Fuzzy Gaze Control-based Navigational Assistance System for Visually Impaired People in a Dynamic Indoor Environment

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***Abstract*—285 million people are estimated to be visually impaired worldwide. Visually impaired people typically use a white cane or a guide dog or both of them to walk down the street. However, such as a cane and/or a dog are not enough to secure them from being collided with obstacles in a dynamic environment. This paper proposes a navigational assistance system based on fuzzy integral-based gaze control for visually impaired people in a dynamic indoor environment. It largely consists of an RGB-D camera and a vibrotactile vest interface. The RGB-D camera detects static and dynamic obstacles and obtains obstacle information on their center positions, sizes, and velocities. The fuzzy integral-based gaze control for obstacle detection is proposed to reduce a blind spot of the camera and obtain more information of the environment. The vibrotactile vest interface notifies a direction to avoid the obstacle using a fuzzy integral-based imminent-obstacle selection algorithm. To confirm the performance of the proposed assistance system for visually impaired people, experiments are carried out in an indoor dynamic environment.**

I. Introduction

285 million people are estimated to be visually impaired worldwide: 39 million people are blind and 246 million people have low vision [1]. Visually impaired people typically use a white cane or a guide dog or both of them to walk down the street and avoid obstacles. The white cane is the most popularly used assistance tool that is simple, light, cheap, and easy to carry. It, however, has weaknesses that detects obstacles only on the ground and within in a short distance, and cannot tell any information except the existence of obstacles. On the other hand, the guide dog can detect obstacles in a far distance, even detect a crosswalk and traffic lights, and give psychological stability to the user. Weaknesses of the guide dog are that the user be trained with the dog and training the guide dog takes time and the cost is expensive.

Many researchers have developed electronic devices for navigation of visually impaired people to reduce weaknesses of the existing assistance devices. These can be classified as follows: vision enhancement, vision replacement, and vision substitution [2]. Vision enhancement takes an input from a camera, processes the information, and outputs on a visual display. Vision replacement involves displaying the information directly to the visual cortex. Vision substitution takes an input from a camera, processes the information, and outputs nonvisual sense, typically tactual or auditory or some combination of the two. Kaveri et al. proposed a vision substitution system for visually impaired people to grasp desired objects using a head-worn RGB camera with an Android phone [3]. They focused on vision substitution, especially electronic travel aids. Electronic travel aids can be categorized depending on sensors gathering information from the environment and also depending on the method of feedback about processed information. Obstacle information can be gathered with ultrasonic sensors [4]–[8], infrared sensors [9]–[11], laser scanners [12]–[14], a stereo camera [15]–[21], and/or an RGB-D camera [22]–[26] and the user can be informed of the information through the auditory and/or tactile devices.

The existing navigational assistance systems using vision system have a blind spot because a camera has a narrow field of view. In this regard, gaze control is needed to obtain environment information more and widely. Yoo and Kim proposed fuzzy integral-based gaze control architecture incorporated with modified-univector field-based navigation for humanoid robots [27]. Han *et al.* proposed fuzzy integral-based gaze control for obstacle detection [28]. Yoo and Kim proposed fuzzy integral-based gaze control of a robotic head for human robot interaction [29]. And the existing navigational assistance systems could typically detect only the distance of obstacles such that they gave feedback to the users using only the distance information between the user and obstacles. Esteban and Michael proposed an wearable navigation system for blind people based on a simultaneous localization and mapping technique using a laser scanner and an IMU sensor [30]. However, they are not appropriate to secure the users from being collided with obstacles in a dynamic environment. In a living world, there are many dynamic obstacles such as cars, people, dogs, and so on. Dynamic obstacles should be notified to visually impaired people in advance to avoid them safely.

To deal with these issues, this paper proposes a navigational assistance system for visually impaired people with fuzzy integral-based gaze control in a dynamic indoor environment. It largely consists of an RGB-D camera and a vibrotactile vest interface. The RGB-D camera detects static and dynamic obstacles and obtains obstacle information on their center positions, sizes, and velocities. The fuzzy integral-based gaze control with five criteria regarding the distance, the size, the velocity of obstacle, an angle for uncertain area exploration, and an angle for localization is proposed to reduce a blind spot of the camera and obtain more information of a dynamic environment. The vibrotactile vest interface with nine vibrating motors notifies the direction of an obstacle requiring urgent attention to avoid it using our proposed fuzzy integral-based imminent-obstacle selection algorithm with the three criteria for the distance, the size and the relative velocity of static and dynamic obstacles.

The remainder of this paper is organized as follows. Section II introduces the RGB-D camera-based navigational assistance system for visually impaired people. Section III presents the fuzzy integral and the fuzzy measure and proposes the fuzzy integral-based gaze control for obstacle detection and fuzzy integral-based imminent-obstacle selection for obstacle avoidance. The experimental results of the proposed navigational assistance system for visually impaired people with fuzzy integral-based gaze control in a dynamic indoor environment are provided in Section IV. Finally, concluding remarks follow in Section V.

II. Navigational Assistance System for Visually Impaired People

Fig. 1 shows the proposed RGB-D camera-based navigational assistance system for visually impaired people. It consists of an RGB-D camera, an IMU, an earphone, a notebook, and a vibrotactile vest. The RGB-D camera detects static and dynamic obstacles and obtains obstacle information on their center positions, sizes, and velocities. The proposed system estimates visual odometry with the IMU. For user localization, landmark-based particle localization algorithm with obstacle information is used [31]. The results of visual odometry and landmark-based particle localization algorithm are integrated by Kalman filter.

The earphone notifies the user of the gaze direction from the fuzzy integral-based gaze control in every two seconds such as left, center and right as shown in Fig. 2. The notebook processes algorithms for obstacle detection, localization, gaze control and imminent-obstacle selection to avoid. The vibrotactile vest that consists of nine vibrating motors and an AVR delivers tactile feedback to visually impaired people for obstacle avoidance. The vibrating motors are divided three groups such as left side, center, and right side. Each group can notify the direction of the selected obstacle to avoid. The AVR communicates with the notebook and controls nine vibrating motors. The selections of the gaze direction and imminent obstacle are formulated as multi-criteria decision making problems. To solve the problems, the fuzzy integral is employed.

III. Multi-criteria Decision Making with Fuzzy Integral

A. Fuzzy Integral and Fuzzy Measure

The fuzzy integral is one of multi-criteria decision making methods. The correlation between criteria is calculated by the fuzzy measure. And then, the global evaluation of candidates are calculated by the fuzzy integral of partial evaluation values for the criteria with respect to the fuzzy measure values.

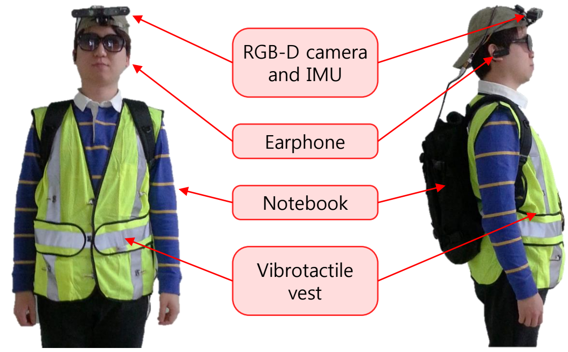


Fig. 1. The proposed an RGB-D camera-based navigational assistance system for visually impaired people

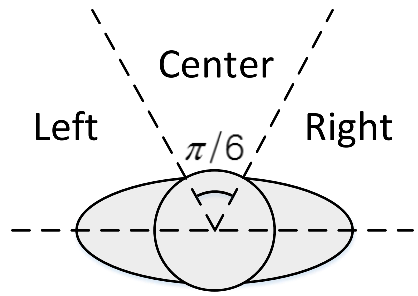


Fig. 2. Auditory feedback for gaze control

Definition 1. Choquet fuzzy integral calculates the global evaluation of each candidate using the fuzzy measure values and partial evaluation value, h as follows [32]:

$$\int_X h \circ g = \sum_{i=1}^{m} (h(x_i) - h(x_{i-1}))g(E_i), \quad (1)$$

where $0 \leq h(x_1) \leq \ldots \leq h(x_m) \leq 1$, $E_i = \{x_i, x_{i+1}, \ldots, x_m\}$, for $x_i \in X$ and $i = 1, \ldots, m$.

The fuzzy measure on the power set of X, denoted as $P(X)$, in the finite space $X = \{x_1, \ldots, x_m\}$ is defined in the following.

Definition 2. A fuzzy measure g defined on $(X, P(X))$ is a set function $g : P(X) \rightarrow [0, 1]$ that satisfies the following axioms along with the continuity axiom:

(1) Boundary condition

$$g(\emptyset) = 0, \quad g(X) = 1. \quad (2)$$

(2) Monotonicity

$$\forall A, B \subseteq P(X), \text{ if } A \subseteq B, \text{ then } g(A) \leq g(B). \quad (3)$$

It can effectively represent the mutual interactions (redundancy, synergy) among criteria.

In this paper, the Choquet fuzzy integral and λ-fuzzy measure are used to determine the user gaze direction for obstacle detection and to select an imminent obstacle for avoidance [27]–[29].

B. Fuzzy Integral-based Gaze Control for Obstacle Detection

Visually impaired people typically look only forward. It means the fuzzy integral-based gaze control for obstacle detection is needed to obtain more information about an environment. The gaze candidate includes bearing angles of detected obstacles, angles for exploration and an angle for localization. To determine the gaze direction, five criteria regarding the distance of obstacle, C_d^G, the size of obstacle, C_s^G, the velocity of obstacle, C_v^G, an angle for uncertain area exploration, C_u^G, and an angle for localization, C_l^G are defined.

The identified fuzzy measures for gaze control from the user-defined diamond pairwise comparison diagram and the hierarchy diagram are provided in Table I.

The partial evaluation functions for criteria are shown in Fig. 3. The distance between the user and the obstacle is an important factor for detection. The partial evaluation function for distance-based criterion C_d^G is defined as:

$$h_d^G = \begin{cases} 1.0 & \text{if } 0.0\ m \le \mathbf{C} \le 2.0\ m \\ \dfrac{(5-\mathbf{C})}{3} & \text{if } 2.0\ m < \mathbf{C} \le 5.0\ m \\ 0 & \text{other cases,} \end{cases} \tag{4}$$

where $\mathbf{C}$ denotes the center position of a detected obstacle in the XYZ coordinates. Small size obstacles should be focused to detect. The partial evaluation function for size-based criterion C_s^G is defined as:

$$h_s^G = \begin{cases} 1.0 & \text{if } 0.0\ m \le \|\mathbf{S}\| \le 1.0\ m \\ \dfrac{(5-\|\mathbf{S}\|)}{4} & \text{if } 1.0\ m < \|\mathbf{S}\| \le 5.0\ m \\ 0 & \text{other cases,} \end{cases} \tag{5}$$

where $\mathbf{S}$ denotes the size of a detected obstacle in the XYZ coordinates. Fast dynamic obstacles should be observed closely in order to detect certainly. The partial evaluation function for velocity-based criterion C_v^G is defined as:

$$h_v^G = \begin{cases} 0.5 & \text{if } -1.5\ m/s \le \|\mathbf{V}\| \le 1.5\ m/s \\ 1.0 & \text{other cases,} \end{cases} \tag{6}$$

where $\mathbf{V}$ denotes the velocity of a detected obstacle in the XYZ coordinates. Keeping gaze on only detected obstacles prevents from exploring the environment. To avoid this, the user should look around to detect new obstacles. To obtain the gaze angle for uncertain area exploration, the front of the user is divided four zones. The center angles of the zones are considered as candidate gaze directions. The partial evaluation function for uncertain area exploration-based criterion C_u^G is defined as:

$$h_u^G = \begin{cases} \dfrac{4\phi_{dif}}{\pi} & \text{if } 0 \le \phi_{dif} \le \pi/4 \\ 1.0 & \text{other cases,} \end{cases} \tag{7}$$

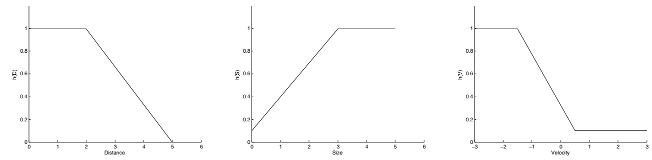
where ϕ_{dif} denotes the angle between the angle of each gaze candidate and the average of gaze angles for the last one second. The accurate position of the user leads to obtain the accurate positions of obstacles because the system calculates the positions of obstacles based on the user position. To obtain the landmark-based localization accuracy, the system should detect obstacles as many as possible. The partial evaluation function for localization-based criterion C_l^G is defined as:

$$h_l^G = \begin{cases} -\dfrac{2\theta_{dif}}{\pi} + 1.0 & \text{if } 0 \le \theta_{dif} \le 0.45\pi \\ 0.1 & \text{other cases,} \end{cases} \tag{8}$$

where θ_{dif} denotes the angle between the average bearing angle of obstacles and an angle of gaze candidate.

TABLE II. Identified fuzzy measures for imminent-obstacle selection

A	$g(A)$	A	$g(A)$	A	$g(A)$
$\emptyset$	0.0000	$\{1\}$	0.7551	$\{2\}$	0.4365
$\{1,2\}$	0.8903	$\{3\}$	0.5887	$\{1,3\}$	0.9375
$\{2,3\}$	0.7903	$\{1,2,3\}$	1.0000		



(a) C_d^V (b) C_s^V (c) C_v^V

Fig. 4. Partial evaluation function for imminent-obstacle selection criteria

C. Fuzzy Integral-based Imminent-Obstacles Selection for Avoidance

The vibrotactile vest cannot notify all detected obstacles to the user and the user does not need to know all detected obstacles information. This leads to that the vibrotactile vest should notify only an imminent obstacle to avoid. The proposed assistance system uses the fuzzy integral to select obstacle. For the selection, three criteria regarding the distance of obstacle, C_d^V, the size of obstacle, C_s^V, the relative velocity of obstacle, C_v^V are defined.

The identified fuzzy measures for obstacle selection from the user-defined diamond pairwise comparison diagram and the hierarchy diagram are provided in Table II, where 1:C_d^V, 2:C_s^V, 3:C_v^V.

The partial evaluation functions for criteria are shown in Fig. 4. The distance between the user and the obstacle is an important factor for obstacle avoidance. The partial evaluation function for distance-based criterion C_d^V is defined as:

$$h_d^V = \begin{cases} 1.0 & \text{if } 0.0\ m \le \mathbf{C} \le 2.0\ m \\ \dfrac{(5-\mathbf{C})}{3} & \text{if } 2.0\ m < \mathbf{C} \le 5.0\ m \\ 0 & \text{other cases,} \end{cases} \tag{9}$$

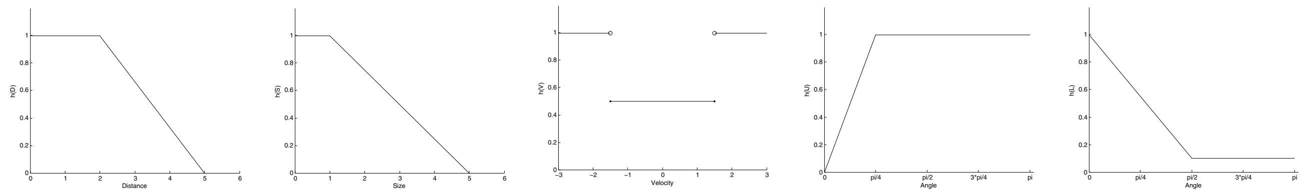
where $\mathbf{C}$ denotes the center position of a detected obstacle in the XYZ coordinates. Large size obstacles should be avoided in advance. The partial evaluation function for size-based criterion C_s^V is defined as:

$$h_s^V = \begin{cases} \dfrac{9\mathbf{S}_x}{25} + 0.1 & \text{if } 0.0\ m \le \mathbf{S}_x \le 3.0\ m \\ 1.0 & \text{other cases,} \end{cases} \tag{10}$$

where $\mathbf{S}_x$ denotes the horizontal size of a detected obstacle. Fast dynamic obstacles should also be avoided in advance. The

TABLE I. IDENTIFIED FUZZY MEASURES FOR GAZE CONTROL, WHERE 1:C_d^G, 2:C_s^G, 3:C_v^G, 4:C_u^G, 5:C_l^G

A	$g(A)$	A	$g(A)$	A	$g(A)$	A	$g(A)$
$\emptyset$	0.0000	$\{4\}$	0.1805	$\{5\}$	0.3535	$\{4,5\}$	0.5362
$\{1\}$	0.2491	$\{1,4\}$	0.4312	$\{1,5\}$	0.6056	$\{1,4,5\}$	0.7899
$\{2\}$	0.0343	$\{2,4\}$	0.2152	$\{2,5\}$	0.4166	$\{2,4,5\}$	0.5997
$\{1,2\}$	0.2838	$\{1,2,4\}$	0.4661	$\{1,2,5\}$	0.6693	$\{1,2,4,5\}$	0.8539
$\{3\}$	0.1419	$\{3,4\}$	0.3234	$\{3,5\}$	0.4971	$\{3,4,5\}$	0.6807
$\{1,3\}$	0.3923	$\{1,3,4\}$	0.5753	$\{1,3,5\}$	0.7505	$\{1,3,4,5\}$	0.9356
$\{2,3\}$	0.1765	$\{2,3,4\}$	0.3581	$\{2,3,5\}$	0.5605	$\{2,3,4,5\}$	0.7445
$\{1,2,3\}$	0.4271	$\{1,2,3,4\}$	0.6103	$\{1,2,3,5\}$	0.8144	$\{1,2,3,4,5\}$	1.0000



(a) C_d^G (b) C_s^G (c) C_v^G (d) C_u^G (e) C_l^G

Fig. 3. Partial evaluation function for obstacle detection criteria

partial evaluation function for velocity-based criterion C_v^V is defined as:

$$h_v^V = \begin{cases} 1 & \text{if } \mathbf{V}_y \leq -1.5\ m/s \\ \dfrac{-\mathbf{V}_y}{2} + 0.25 & \text{if } -1.5\ m/s \leq \mathbf{V}_y \leq 0.5\ m/s \\ 0.1 & \text{other cases,} \end{cases} \tag{11}$$

where $\mathbf{V}_y$ denotes the relative velocity in the forward direction of the user.

After calculating the global evaluation of each obstacle candidate using Choquet fuzzy integral, vibration areas of vibrotactile vest are selected to notify the user of the imminent obstacle. If the global evaluation is larger than the threshold for a strong vibration, the area of the selected obstacle direction vibrates strongly. Likewise, if the global evaluation is larger than the threshold for a weak vibration, the area of the selected obstacle direction vibrates weakly. A weak vibration means that there is an obstacle to avoid but not immediately. On the other hand, a strong vibration means that there is an obstacle to avoid immediately.

$$A_{\{l,c,r\}} = \begin{cases} \mathbf{V}_s & \text{if } \mathbf{E}_g \geq T_s \\ \mathbf{V}_w & \text{if } T_w \leq \mathbf{E}_g \leq T_s \\ \text{None} & \text{other cases,} \end{cases} \tag{12}$$

where $A_{\{l,c,r\}}$, $\mathbf{V}_s$, $\mathbf{V}_w$ denote vibration areas of left side, center side, and right side, a strong vibration and a weak vibration, respectively; $\mathbf{E}_g$, T_s, T_w denote the global evaluation from Choquet fuzzy integral, the threshold for a strong vibration and the threshold for a weak vibration, respectively.

IV. EXPERIMENTS

A. Simulation

To confirm the performance of the proposed gaze control algorithm, it was tested by a simulator. In this simulation, there were an user, static obstacles, dynamic obstacles and one goal in an environment, as shown in Fig. 5. The small circle located at (0,0) is the initial position of the user and large circles with a star at the center denote obstacles. The size of the circle means the obstacle size and the length of the line in the circle indicates the speed of the obstacle. The hexagon located at (700,0) is the goal point for the user to arrive at. The system was assumed to have an RGB-D camera which can move to a desired pan angle. In Fig. 5, a polygon denotes explored area. The system could obtain obstacle information (distance, size, velocity) only within the view area that is drawn as a trapezoid. The user moved at a speed of 30.0 cm/s and the period of detection and gaze control processes was 100.0 ms.

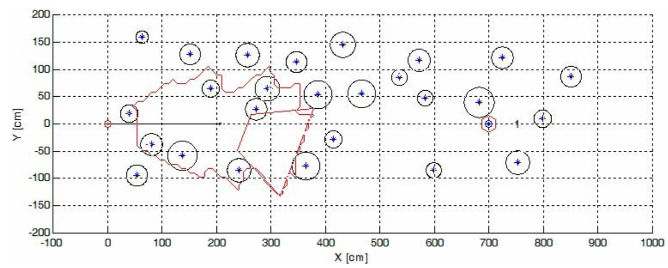
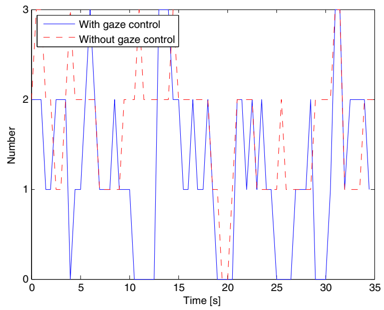


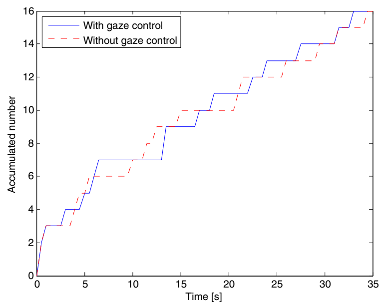
Fig. 5. Simulation environment

Fig. 6 shows simulation results about the number of detected obstacles with the proposed gaze control and without the gaze control. It shows that results with the gaze control were very similar to them without the gaze control about the number of detected obstacles and the cumulative number of detected obstacles. However, the system with the proposed the fuzzy integral-based gaze control for obstacle detection could explore widely, as shown in Fig. 7.

Consequently, the system applied the proposed the fuzzy integral-based gaze control for obstacle detection had a similar performance to system without the gaze control, but it can explore widely in a dynamic environment.

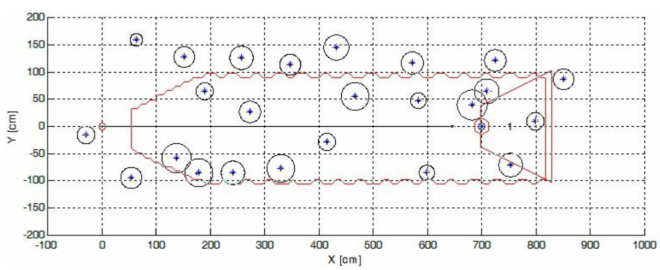


(a) The number of detected obstacles

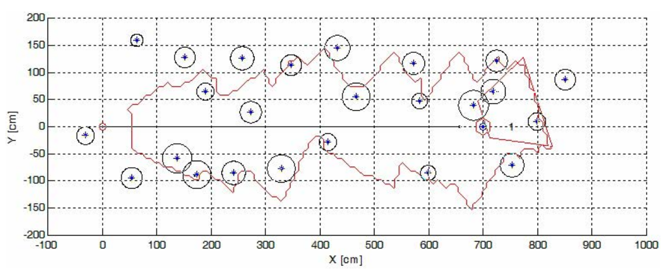


(b) The cumulative number of detected obstacles

Fig. 6. The number of detected obstacles



(a) Without gaze control



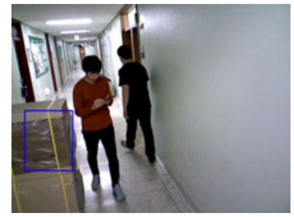
(b) With gaze control

Fig. 7. Simulation results

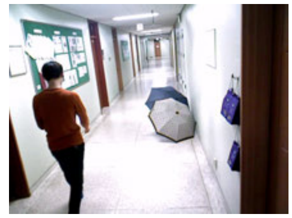
B. Real environment

The real experiment was conducted in a hallway and an office as shown in Fig. 8 and 9, respectively. There were umbrellas, box shape obstacles and walking people in the hallway and one entrance of laboratory, desks and chairs in the office. The user wore an eye patch to pretend to be a visually impaired person and walked forward with the proposed gaze control for obstacle detection and the vibrotactile vest for obstacle avoidance. Fig. 10 shows localization results of visual odometry, landmark-based particle localization algorithm and integration of them in the hallway and the office. It shows that the user could walk without collision in a dynamic environment. The proposed system has a limit in computing odometry in a feature-less envionment like a hallway because localization is computed based on visual feature points. Fig. 11 shows the gaze angle from the gaze control and the user heading angle during the experiment. The user gazed at the direction announced by the proposed system using the auditory feedback. The user could follow the direction announcement for gaze control and it made exploration widely. Fig. 12 shows the results of vibration areas in the hallway and the office.

(a) Hallway environment 1



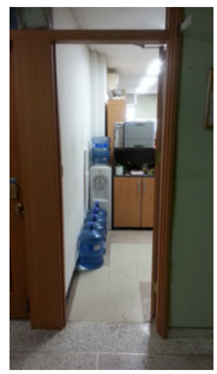
(b) Hallway environment 2



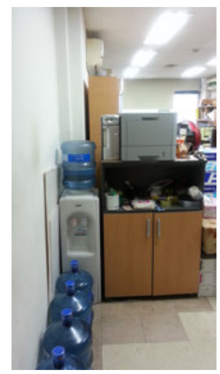
(c) Hallway environment 3

(d) Hallway environment 4

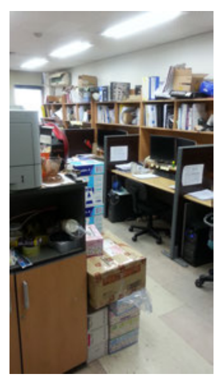
Fig. 8. Hallway experiment environment



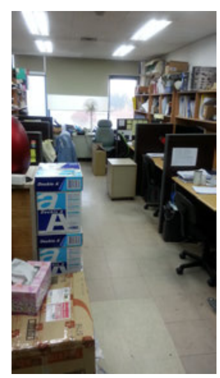
(a) Office environment 1



(b) Office environment 2

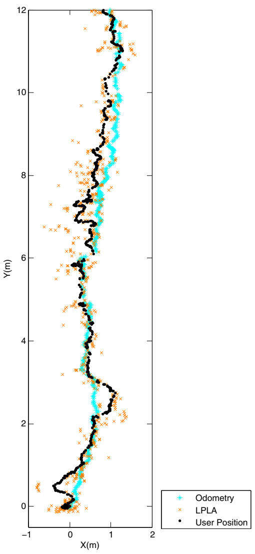


(c) Office environment 3

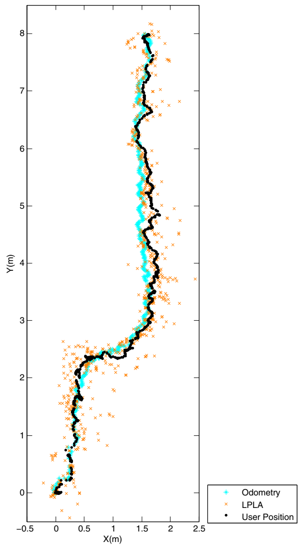


(d) Office environment 4

Fig. 9. Office experiment environment

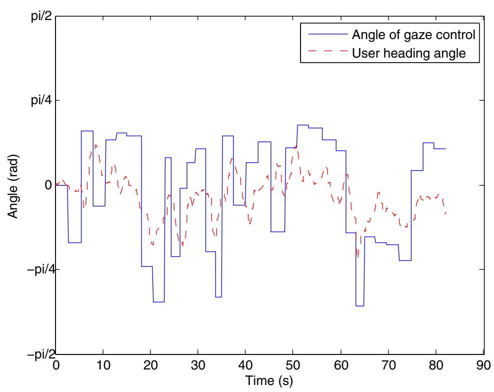


(a) In the hallway

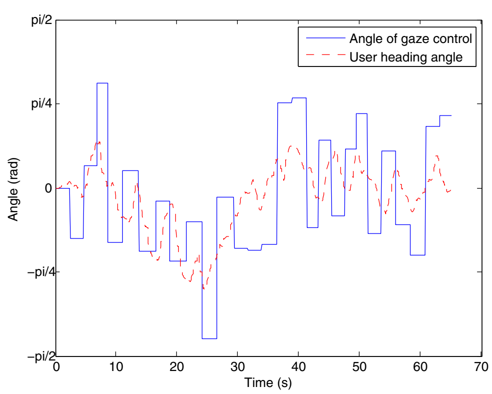


(b) In the office

Fig. 10. Localization results



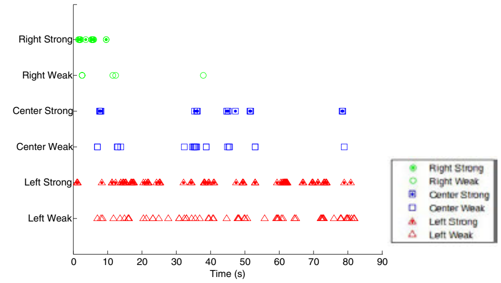
(a) In the hallway



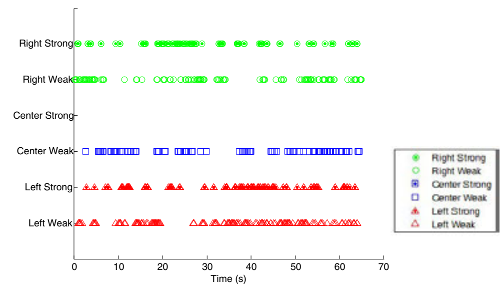
(b) In the office

Fig. 11. Gaze angle results

In summary, the proposed navigational assistance system with the fuzzy integral-based gaze control for obstacle detection could assist visually impaired people in waking without collisions.



(a) In the hallway



(b) In the office

Fig. 12. Vibration areas results

V. Conclusion

This paper proposed the navigational assistance system for visually impaired people with the fuzzy integral-based gaze control in a dynamic indoor environment. The proposed system consists of an RGB-D camera, an IMU, an earphone, a notebook and a vibrotactile vest. It detects obstacles, estimates the user position and notifies the user of the direction of an imminent obstacle to avoid. The proposed fuzzy integral-based gaze control was used to widely explore for obstacle detection. To determine the gaze direction, five criteria regarding the distance, the size, the velocity of obstacle, an angle for uncertain area exploration and localization were defined. The proposed fuzzy integral-based imminent-obstacle selection notifies the avoiding direction to the user with the vibrotactile vest. Computer simulation demonstrated the effectiveness of the fuzzy integral-based gaze control for obstacle detection and experiments were carried out in an indoor dynamic environment to confirm the performance of the proposed system.

Acknowledgment

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