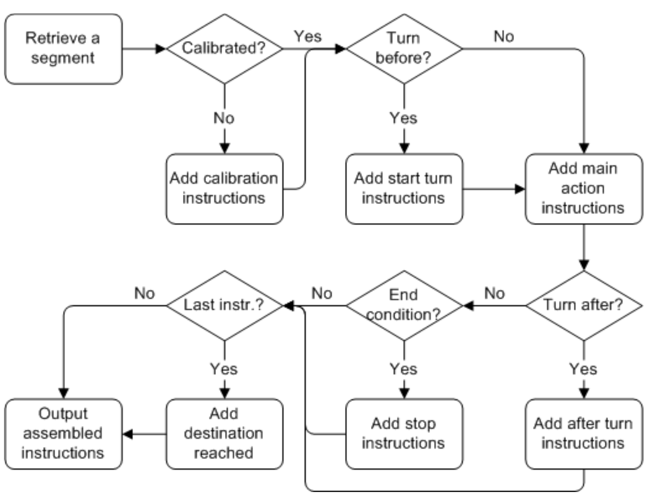

Figure 3. Segment Translation Flow Chart

Since one instruction may include several short and long sentences, we connect the phases with words such as "and" or "then". For example, "turn left" and "follow the wall on your left" will be connected with " and "; but "follow the wall on your left to pass three recessed areas" and "stop at the next opening" will be connected with ", then ".

V. Test and Results

We deployed the system in a three-story building at the University of Massachusetts Amherst, MA. The building includes 59 doors, 9 corridors, 4 open areas, 24 recessed areas, one elevator, three exits and two stairwells. The generation of the user-centric graph (1.2MB) was performed on a server and took 77 seconds. The graph was downloaded into a client device (GALAXY S4 smartphone), which was used by each subject to acquire the navigation instructions.

The tests of this system mainly focus on three aspects: efficiency of the instruction generation algorithm, the correctness of the generated paths, and the quality of the navigation instructions.

A. *Instruction generation efficiency*

The instruction generation time is measured from the time the user inputs the destination until the instructions are generated. The instruction generation time for over 99% of the paths is less than 15.5 seconds. Since this time depends on the processing power of the Smartphone, as the phone's CPU doubles its processing power with each generation, this instruction generation time will significantly decrease.

B. *Correctness*

The correctness of the paths generated between each pair of source and destination pairs is an important feature of a navigation system. We tested the correctness of these paths by manually following the paths on the building blueprint. A path will be considered as a failure if it fails to be generated, or the path does not lead to the chosen destination. There are 2162 paths in total, which are all successfully generated and lead the users to the correct destination.

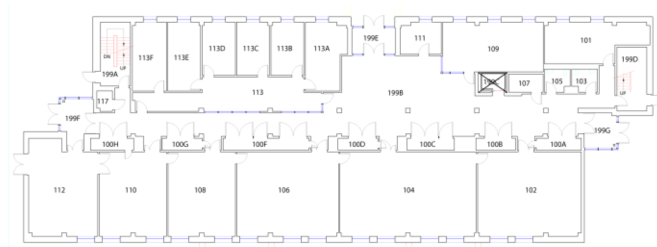

Figure 4. First floor layout

Figure 5. Third floor layout

C. *Instruction Quality*

The testing area includes the first and third floors of the building (see Figures 4 and 5). We tested the quality of the instructions with four blindfolded sighted subjects using a white cane. Each subject followed each of the 10 paths shown in Table IV. For each subject and each path we recorded the total time required to reach the destination and the navigation efficiency index (NEI) [20]. NEI is the ratio between the length of the actual path and the path generated by our algorithm. The average total time and the average NEI are shown in Table IV. From Table IV we observe that all subjects have reached their chosen destination. In 9 out of 10 paths the NEI is very close to 1, i.e., the subjects followed the navigation instructions correctly with minor deviations from the paths. For one path (path from room 308 to Room 108) the subjects overshoot the destination (the subjects missed the recessed area) but since our system provides dynamic instructions from any source to any destination the subjects eventually reached the destination.

TABLE IV INSTRUCTION QUALITY TEST RESULTS

Path	Total Time (s)	Time/Step (s)	NEI
Room 312 to Room 307	119.00	39.67	1.00
Room 307 to Room 308	89.50	22.38	1.00
Room 308 to Room 108	273.00	34.13	1.13
Room 108 to Men's room	178.00	59.33	0.97
Men's room to Room 111	57.00	57.00	1.00
Room 111 to Room 302	175.00	35.00	1.00
Room 302 to Women's room	56.00	18.67	1.00
Women's room to Room 309	77.00	77.00	1.00
Room 309 to Room 301	97.50	97.50	1.00
Room 301 to Room 312	139.00	46.33	1.03

The average time per step for each path is no longer than 2 minutes. For most of the tests, subjects can reach the destination in one attempt, except three paths below. Overall, the results show the ease to understand and stability to generate instructions for different paths.

- Path from room 108 to men's room is blocked by some furniture, which is not recorded in building structure. The detour at that point creates a shortcut compared with original path. So the NEI is less then 1.
- In the path from room 308 to room 108, some subjects walk into a recessed area when instruction tells cross the corridor. It leads them miss this recessed area while following the next instruction and overshoot the destination. But by scanning the tag there, they get the instruction back to Room 108 again.
- Similar, in path room 301 to room 312, subjects misunderstand the instruction of "pass the second door" as "stop at the second door", which causes them turn before the turning position. Further when they cross the corridor, they walk into a recessed area. However, the destination is the next recessed area on left; it doesn't bother them to reach the destination.

VI. CONCLUSION AND FUTURE WORKS

To the best of our knowledge this is the first paper that introduces a solution for automatic generation of navigation instructions for blind and visually impaired users.

We successfully tested the system in a three-story building. The testing included the efficiency of the instruction generation algorithm and the correctness of the generated paths. Four blindfolded sighted users that used a cane and a Smartphone were all able to successfully reach the chosen destination in 10 different scenarios.

Our next steps are to test the system with blind and visually impaired users.

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