Semantic indoor navigation with a blind-user oriented augmented reality

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***Abstract*—The aim of this paper is to design an inexpensive conceivable wearable navigation system that can aid in the navigation of a visually impaired user. A novel approach of utilizing the floor plan map posted on the buildings is used to acquire a semantic plan. The extracted landmarks such as room numbers, doors, etc act as a parameter to infer the way points to each room. This provides a mental mapping of the environment to design a navigation framework for future use. A human motion model is used to predict a path based on how real humans ambulate towards a goal by avoiding obstacles. We demonstrate the possibilities of augmented reality (AR) as a blind user interface to perceive the physical constraints of the real world using haptic and voice augmentation. The haptic belt vibrates to direct the user towards the travel destination based on the metric localization at each step. Moreover, travel route is presented using voice guidance, which is achieved by accurate estimation of the user's location and confirmed by extracting the landmarks, based on landmark localization. The results show that it is feasible to assist a blind user to travel independently by providing the constraints required for safe navigation with user oriented augmented reality.**

***Index Terms*—floor plan, signage, human motion, indoor navigation, augmented reality**

I. INTRODUCTION

According to the World Health Organization, about 285 million people are visually impaired, with 39 million completely blind [1]. These people live in this world with incapacities of understanding the environment due to visual impairment. Individuals with normal vision, who view a floor-plan in order to navigate to a room of interest, can infer a shortest route to safely reach a destination and confirm the travelled route based on the identification of landmarks on their way. Whereas, in case of individuals with visual impairment, its highly challenging to make them independently navigate to a destination. So, research in the field of navigation, applied to power the mobility of visually challenged has concerned sophisticated technology and techniques. A more effective approach is to solve this problem in real-time using an AR interface by taking advantage of semantic cues in the surrounding real environment of the user.

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In robotics, a precise model of the relationship between control parameters and body kinematics is designed as a motion model. This is influenced by physical constraints in the environment in order to navigate a robot to next step towards the destination. In contrast, a human acquires control parameters that yield safe navigation from the physical constraints of the environment. If these constraints change, a Human may adapt to optimize those parameters until path is stabilized again. Whereas, a visually impaired person is still a human, who can actively adapt to the environmental parameters, provided these constraints are precisely nurtured, in a blind perceivable manner. So, this paper focuses on enforcing those constraints required for safe navigation of a visually impaired person using an AR interface.

A. Challenges

The challenges involved in designing a navigation framework for a blind user oriented AR are as follows:

- How to conceive an AR environment that enforces the constraints of a real word required for safe navigation?
- How to enhance the perception of the user at each step based on a real-time augmentation?
- How to emphasize the semantic cues inferred from a floor plan to design a meaningful schema?
- How to direct the travel route in terms of blind understandable units to notify the intended travel route?
- How to predict a human walk and plan a path by avoiding the obstacles on the way towards the destination?

B. Contribution

This work is a significant extension of the previous works by the authors on visual semantic parameterization [2], fast visual odometry [3] and optical character recognition [4]. In this paper, we implemented our proposed visual semantics by conducting blind folded experiments in real-time while the previous paper had simulated results. Haptic augmentation is provided at each step of the user through vibrotactile belt based on the location updates from the metric localization. It is implemented using our proposed visual odometry, which is adapted to the human steering dynamics to conceive AR and imitate natural human walk. This visual odometry estimates the user's trajectory even if the user stops or stands still using zero velocity model. This replaces other inertial sensors or pedometer to predict step length on the fly. Voice augmentation is provided through the speaker, based on the annotation of the landmarks from landmark localization using optical character recognition algorithm. This assists the user to be aware of their location specific information, when the user traverses to the corresponding landmarks within the floor-plan map. Both metric as well as landmark based localization is integrated in our system to accurately track the user on the acquired floor-plan schema. This solves the kidnap problem, wherein our system will be able to recognize the user location anywhere on the floor-map based on the landmarks, in case the visual odometry fails. We only integrate a head-mounted camera and waist-mounted kinect to conceive the user environment. Haptic belt and speaker are integrated to enhance the perception of the user. This design promotes an inexpensive conceivable wearable navigation system for the blind user.

II. Literature review

In order to conceive an indoor map for navigation of a blind user similar to a normal visioned person (who can visualize clues inherent in the building and navigate), several systems are developed using the conventional approach of generating a travel route by utilizing a precise 'pre-build map' maintained in its database. This interaction style of manually feeding the constraints in the environment and then initiating the navigation process is referred as mixed-initiative modeling of navigation.

The system providers need to manually create a building infrastructure and feed the floor-plan into the system after explicitly annotating the landmarks within the map, before the blind user initiates a navigation task. Apostolopoulos and Fallah et al proposed Navatar that requires collection of building map and manual preprocessing to annotate landmarks required for navigation [5], [6]. The advantage of this mixed-initiative model is to utilize a powerful desktop computer that can augment a map with meaningful information within a short timespan.

Lee et al proposed universal circulation network for the wheel-chair access in architecture planning. It is derived from the Building information model (BIM) by using the door points to generate a graph plan [7]. Karimi et al proposed an approach in universal navigation on smartphones. It requires an interpolation scheme that uses spatial data on the end nodes of hallway segments. Geocodes that are computed from the co-ordinates of Point-of-interests are retrieved from a navigation database [8]. Lorenz et al proposed a navigation model with qualitative and quantitative labels for representing nodes (rooms and corridors) and edges (doors and passways). It uses access points to elevators to reach different floors from those interface nodes, provided by a graph hierarchy algorithm [9]. The main drawback with all these approaches are that the building information needs to be collected from the building owners and its meaningful information needs to be manually integrated into their system in order to generate a metric map for the indoor navigation.

Certain devices can track the user location and provide descriptive guidance to navigate to the desired route. Brock et al proposed a map prototype for the visually impaired based on a tactile paper map placed on a multi-touch screen which provides audio feedback of the map associated with touch events. However this prototype is very naive unless the tactile paper map is integrated inside a touch screen technology [10]. Heuten et al designed six vibrators on belt to indicate the travel direction through the changes in the intensity of the vibration depending on the deviations from the desired route [11]. This system requires more knowledge to understand the intended feedback to be used by a lay person.

The idea of solving the limitations and incapacities of the human misunderstanding due to the visual impairment is still an open problem. We propose a novel approach of indoor navigation by enforcing the environmental constrains that are perceived using an AR interface specifically for the ambulation of a blind person.

III. Problem formulation

Conceiving a navigation map from an unknown environment is a challenging problem. Although, in order to build a map, some complex task of acquiring the surroundings with sensors that approximately senses the environment can provide a layout of an indoor environment. However, in order to be used by a blind user, acquiring meaningful information or point of interest on that map is imperative. In the literature, research in the field of probabilistic robotics have solved the mapping approach using the simultaneous localization and mapping (SLAM) algorithm from the data acquired by sensors traversing along the entire environment [12]. But in our approach, we design a navigation framework called 'semantic schema' by inferring the meaningful information encrypted in the snapshot of a floor-map and finally, the designed schema will be updated or corrected when the human-user traverses to the corresponding locations on that map based on the landmark extraction. Moreover, a novel blind user oriented AR interface is integrated into the system to render the physical constraints of the real world around the blind user

IV. System overview

The process chart of the proposed conceivable navigation framework to augment the blind user perception is shown in Figure 1. If a normally sighted person identifies a floor plan posted on the building, then a snapshot of a floor plan can be acquired using the camera and provided to the blind user. The Visual semantic parametrization (section V) acts as a conception unit for our system. It employs a heuristic method of extracting room numbers and door shapes from a raw floor plan data, which further acts as a parameter for defining an entry point to each room. Semantic schemata (section VI) acts as a central processing unit of our proposed system. It perceives a mental mapping of the environment and organizes the semantic information to generate a navigation framework called 'semantic schema' for the future use. When the user specifies a room of interest, both the qualitative and

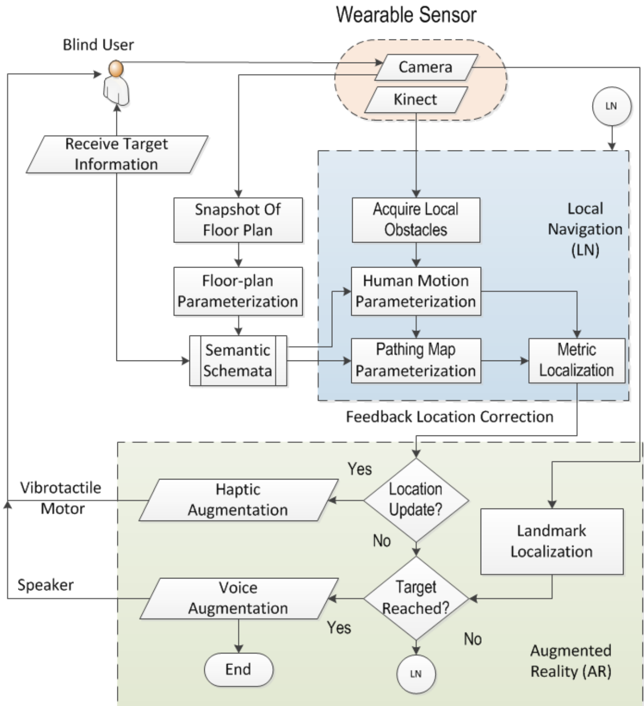

Fig. 1. Process chart of the proposed approach

Fig. 2. Partial view of a typical floor plan map with detected regions of room numbers marked in red (best viewed in color version)

the quantitative information of the desired room is inferred from the semantic schema. It also provides the shortest route to reach a destination, including all the landmarks within the intended route. Human motion parametrization (section VII) solves the local obstacle avoidance problem by predicting a human path to reach those landmarks using a real-time path finding in local map. Pathing map parametrization (section VII) acts as a guidance module to direct the user towards the travel direction, adapted from the floor-plan map. AR Interface (section IX) acts as a feedback unit for rendering the real world around the blind user through haptic and voice augmentation.

V. Visual semantic parameterization

In order to make the user aware of their location specific information, contextual information from landmarks such as floor-plan, signage, room numbers on the door, etc are parameterized to infer its meaningful information.

A. Floor-plan parameterization

This paper uses a novel heuristic method of extracting layout information from a floor map, which employs room numbers and door shapes, etc., as a parameter to infer the way points to each room. It is closely based on the previous work of the authors [2]. This method can be divided into two steps: room number detection and door shape detection. We implement a rule-based method to localize the positions of all room number labels. First, Canny edge detection is applied to obtain the edge map. Second, the boundaries that are composed of connected edge pixels are extracted from the edge map. Each boundary is assigned a bounding box with compatible size. Third, for each bounding box, we check whether it is located at the middle of two neighboring bounding boxes in similar height and horizontal alignment. If yes, we merge the three bounding boxes into a boundary group. Fourth, each boundary group is then extended into a room number region.

Based on the detected regions of room numbers as shown in Figure 2, we search for the range of the rooms and positions of the room doors in the floor map. As our observation, the door in the floor map is mostly in the form of D-shape. To detect the D-shape, a horizontal and a vertical scan are respectively generated from the region of room number. If the scan line touches the D-shape, one of its ends will have a monotonous variation. Therefore, we could detect a rough position of the D shape door. Assuming that all the doors correspond to the hallway path of this floor, we generate anchor point by using the room number label and the D shape door.

B. Landmark Localization

The floor-plan parameterization provides a global layout of an indoor map which is comprised of room numbers, its location, links to its neighboring landmarks, etc. These landmarks that are also displayed on the doors or walls are further extracted to localize the user, specific to the corresponding landmark on the global map. So, when the user traverses to the corresponding landmarks, the semantic information on the door landmarks such as room number or signage are extracted using a novel optical character recognition algorithm closely based on the previous work [4]. Then, the user's location specified by the landmarks on the global map are compared to confirm the correct travel direction of the user even if the user gets lost.

VI. Semantic schemata

In order to provide a navigation framework for the future understanding of the environment, we use schemata to organize the knowledge acquired on the floor plans from the previous section. So, semantic schemata acts as a central processing unit of our proposed system which is used to perceive a mental mapping of the environment.

The extracted meaningful information such as room number labels and its entry points on the hallway boundaries obtained from the previous section are used to generate a graph of nodes. A precise plan or schema is designed using those nodes which consists of all the waypoints to enter a room of interest in the building. Thus, a database with both the quantitative and the qualitative information is maintained to provide knowledge on the following: (1) identify a room of interest, (2) its location on the global map, and (3) all the neighboring waypoints connected to it. These information can be used to explore the shortest path using conventional path planning techniques.

VII. Human motion parameterization

In order to navigate to a desired room, a blind person might need to pass through other rooms on the intended travel route provided by the semantic schema. These passing room numbers or signage can act as landmark to the blind person for confirming the user's planned route. So, the intended paths towards each door is emphasized as an instant goal. The problem of reaching each instant goal inferred from the semantic schema can be solved by a real-time path finding in local map which is considered as an obstacle avoidance problem.

To reach each instant goals towards the nearest landmarks, a bio-inspired motion model is required to predict the user path. This motion model should effectively repel from the obstacles and safely navigate towards the nearest landmark. Hence, a human motion model originally proposed by Fajen et al. [13] is employed to imitate how humans walk towards the goal by avoiding obstacles using behavioral dynamics.

An illustration of the proposed working scenario with the model parameters involved in the blind inferenced motion model is shown in Figure 3. Here, we consider a scenario where a blind person intends to start from the exit to reach a final destination of laser research lab. The instant goal from the exit is identified as restroom. A typical floor plan view with a blind person on the intended travel path in a local framework, is augmented with real-time obstacles. This is integrated into the semantic schema to predict the state of a Human model inferred from the following parametrization:

- the heading direction, Θ of the blind person (blue dotted line) with respect to the reference frame (black segmented line)
- the orientation, Ψ_g and distance, d_g towards the goal (green dotted line) with respect to the reference frame;
- the orientation, Ψ_{o_i} and distance, d_{o_i} towards the obstacles (red dotted lines) with respect to the reference frame, where i is the number of obstacles;
- intended signage of the restroom to confirm the instant goal.

Thus, the real-time obstacle avoidance problem is solved by finding a path in local map using the following human motion

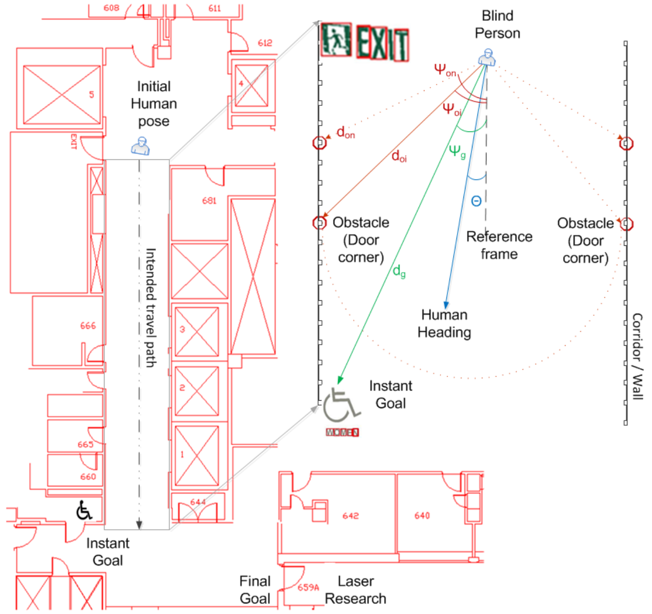

Fig. 3. Illustration of the proposed working scenario with the model parameters involved in the human motion parameterization

model,

$$\frac{\partial^2 \Theta}{\partial t^2} = -f_d\left(\frac{\partial \Theta}{\partial t}\right) - f_g(\Theta - \Psi_g, d_g) + \sum_{i=1}^{n} f_o(\Theta - \Psi_{oi}, d_{oi})$$

Where f_d, f_g, f_o are damping, goal and obstacle components, respectively. So, Ψ_g, d_g, Ψ_{o_i} and d_{o_i} change as the position of the human changes and a new path is generated to reach the instant goal. Again, the same process is repeated in order to enforce the user to continue and follow the generated path towards the next landmark (new instant goal) until the final destination is reached.

VIII. Pathing map parameterization

In order to direct the user towards the correct travel direction, an accurate estimation of the current user location is required. This is achieved by using a localization algorithm which is adapted to the floor plan.

A. Metric Localization

This paper uses a novel technique of a real-time fast visual odometry and mapping approach for RGB-D cameras. It is closely based on the previous work of the authors [3]. The visual odometry relies on computing the locations of Shi-Tomasi [14] keypoints in the incoming RGB-D image, and their corresponding 3D coordinates in the camera frame. Next, we align these features against a global model dataset of 3D features, expressed in the fixed coordinate frame. Aligning is performed with the ICP algorithm [15]. After calculating the transformation, the model is augmented with the new data. We associate features from the RGB-D image with features in the model, and update them using a Kalman Filter framework. Any features from the image which cannot be associated are inserted as new landmarks in the model set. The model (which starts out empty) gradually grows in size as new data is accumulated. To guarantee constant-time performance, we place an upper bound on the number of points the model can contain. Once the model grows beyond that size, the oldest features are dropped to free up space for new ones. The entire process is presented in Figure 4. To be able to perform the data association and filtering accurately, we develop a novel method for estimating the uncertainty in the depth reading of the RGB-D camera. The method is based on a Gaussian mixture model, and is able to accurately capture the high uncertainty of the depth in problematic areas such as object edges. By performing alignment against a persistent model instead of only the last frame, we are able to achieve significant decrease in the drift of the pose estimation. We show that even with a small model size, we can accurately map out an environment the size of an office room, and accurately close the loop without the need of any additional back- end processing techniques typically associated with Visual SLAM algorithms.

The human motion parameterization predicts the user location on the global map which is used as an initial location estimate. The pose from the visual odometry provides a location update to adapt the user towards the correct travel direction. Hence, based on the location correction from the metric localization, a location update is feedback to the AR interface to direct the user to towards the correct travel direction.

B. Adaptation to Floor-plan

When the 3D map generated using the RGB-D sensor, based on the visual odometry is integrated with the 2D floor-plan layout generated from the schema, there might be some misalignment due to accumulated pose estimation errors. So, it is necessary to adapt the pose estimates in order to project the user location on the floor-plan. Our system passes RGB-D data on each step of the user to visual odometry module as discussed in the previous section. It projects the 3D point cloud onto 2D horizontal plane and stores the 2D projections with their current pose in buffer. The floor plan adaptation module samples and constructs the latest couple of 2D-projections into a unified binary matrix according to their recorded pose. Then, a geometric branch and bound matching is implemented using the maximum likelihood matching method to match the unified matrix and the binary matrix of floor plan ground truth. This obtains the current pose of the user with respect to the floor plan. Thus, a link between the current position from visual odometry and the location on the floor plan is established and the user location is acknowledged accordingly. As the projected 2D unified matrix has certain distortions and noises, the alignment of the RGB-D images to the floor plan is adapted similar to a particle filter algorithm. The system will keep an arbitrary number of ‘current locations on the floor plan’ with high likelihoods, and update the likelihoods after each given arbitrary interval. Thus, the adaptation can effectively correct the accumulative error caused in visual odometry by taking advantage of the floor plan which is regarded as the absolute ground truth.

IX. Augmented Reality Interface

In order to enhance the blind user’s perception of the surrounding environment for a safe navigation, our system integrates both the haptic augmentation and voice augmentation, which enforces the physical constraints of the user’s real world.

A. Haptic Augmentation

The Haptic belt is comprised of six vibrating motors embedded equidistance on the front-side 180 degrees of the waist belt. It is manipulated by a raspberry pi single board computer, which acts as a server to connect with the client in order to control the vibrators. If the metric localization provides a location correction, then the corresponding motor in the belt, vibrates to direct the user towards the correct travel orientation. This location update is adapted from the human steering dynamics to augment the user position at each step and imitate a natural human walk. We render the constraints surrounding the blind user through this position augmentation which acts as an interface to the user to perceive the real world.

B. Voice Augmentation

The semantic information conceived from the room numbers or signage can be used to annotate the landmarks. Voice augmentation is provided through the speaker based on the annotations provided by the landmark localization. This makes the user to be aware of their location specific information, when the user encounters the corresponding landmarks within the floor map. Even if the user is traveling in a wrong direction, this landmark localization feature enables the user to take an alternative route to reach the destination. Thus, our system can continuously guide the blind user until the target destination is reached.

X. Results and Discussion

In order to examine how our proposed system fits the requirements of a blind user to navigate on a natural way, similar to how a normal sited person walks, we conducted blind-folded experiments with four participants walking at different speeds. A scenario as discussed in Figure 3 is identified in all six floors of the building with landmarks such as exit, restrooms and other room numbers.

Initially, a real floor plan posted on each floor of the building is snapshot and processed to conceive the meaningful information encrypted on it using our proposed approach of visual semantic parameterization. When a goal is fed into the semantic schemata, it designs a schema with the linked landmarks and the shortest route to navigate from the exit to reach the destination. In our case, in order to reach the target destination, the user has to pass through an instant goal of restroom landmark. So, the task of navigating to an instant goal (restroom) using the proposed navigation approach is as follows:

The initial start location of the user is inferred based on the visual cue, shown in Figure 5(a). The semantic information encrypted in this cue is extracted as discussed in landmark

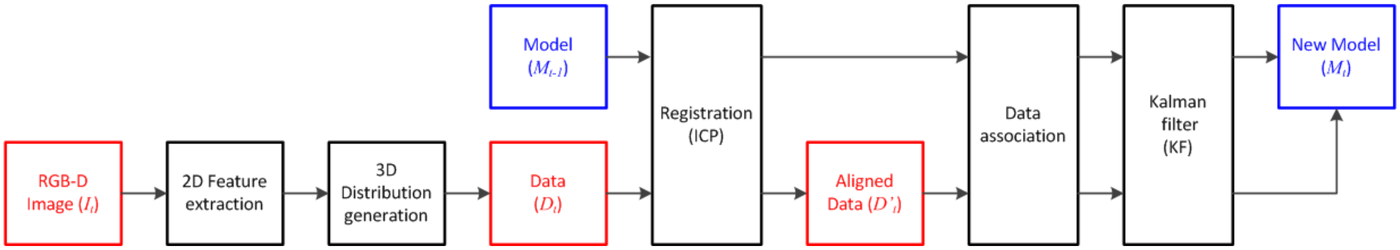

Fig. 4. Pipeline for the trajectory estimation. We align sparse feature data from the current RGB-D frame to a persistent model. The data is represented by 3D points with covariance matrices.

localization. The location of the user is confirmed after extracting the encrypted location cue as 'exit', see Figure 5(b). Now, the kinect camera is used to further analyze the environment around the user to identify any obstacles. If there is a local obstacle identified along the intended route previously planned by the schema, the human motion model repels the obstacles and predicts a path around the obstacle on the way towards the destination as shown in Figure 6. Then, the pathing map parametrization provides feedback to the AR interface to alter the travel route based on the metric localization at each step of the user.

The real path generated by a user towards the travel direction at sixth floor is shown in Figure 8. The green trajectory is the path travelled by the user and the number specified on the path is the step count of the user. Initially, the user starts near the exit landmark denoted by '1' and then starts moving towards the travel direction until the instant goal is reached which is confirmed after inferring the visual cue, as shown in Figure 5. The location of the user is confirmed after extracting the encrypted location cue as 'Women', see Figure 5(b). Then, the same process of navigating to the instant goals with new neighboring landmarks is repeated until the final destination is reached.

To test the reliability of the system, an error analysis is performed in the real-time environment on six floors. Figure 7 provides the localization error based on the data collected from the paths travelled by the users.

As the user travelled towards the instant goal, we noticed that there is an accumulation of error on estimating the pose generated by the visual odometry which further drifts over time. The error accumulated in this metric localization can be corrected using the landmark localization. So, when the user walks along the corresponding landmarks in the real environment, the location of the user is updated and then the generated path is further adapted to the floor-plan map as shown in Figure 9. Thus, the accumulative error caused in visual odometry is rectified by adapting it to the floor plan, which is regarded as the absolute ground truth. Now, the user will be acknowledged with the landmark information specific to the location of the user.

Table I provides the average distance between the true path of the user and the path estimated using localization in all six floors based on the intended travel route. The paths travelled by the user shows less deviation in the error values, which proves that our location estimate is much accurate in tracking

(a) Snapshot of scene (b) Extracted visual cues

Fig. 5. Snapshot of initial and final scene with inferred cues [2]

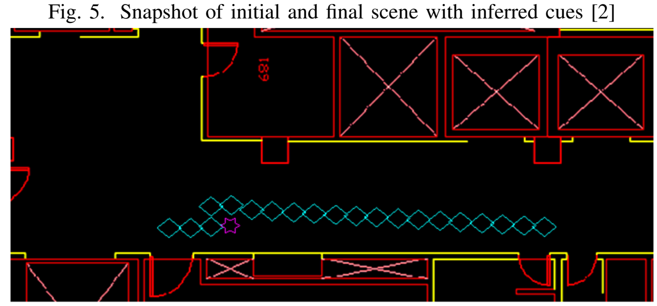

Fig. 6. Human motion model repels from the obstacle (star) and alters the travel path towards the goal.

the user. This demonstrates the capability of our system to navigate the user accurately to their desired location in real world scenarios.

XI. Conclusion and Future Trends

We demonstrated the fact that it is possible to assist a blind person to navigate independently and safely reach a destination, provided – the person is augmented with our proposed conceivable navigation system to enhance the user perception of the real world. Our system has the ability to provide haptic augmentation at each step taken by the user and also verbal description through the AR user interface. Moreover, when the blind user gets lost, the system will be able to recognize a previously visited location and further plan

TABLE I
Distance between true path and localized path

Path travelled	range	mean	std
1st Floor	13.37 m	0.5544	0.507
2nd Floor	16.26 m	0.4921	0.4934
3rd Floor	12.02 m	0.9314	0.8324
4th Floor	13.86 m	0.7855	0.7331
5th Floor	13.79 m	0.7729	0.776
6th Floor	14.63 m	0.5445	0.508

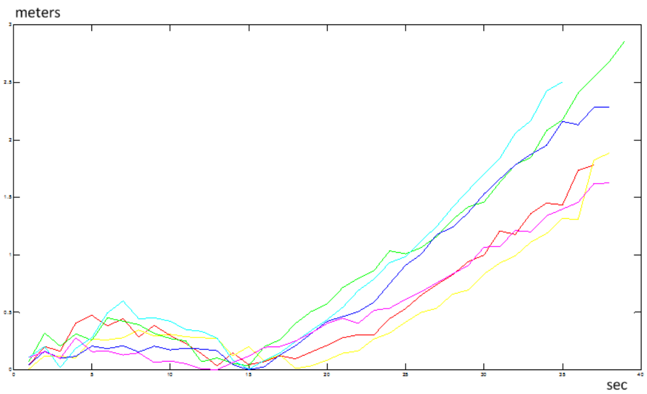

Fig. 7. Localization error

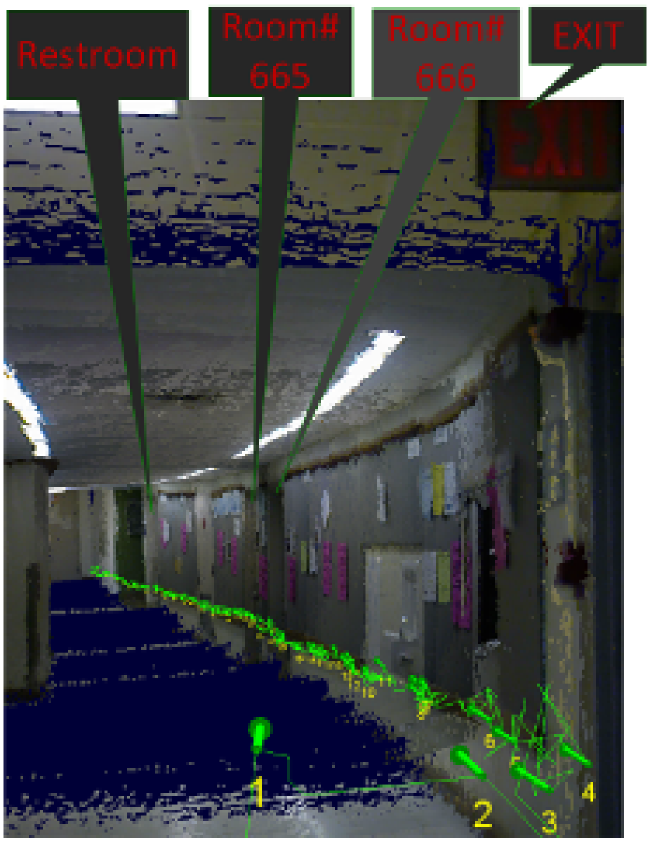

Fig. 8. Trajectory of the user on a 3D map provided by Metric Localization and annotation provided by Landmark Localization. The step count is denoted in numbers on the green path travelled by the user.

a different route to reach the desired goal position. This can promote independent living of the blind person.

In future, we will integrate cloud computing to incorporate social media information that is currently not available to the blind people for predicting real-time potential threats or opinions using "Internet of Things". Recently, the API for the Google glass is released, so we plan to augment the AR features that is currently not accessible by the blind user with our proposed AR interface. This can further enhance the safety features and create awareness to the blind user to navigate in a real world situation.

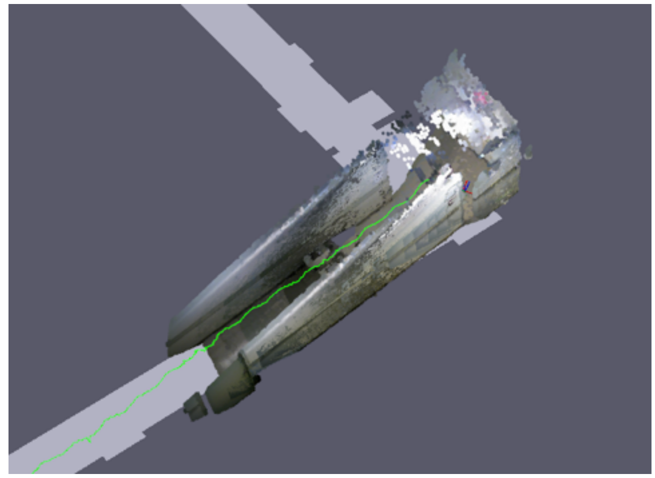

Fig. 9. 3D path provided by Metric Localization is adapted to the floor-plan map (ground truth) to rectify the accumulated pose errors in the visual odometry

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