ISANA: Wearable Context-Aware Indoor Assistive Navigation with Obstacle Avoidance for the Blind

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Abstract. This paper presents a novel mobile wearable context-aware indoor maps and navigation system with obstacle avoidance for the blind. The system includes an indoor map editor and an App on Tango devices with multiple modules. The indoor map editor parses spatial semantic information from a building architectural model, and represents it as a high-level semantic map to support context awareness. An obstacle avoidance module detects objects in front using a depth sensor. Based on the ego-motion tracking within the Tango, localization alignment on the semantic map, and obstacle detection, the system automatically generates a safe path to a desired destination. A speech-audio interface delivers user input, guidance and alert cues in real-time using a priority-based mechanism to reduce the user's cognitive load. Field tests involving blindfolded and blind subjects demonstrate that the proposed prototype performs context-aware and safety indoor assistive navigation effectively.

Keywords: Indoor assistive navigation · Context-aware · Semantic map · Obstacle avoidance · Tango device

1 Introduction

In recent decades, numerous indoor assistive navigation systems have been explored to augment the navigation capabilities of people with mobility impairments, especially the blind and the visually impaired. According to the fact sheet of Visual Impairment and Blindness from World Health Organization as of August 2014, 285 million people are estimated to be visually impaired worldwide, among which 39 million are blind and 246 million have low vision [1]. In addition, according to statistics data from the National Eye Institute, cases of blindness in the United States have increased from 0.9 million in 2000 to 1.3 million in 2010, showing that the number of people living with blindness is increasing [2].

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Indoor assistive navigation has been an important research focus in the robotics community, especially addressing the following multiple challenges: (1) Indoor localization where GPS fails; (2) Obstacle avoidance for safe travel in dynamic environments; (3) High-level indoor spatial-temporal modeling to support semantic context awareness; (4) System integration to produce a compact and wearable device. Various proprioceptive and exteroceptive sensors have been applied to indoor autonomous robots, such as inertial measurement units (IMU), magnetometers, wireless models, infrared, sonar, laser scanners, and vision (RGB or/and Depth) cameras. Recently, compact mobile devices have emerged with real-time 3D vision computational capabilities, including embedded graphics processing units. The availability of visual-inertial odometry (VIO) algorithms on these platforms (such as Google Tango or Structure IO) provides the potential to support portable real-time indoor assistive and safe navigation.

Based on our previous research on visual SLAM-based assistive navigation and obstacle avoidance [3–6], in this paper, we present the Intelligent Situation Awareness and Navigation Aid (ISANA) system for the blind. Its functions include indoor assistive navigation with context-aware indoor maps, navigation guidance, obstacle avoidance and user-friendly speech-audio human machine interaction (HMI) [7]. We developed the ISANA system based on the Google Tango device[1], an RGB-Depth camera integrated mobile Android tablet, with the capabilities of six degree-of-freedom (6-DOF) ego-motion VIO tracking and feature-based localization.

The main contributions of this research are as follows:

(1) Novel semantic maps to support high-level semantic localization, navigation and context awareness, through alignment of the semantic map with feature-based localization maps from Tango device. We developed an indoor map editor to parse semantic and topological information from the building architectural model files, and alignment algorithm to bridge the localization among semantic map and 6-DOF pose from the device.
(2) An efficient and real-time obstacle detection and avoidance approach was designed based on the 2D projection and analysis from the point cloud detection. Obstacles are tracked using a connected component labeling algorithm.
(3) Our implementation of the ISANA prototype in field tests with blindfolded and blind subjects demonstrates the effectiveness of the system in aiding the blind safely with indoor independent navigation.

The remainder of this paper is organized as follows. In Sect. 2, several recent vision-based indoor assistive navigation systems for the visually impaired are reviewed. Subsequently, an overview of our system is presented in Sect. 3. In Sects. 4 and 5, we explain our approaches to how the semantic map, semantic localization, navigation with obstacle avoidance, and speech-audio user interaction all work together. In Sect. 6, the experimental obstacle detection and avoidance, and system evaluation are described. Finally Sect. 7 presents conclusion and discusses directions of future research.

[1] https://developers.google.com/tango/.

2 Related Work

In this section, various vision-based portable/wearable assistive navigation systems are reviewed. Because vision cameras can be context-rich, low cost, low-power consumption and light weight, they have been utilized for real-time assistive navigation systems in several variants, such as monocular cameras [8–11], stereo cameras [12–14], fisheye cameras [15], omnidirectional camera [16], and RGB-D cameras [17–20].

The University of Southern California stereo system [13] is known as an early complete wearable navigation prototype which applied a head-mounted vision sensor and a tactile feedback actuator. Stereo visual odometry (VO) is estimated by matching features across two stereo views, then simultaneous localization and mapping (SLAM) is performed. Obstacle detection is obtained from stereo point cloud processing and represented in the traversability map. Finally, the system alerts the subject for the existence of the obstacles. However, the system still lacks obstacle modeling in a global map representation for navigation with obstacle avoidance.

RGB-D camera-based indoor assistive navigation systems have been also explored by researchers in recent years. The release of affordable commercial RGB-D cameras (such as Microsoft Kinect, Asus Xtion Pro Live) has attracted a great deal of attention among researchers and produced a surge in 3D SLAM research. It has been utilized effectively to acquire 3-Depth information, along with RGB images to augment indoor assistive navigation [17,18,20–22]. In the system of [20], the fast odometry from vision (FOVIS) algorithm is designed to perform real-time VO using RGB and depth images. Then a traversability 2D grid map is built for path planning. Obstacle avoidance is performed locally in real time. Finally, a tactile feedback system generates cues to guide the user (visually impaired) along the computed path and alerts obstacle existence. The mobility experiment shows the efficiency of the system. However, it relies on heavy and complex handhold devices, which limits its portability and feasibility for daily use.

The notion of "context-aware computing" was first advanced in the early 90's [23]. It was gradually integrated into assistive navigation systems [24–29]. However, this early research was more from a spatial-temporal knowledge modeling and management perspective, rather than being adopted into an assistive navigation prototype.

By integrating cutting-edge techniques and taking advantage of the feature-based localization on the Tango platform, the proposed system aims at providing a complete indoor assistive navigation prototype for the blind, with indoor semantic maps to support context awareness and real-time obstacle alert and avoidance for safety.

3 System Overview

Our platform is running on a portable Tango Android tablet mobile device, which has builtin functionalities of area description file (ADF, a feature map of the environment) and VIO. The VIO and loop closure with ADF provide the localization/re-localization capabilities for the device. The functionalities of ISANA include:

(1) An indoor map editor parses semantic information from architectural CAD models;
(2) Localization alignment on the semantic indoor maps based on the ADF and VIO;
(3) A path planner and waypoint algorithm design [5];
(4) Obstacle avoidance and alert, for both in-front and head-height obstacles;
(5) Assistive text and sign reading [30];
(6) Speech-audio HMI [7].

The physical configuration of ISANA is shown in Fig. 1, which shows a Tango device, a holder, and a white cane.

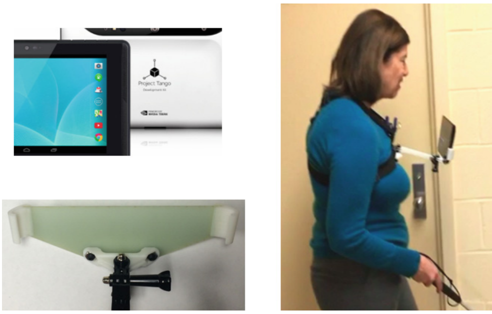

Fig. 1. ISANA system configuration on a blind subject (photo courtesy)

ISANA provides blind users with high-level context awareness based on semantic indoor maps and navigation with obstacle avoidance functionalities, along with user-friendly speech-audio interaction. The system architecture of ISANA is illustrated in Fig. 2. Indoor maps provide spatial models of the environment as well as user profiling (such as stride length). The RGB-D camera supports scene recognition and obstacle detection. Assistive navigation generates the route and interacts with the user by speech-audio interface. The blind user is the final decision maker, since ISANA will respond to the user's motion, rather than controlling it. In addition, the blind user still can, as usual, use a white cane to gain tactile feedback for the safety zone in front.

There are two distinct applications in our system. The ISANA indoor map editor performs offline semantic map construction by parsing architectural model files. The ISANA App performs the functionalities of semantic localization on the semantic map, navigation guidance, obstacle avoidance and alert, and speech-audio HMI for the user.

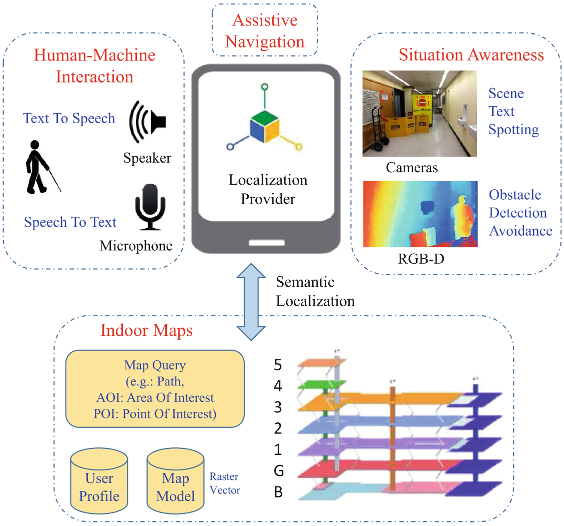

Fig. 2. ISANA navigation system overview

4 Indoor Semantic Maps and Localization

Computer-aided design (CAD) files are the most commonly used models for building architectural drawings. They oftern contain raw geometric information about the building, such as door sectors, room text labels, fire exit labels, wall.

4.1 Semantic Map Analysis

We have automated the semantic map generation process by developing our indoor map editor which converts raw building drawing exchange format (DXF) files of architectural floor plans into spatial semantic information maps. Then, based on region segmentation analysis and the dimensional information for all regions, our indoor map editor recognizes hallways, and topographic relationships between room and labels of corresponding doors are further retrieved (although with some failures, shown as red area) in Fig. 3.

4.2 Alignment for Semantic Localization

By parsing the CAD file of an architectural floor, we acquire an indoor semantic map of the floor with semantic information marking the locations of rooms and doors. Then, using the indoor map editor, necessary semantic landmarks such as elevators, stairs, and labeling information for each room are added into the semantic map.

ISANA provides semantic localization on top of the ADF map. The ADF map is created by the Tango device, containing the visual features of keyframes

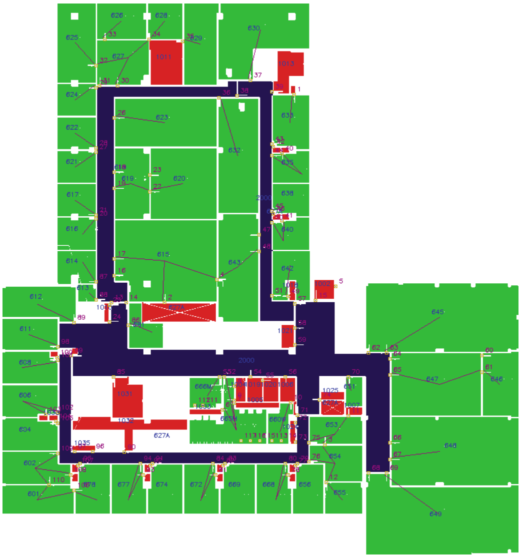

Fig. 3. The semantic and topology information retrieving (with room labels, doors, topologies, hallways, etc. Red areas are regions fail to find topological connections to doors.) (Color figure online)

from camera images. Figure 4 illustrates the concepts of maps alignment for localization on the semantic map.

The procedure of map alignment is:

(1) ISANA starts and localizes itself within the ADF map, based on the loop closure of the Tango VO.
(2) The user walks around the environment and stops by several doors. The user may request ISANA's scene text recognition module [30] to acquire door label text. In the case where no text regions can be found, control points will be set in the semantic map for the alignment, using screen tactile input during walking.
(3) Pairs of door locations on the semantic map and corresponding locations in ADF are recorded.
(4) Using singular value decomposition (SVD) algorithm, calculate the affine transformation alignment matrix between ADF and the indoor semantic map.

5 Navigation in Dynamic Environments

In this section, we elaborate the design of the navigation functionalities of ISANA in dynamic environments. With the semantic map and alignment localization, a quick-response obstacle detection approach is performed in real-time to update

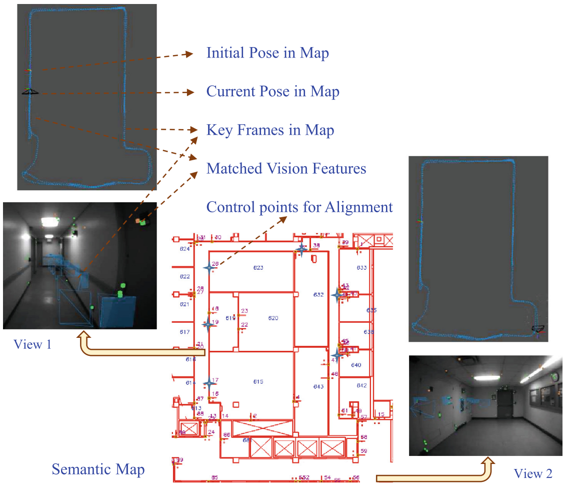

Fig. 4. Indoor semantic and ADF maps alignment (The middle is the semantic map with POIs, and control point are shown as the stars which are detected by text recognition. The side figures show the ADF features in keyframes.)

the global traversability 2D grid map and provide safety alerts, with head-height obstacle detection as well. Then the path planner [5,31] generates a safe route based on the updated map information. Finally, a priority-based speech-audio HMI provides interaction guidance and alert cues for the user.

5.1 Obstacle Detection

For the safety of blind users, we designed a quick-response obstacle detection procedure using the 5HZ Infrared (IR) depth camera to run in real-time on the Tango device. This operates efficiently without model retrieving of 3D point cloud. A novel two 2D depth projection approach provides both obstacle updates for the navigation map (by horizontal projection), and front obstacle alert (by vertical projection). We improved computational efficiency by handling the data processing with linear complexity regarding point number in the detected range, comparing with our previous result [6] using random sample consensus (RANSAC) segmentation. As shown in the left part of Fig. 5, first a noise filter is performed to remove the stand-alone points, and then based on the pitch angle of the current pose information, a de-skewing process is performed to align the 3D point cloud with the horizontal floor plane. The local 2D grid map is acquired by the 3D to 2D projections, in both horizontal and vertical directions.

Then in the right of Fig. 5, the depth data is updated for the 2D grid maps in the local and global world frame, for purpose of obstacle detection. A connected component labeling algorithm [32] (or [33]) is applied to cluster the connected objects in the grid maps.

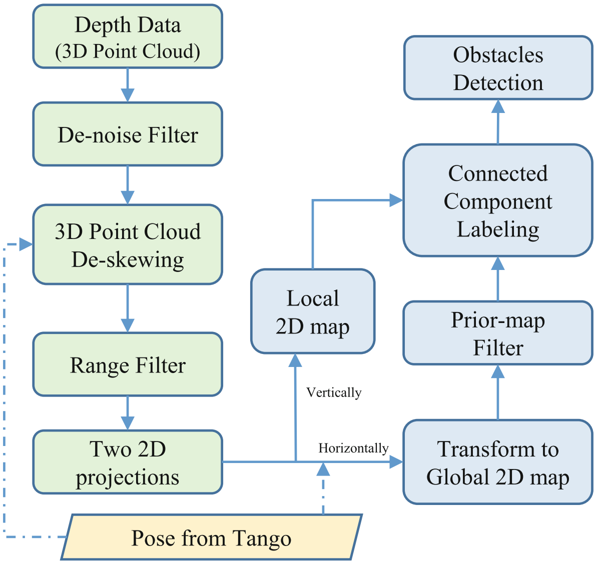

Fig. 5. Obstacle detection process flowchart

5.2 Navigation with Obstacle Avoidance

Based on the semantic map and localization, A^* [5,31] algorithm is applied in ISANA as the path planner to find the route to a desired destination. Meanwhile, we perform obstacle avoidance for safety route as a safety measure.

Obstacle avoidance is supported both locally and globally. For the non-navigation model (which the user has not set his/her destination), local obstacle avoidance provides the user with obstacle-free direction guidance when there are obstacles detected based on the vertical projection. During the navigation process, global obstacle avoidance is performed by updating the global 2D grid map based on the horizontal projection. Then, ISANA generates a new path and gives the user new guidance direction information. The procedure for obstacle avoidance during navigation is as following:

(1) Obstacle detection using a connected component labeling algorithm.
(2) Update occupancy information of obstacles into grid map.
(3) Use A^* to compute a new guidance route on the gird map.
(4) Deliver audio guidance on user direction, incorporating updated path information.

5.3 Navigation Guidance HMI

Speech-audio HMI is an important and challenging part for any assistive navigation system. Traditionally, many assistive navigation systems have used other HMI modes, such as tactile feedback, limited audio feedback, or a keyboard to minimize cognitive interference with the user's auditory environment. However, in order to provide rich and effective semantic and guidance information, ISANA uses speech-audio HMI, and delivers safety alerts to the user using a priority-based mechanism. This allows high priority messages to be delivered in real-time to the user, with permission to overwrite the current occupied delivering message.

Specifically, we use the Android Text-to-Speech (TTS) module[2] to convey obstacle detection results and other environmental information to the user, including HMI command feedback, real-time guidance, current location, etc.

As for system input, many previous assistive navigation systems rely on a physical button or touchscreen devices. However, these tend to be inconvenient for a blind user since they require the use of at least one hand. Instead, we implemented a Speech-to-Text (STT) module [7] based voice input to help the user interact with the ISANA system. We use the CMU PocketSphinx[3] STT engine to receive the voice commands from the user. The blind user can also query his/her real-time location based on the semantic localization. A specific acoustic model is also trained to further improve the recognition accuracy and decrease the influence of the environmental noise. We also built a keyword list and grammar to narrow down the search space of the speech recognition module and improve the performance of the statistical language model. The effectiveness of the TTS and STT modules has been validated in our experiments, and holds promise for significantly enhancing the practicability of our proposed algorithm and system.

6 Experiment

We tested the ISANA system using blindfolded and blind subjects, for its qualitative effectiveness in guiding users to their destinations. By defining the graph connections between different floors through connectors such as stairs, elevators or escalators, multi-floor navigation is supported as well.

6.1 Obstacle Detection

Figure 6 shows a final visualization of detected obstacles in a hallway on the ISANA graphic user interface (GUI), with wall filtering based on the semantic map and localization. Different objects are shown as different bounding boxes in front of the user.

A more detailed evaluation of the obstacle detection including walls was performed in a hallway, where both the user and a cart are moving. The horizontal 2D projection and its histogram analysis are shown in Fig. 7, and the vertical 2D projection and its histogram analysis in Fig. 8.

Figure 7 (left) shows the 2D projection to floor plane. Walls are shown on the two sides of the figure, and we compute the closest obstacle point (shown as red

[2] http://tinyurl.com/Android-TTS.
[3] http://cmusphinx.sourceforge.net.

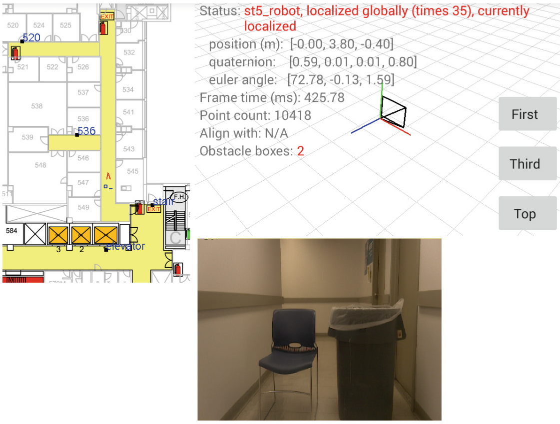

Fig. 6. Obstacle detection results from depth detection projection (The two objects in-front are projected from the 3D point cloud horizontal projection, and are detected and tracked by the connected component labeling algorithm.)

"x" in front). Figure 7 (right) is the weighted histogram of the floor plane projection to show the obstacle-free path direction based on vector field histogram (VFH) [34] approach.

To handle head-height obstacles, we performed a vertical plane 2D projection, as shown in Fig. 8 (left). The red "x" shows the obstacle height (relative to the Tango device) as the closest obstacle detected by the vertical floor projection. Figure 8 (right) shows the front obstacle-free VFH histogram of vertical plane projection with respect to the front direction in degree.

6.2 Navigation with Obstacle Avoidance

After we acquire the detected obstacle boxes and points in the global world frame, obstacle avoidance is performed based on the path planner of A^* algorithm. Figure 9(1) shows the path when there are no obstacles. Then when ISANA detects obstacles in front, a new route will be generated as shown in Fig. 9(2), and as the obstacles move, routes will be updated according to the obstacle detection, as shown in Fig. 9(3).

6.3 System Evaluation

An ISANA single floor navigation screenshot on the Tango device is shown in Fig. 10. Semantic maps with grid maps are processed by the indoor map editor. The online and dynamic path to a desired destination is updated by the path planner based on obstacle detection, with multiple waypoints on the path for guidance. Obstacles are detected using the RGB-D sensor and point cloud is projected in 2D horizontally and vertically. To make alerts more relevant, existing walls and objects whose height is within the white cane's sensing range do not

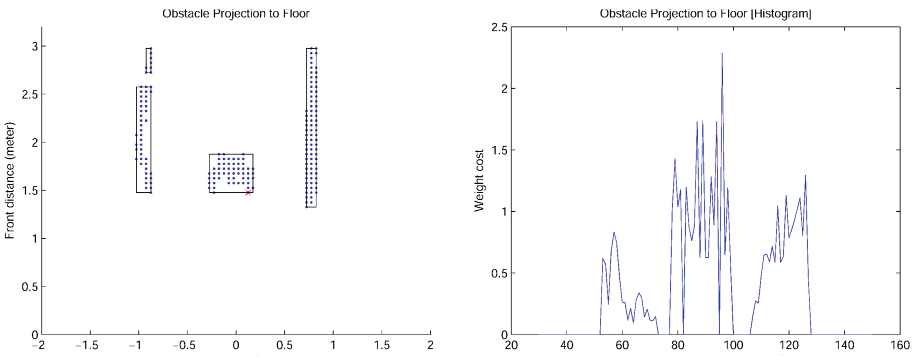

Fig. 7. Left: Obstacle detection floor plane projection, red "x" is the closest point, the horizontal axis is the left to right direction in meter, and the vertical axis represents the forward direction in meter. Right: Obstacle histogram, the horizontal axis is the angular directon of obstacle in degree, and the vertical axis represents the weighted cost of obstacle points with related to their distance in horizontal plane to the user. (Color figure online)

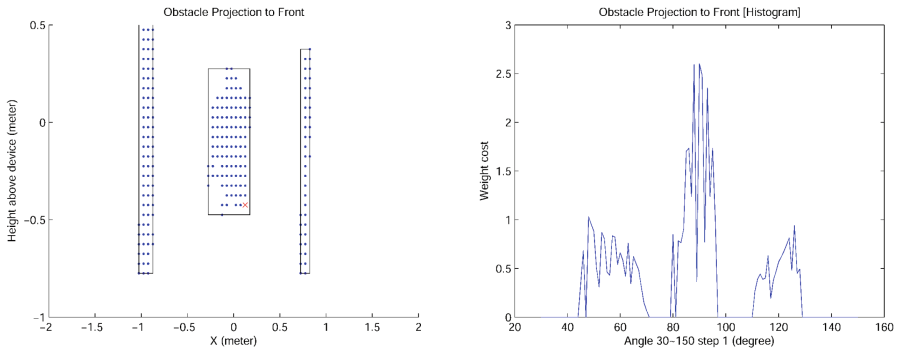

Fig. 8. Left: Obstacle detection vertical plane projection, red "x" is the closest point, the horizontal axis is the left to right direction in meter, and the vertical axis represents the upward direction in meter. Right: Obstacle histogram, the horizontal axis is the angular direction of obstacle in degree, and the vertical axis represents the weighted cost of obstacle points with related to their distance in vetical plane to the user. (Color figure online)

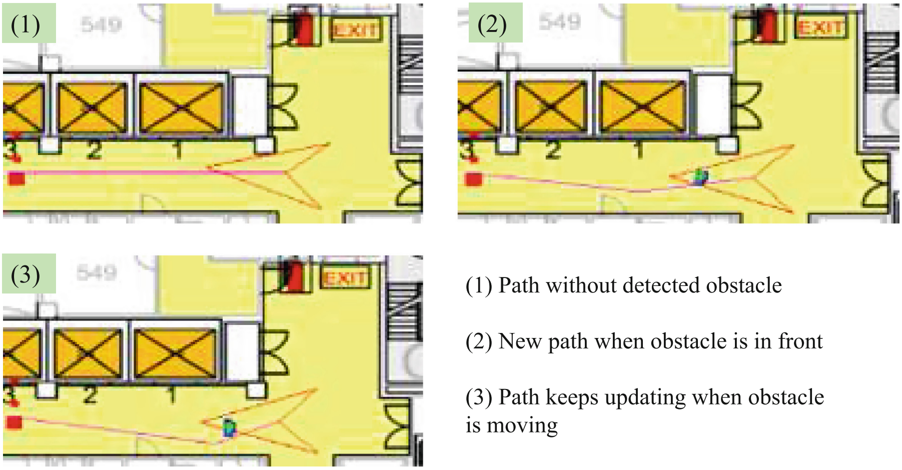

Fig. 9. Obstacle avoidance

elicit alerts from ISANA. As shown in Fig. 10, the yellow safety fence is detected as an front-left obstacle and alert is issued to the user. A beeping alert sound is also conveyed to the user, with distance to the obstacle signaled by beep frequency.

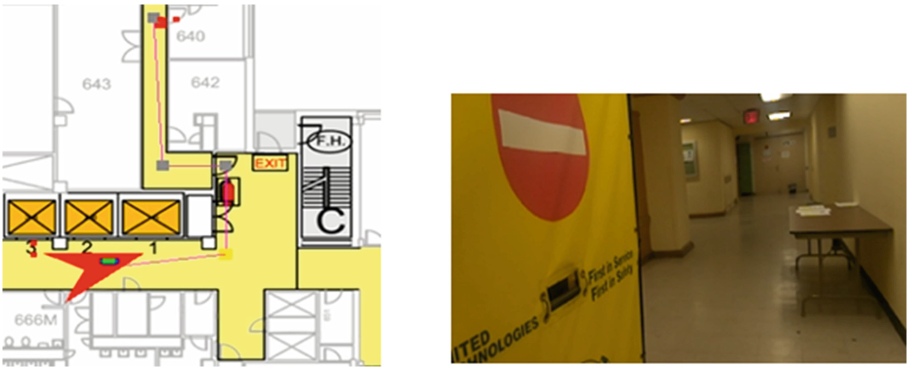

Fig. 10. ISANA App GUI with camera view

7 Conclusions and Future Work

In this research, we have proposed and designed a mobile wearable context-aware Intelligent Situation Awareness and Navigation Aid (ISANA) prototype system as an aid to the blind people for indoor assistive traveling. Our experimental demo with blindfolded and blind subjects demonstrates the effectiveness of our ISANA prototype in providing the blind community with an aiding tool for indoor traveling, context awareness and situation awareness of the user's surrounding cyber-physical world. Our future work will focus on dynamic obstacle modeling and prediction, and on environment understanding.

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