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VIVR: Presence of Immersive Interaction for Visual Impairment Virtual Reality

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ABSTRACT The immersive virtual reality (VR) to provide a realistic walking experience for the visually impaired is proposed in this study. To achieve this, a novel immersive interaction using a walking aid, i.e., a white cane, is designed. The key structure of the proposed interaction consists of a walking process that enables users with visual impairments to process the ground recognition and inference processes realistically by connecting the white cane to the VR controller. Additionally, a decision-making model using deep learning is proposed to design interactions that can be applied to real-life situations instead of being limited to virtual environment experiences. A learning model is designed that can accurately and efficiently process sensing of braille block, which is an important process in the walking of visually impaired people using a white cane assistance tool. The goal is to implement a white cane walking system that can be used in the real world in addition to a virtual environment. Finally, a survey is conducted to confirm that the proposed immersive interaction provides a walking experience with high presence in virtual reality when compared with the real-world experience. The applicability of the proposed deep-learning-based decision-making model in the real world is verified by its high accuracy in recognition of braille block.

INDEX TERMS Immersive virtual reality, presence, immersive interaction, visual impairment, deep learning.

I. INTRODUCTION

Virtual reality (VR) reflects interactions that fulfill various senses, such as vision, sound, and touch, to provide users with realistic and diverse experiences through high immersion. Moreover, the immersive VR based on these focuses on the sense of presence and immersion, which is a psychological state in which the users feel real lifelike experiences of where they are, who they are with, and what they do, by using their senses. Using this concept, new applications are continuously being developed and produced through convergence with various fields, including education, tourism, manufacturing, and healthcare, in addition to entertainment fields, such as games. As a part of the related technology, the immersive VR is developing into an experience environment where users can be more immersed through the combination of systems, such as treadmill, simulator, and haptic gloves, and VR head-mounted displays (HMDs), such as Oculus Quest, HTC Vive, and PlayStation VR. In addition, studies on the user interface and haptic feedback in immersive VR that make it possible to interact directly with the virtual environment and control objects as in reality are being widely conducted from different perspectives. In recent years, various applications have been designed and developed as a way to enable VR to become more closely involved in everyday life, and numerous studies are being conducted to approach VR through analysis of human-centered psychology and social science [1]–[4].

It is important to consider how users interact with the virtual environment and how this interaction improves the sense of presence. Thus, various studies are being conducted on haptic systems and motion platforms to provide feedback about physical responses that occur in the process of interacting with the VR environment through actions. In addition to detecting and measuring changes in joints or strengths for the purposes of realistically expressing user motion more accurately [5]–[9]. Furthermore, studies on algorithms and walking simulators are being conducted to simulate free walking in a wide VR environment within a limited experience space [10], [11].

Numerous studies have been conducted to develop applications by merging with various application fields, such as shopping malls, museum, and theme park, based on studies

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related to interaction in immersive VR [12]–[14]. These studies confirmed that enhanced effects (education, treatment, etc.) can be acquired through a real lifelike experience environment that increases immersion based on VR in conditions where a user has a specific purpose or a clear given goal. However, while the subject of immersive VR applications is quite diverse, most of the targets usually deal with general-purpose interactions from the perspective of general users. Additionally, studies conducted on a VR experience environment and specialized interactions for users who are in a special environment (industrial environment, safety field, etc.) or users having temporary or permanent health issues resulting from accidents or diseases are lacking.

Accordingly, in this study, immersive VR that enables users to experience a more diverse experience was developed. The main goal of the proposed VR is to design immersive interaction that can provide realistic experiences to the visually impaired. For this purpose, it is essential to present different types of unpredictable situations in consideration of realistic walking experience adaptation from the perspective of the disabled, rather than just fulfilling the purpose of simply enhancing education and experience effects or the indirect experiences from the perspective of general users. Furthermore, a novel structure of immersive interaction was designed that can be applied to the real world, in addition to the virtual environment. To achieve these goals, the immersive interaction of visual impairment virtual reality (VIVR) is proposed in which the following core functions are implemented.

1. **Virtual Reality:** An immersive interaction is designed through a white cane based on VR that combines a white cane, a walking aid for users with visual impairments, and a VR controller. The purpose of this is to provide users with an experience that is similar to reality by presenting a walking experience environment that is identical to a real one.
2. **Actual Reality:** A comprehensive processes for classifying, judging, and recognizing braille block on the road through a white cane are implemented using deep learning. The learning model is designed to accurately recognize braille block on roads consisting of sidewalks, roadways, and braille blocks. Based on this learning model, a white cane interaction system applicable to actual reality in addition to VR is designed. Using the proposed braille block recognition method implemented via deep learning, a novel interaction that applies technology that can be applied to the white cane in actual reality in addition to the virtual walking experience environment is proposed.

The goal of the proposed VIVR is to design a novel walking experience environment that connects VR to actual reality, along with an immersive interaction technology that supports such an environment. In addition, in terms of portability, it does not use additional equipments other than a controller and a white cane, and tries to recognize the braille block and feedback effectively.

II. RELATED WORK

To provide a realistic experience in a virtual environment based on the user's senses of vision, sound, and touch, immersive VR involves enhanced display and rendering technology that delivers three-dimensional visual information, surround sound processing using audio sources for maximizing the sense of space, and a way to interact directly with the virtual environment. Several studies on haptic systems based on the human body, such as hands, gaze, and legs, and on motion platforms designed for natural walking are being conducted [2], [15]–[17]. Realistic interactions are necessary to break the boundaries between VR and reality to improve the presence in VR through high immersion. To achieve this, research is being conducted to accurately detect human joints that move according to the user's motion in real space, identify the intention of the motion, and realistically express the action in VR. To detect human joints accurately, studies have been conducted by attaching surface or optical markers to joints, detecting and tracking markers with a camera, and mapping them to the motion of a virtual model [5], [6]. This approach has expanded to a study that captures hand gestures, facial expressions, and movements of the entire body, and a technology that expresses realistic motion in the VR is being developed [1].

During the interaction process, it is also important to realistically express the motion that suits the user's intention and purpose, as well as provide accurate feedback of physical responses generated by the force to the user after measuring the force exerted by the user. Jayasiri *et al.* [18] proposed a haptic system and interface that express physical interaction based on the user's exerted force. Various application studies have been conducted as well, including a 3-RSR (revolute–spherical–revolute) device [19], a 3-DOF (degree-of-freedom) wearable haptic device [20], and a portable hand-held haptic system [17]. Furthermore, studies on expressing free walking in a limited indoor space are being conducted through the implementation of algorithms [10] and portable walking simulators [11]. Nevertheless, because the haptic systems and motion platforms mainly focus on handling the hand gestures or walking motion of general users, there is a need to extend and apply them to tools that assist the motion of users who face difficulties in movements because of special situations.

Ultimately, for studies that deal with interaction in immersive VR, it is important to provide a high presence that enables users to feel experience that is close to real-life experience within VR. Studies on presence, led by Slater *et al.* [21], [22], are being conducted focusing on various cases. The studies range from general studies analyzing presence in a user's walking experience and communication process [15], [23] to studies that apply the presence of VR to other fields, such as ones that analyze physiological responses to a stressful VR environment [24] and strategies for reducing the severity of chronic arm pain through virtual body changes [25]. In addition, for implementation of immersive VR applications, several studies have been performed to analyze the factors affecting the enhancement of presence by using the gaze and hands through comparative experiments [26]. Based on these studies, additional research is being carried out to develop VR applications and verify and analyze the performance and effects on the users. The studies that present directions in which VR can be applied to various fields include a study on gesture interaction that supports immersive VR shopping applications [12], a systematic analysis and review of the application of interactive VR to sports [27], a study on Viking VR, which is a VR experience design for museums [13], and an application study on supporting the development of a VR maze theme park [14]. However, these applications are mostly developed by focusing on the experience environment of ordinary users. Hence, there is a need to expand the scope of the application field to feature an experience environment that reflects interactions of various types of user.

Accordingly, in this study, a novel approach is proposed to provide interaction realistically in special situations while expanding the user range of the VR experience environment. To achieve this, a novel system that supports walking and immersive interaction was developed by combining a white cane, i.e., a walking aid, and a VR controller as a VR walking experience environment for users with visual impairments. Furthermore, a deep-learning-based learning model is proposed that supports the processing of recognition and inference of braille block. The model can be applied not only in VR but also in the real world.

III. VIVR: VISUAL IMPAIRMENT VIRTUAL REALITY

The purpose of the proposed immersive VR is to present an outdoor walking experience environment with high immersion for the visually impaired. First, the perspective of users with visual impairments has been considered as the experience subject of this study. Based on this perspective, an attempt was made to develop a highly immersive walking interaction for the walking experience. In the proposed experience environment, the scope of visual impairment includes visual disorders, such as glaucoma, in which the visual field is reduced, and cataracts, in which the visual field is gradually blurred, in addition to complete vision loss. Furthermore, the experience scope consists of the process of classifying the sidewalks and roadways in an outdoor road environment where braille blocks are installed, as well as the process of identifying the braille blocks placed on sidewalks and judging the situation to find a suitable walking route.

To this end, a walking experience environment was designed that can maximize the immersion of users. First, immersive interaction was achieved by combining a VR controller with a white cane, which is the most common walking aid for the visually impaired, to provide a realistic walking experience for the visually impaired in VR. Subsequently, a novel deep-learning-based model was developed for an interaction system that helps the visually impaired by expanding the virtual experience to the real-world walking experience.

Canetroller of Zhao *et al.* [28] also produced haptic cane controller to navigate visually impaired people in VR. However, this study is proposing new equipment using haptics and auditory cane simulation. Unlike this, this study propose a new interaction that focuses on the use of high accessibility and braille block recognition using deep learning.

A. IMMERSIVE WALKING EXPERIENCE ENVIRONMENT

The immersive VR walking experience environment for the visually impaired consists of the user (suffering from vision loss, glaucoma, cataracts, etc.) who is the subject of the experience and the experience space. Based on this, the environment is developed into an interaction in immersive VR and a learning model in the real world. Figure 1 shows the core structure proposed. The user wearing an HMD is provided with a walking experience within a VR outdoor environment through a VR white cane that connects the VR controller and the white cane.

FIGURE 1. Immersive walking experience environment and application system structure of the proposed VIVR.

To provide a walking experience that features high presence, a series of processes—walking surface contact, braille block recognition (with friction sound), and walking guidance inference—for recognizing the braille block and judging the situation using the VR white cane were designed. Furthermore, a learning model that provides accurate braille block recognition and inference was developed to prevent safety accidents that may occur during the walking process in VR and the real world. The immersive walking experience environment used an Oculus HMD and a dedicated controller, Oculus Touch [29]. The overall virtual scene of an outdoor walking space was designed using the Unity 3D engine [30].

B. VIRTUAL REALITY WHITE CANE

An immersive interaction is proposed to provide a realistic walking experience during the process of recognizing braille block and determining the route, from the perspective of users with discomfort and fear resulting from visual impairment.

1) CONTROLLER-BASED VR WHITE CANE

In general, the walking methods of visually impaired people include walking without any assistive equipment (detecting and defending with hands and feet within a short distance and familiar space), guided walking (requesting help from nearby people), walking using an electronic device (detecting obstacles), and walking with guide dogs. Among them, the most common method is walking with a white cane. This method is widely used because it has the advantages of high independence, safety, and efficiency. However, it requires a certain period of walking training. The users who intend to use guide dogs or electronic walking devices also need to receive independent training for walking with a white cane before they can choose their walking methods. Therefore, in this study, a VR white cane was constructed to establish a VR walking experience environment using a white cane. Figure 2 shows the developed VR white cane. The white cane is attached to an Oculus Touch controller to provide the users with a realistic experience of walking with a white cane. In consideration of the user's convenience, without connecting the controller and the white wand, the user can control it according to a comfortable grip. During the process, although the tactile sense transmitted when the white cane touches the braille block is replaced by the vibration module of the controller and has a slight difference compared with real-life tactile sensing, the experiential environment is configured to enable users to feel the experience of the sense of touch.

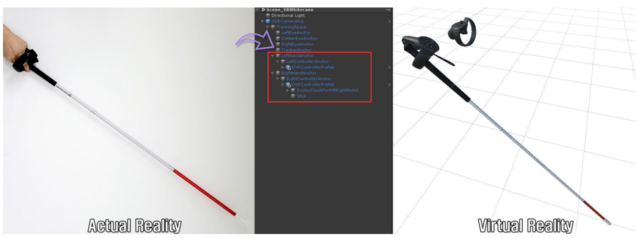

FIGURE 2. Proposed controller-based white cane and the result of constructing the VR white cane in the Unity 3D engine.

Algorithm 1 expresses the process of implementing the white cane connected to the controller in a VR environment. First, the procedure for preprocessing is defined to make accurate walking possible using the white cane in a VR experience environment after reflecting the physical differences (height, arm length, etc.) of each user. Subsequently, the tactile process is implemented for the case when the white cane touches the ground. During the process, a structure of a deep-learning model that supports classifying braille block on the ground through the VR white cane and deriving a route guide is considered for application. The modules are designed considering the learning model that can be applied to actual reality in addition to VR.

Equation 1 shows the process of calculating the length of the VR white cane (l_{vr}) based on the height of the user (h_{user}), the length of the white cane (l_{ac}) in the real world, and the height of the HMD (h_{vr}) character in the virtual environment. Here, a weight (α) for adjusting the length of the VR white cane is applied in consideration of the user's body shape (arm or leg length, etc.).

$$l_{vr} = \frac{(l_{ac} * h_{vr})}{h_{user}} + \alpha \tag{1}$$

Algorithm 1 Process of VR White Cane Braille Block Recognition

procedure VR white cane Initialization
    $l_{vr} \leftarrow$ Calcuate the height of VR white cane after reflecting the height of the white cane and the ground using Equation 1.
end procedure
procedure Braille block recognition
    $c_{vr} \leftarrow$ Condition on whether the ground point of the VR white cane collides with the ground.
    if c_{vr} is True **then**
        Capture VR white cane camera.
        $r_{vr} \leftarrow$ Inference derived based on captured image and training data.
        if r_{vr} is point braille block **then**
            Vibration and stop sound.
        else if r_{vr} is linear braille block **then**
            Continuous vibration.
        else if r_{vr} is roadway **then**
            Warning sound.
        end if
    end if
end procedure

2) USER WALKING PROCESS

The walking interaction that controls the walking process using two legs is a process required for walking with a white cane. Lee *et al.* [11] demonstrated that expressing the motion of walking using both legs has a direct effect on preventing VR motion sickness while providing improved presence when compared with processing the motion of the character within the application via an input device, such as a keyboard or controller. However, while the walking interaction using treadmill-based motion platforms or motion capture systems may help maximizing presence, there is a limitation in implementing it for general users because of the high cost. As a way to address this issue, Lee *et al.* [11] proposed a walk-in-place-based portable walking simulator. This study used gaze to process walking for easier accessibility by focusing on the method of Lee *et al.* [11].

The process of identifying walking in place using gaze is as follows. First, the presence of walking is identified by measuring the difference in the gaze pointer that occurs when the user walks in place, as shown in Figure 3. During this process, the motion of walking in place is identified by the amount of difference in movement in the x- and y-axis directions and amount of difference in rotation in the z-axis based on the gaze pointer at rest. In detail, when the difference between the previous and current values of the gaze pointer's x- and y-position and z-axis rotation angle are within the threshold range, the state is changed to the walking-in-place state. Here, the threshold value plays a role of limiting the motion within a given range to distinguish the amount of

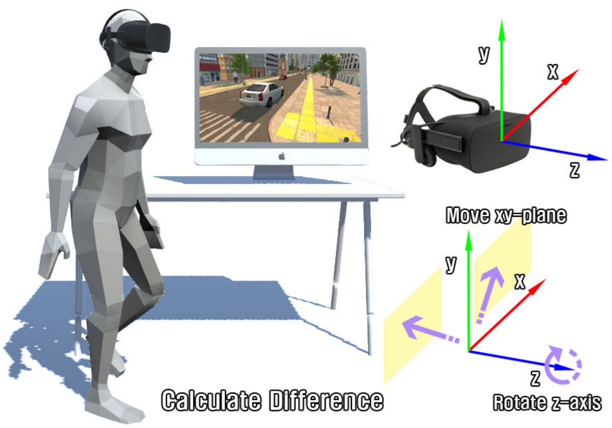

FIGURE 3. **Walking in place considering the movement of the gaze pointer.**

difference in the gaze pointer that may occur during the course of gaze difference related to something other than walking. The amount of difference in the gaze pointer is an auxiliary means to induce the user to walk in place. The user makes the final decision on whether to perform motion by reflecting the gaze pointer measured above the threshold value in the situation in which the primary key input of the controller is performed to express the intention of the motion. Thus, the process is designed so that the accuracy of the difference amount of the gaze pointer does not cause any inconvenience by inaccurately judging the motion.

C. FROM VIRTUAL TO REAL: WALKING INTERACTION APPLICABLE TO REAL ENVIRONMENT

A VR white cane is a device that helps the user walk safely by recognizing the braille block on sidewalks in a VR environment. Thus, a process of recognizing braille block and judging the situation by means of the VR white cane is required. As shown in Figure 4(a), braille block includes linear braille blocks that help indicate walking direction and point braille blocks designed for the purpose of warning about cross points and situational awareness. However, the braille block found in daily life includes not only normal braille blocks, as shown in Figure 4(b), but also blocks damaged by environmental (aging, weathering, etc.) or management issues, as shown in Figure 4(c). These damaged blocks can also interfere with walking and even pose safety threats in some cases. Thus, it is important for the proposed VIVR environment to reflect such conditions in the process of walking using a white cane.

The goal of this study was to reflect various unpredictable situations that may occur in the real world, instead of a simple experiential environment that is composed of a scene with a normal braille block system only. To achieve this, a deep-learning model was designed, and a braille block recognition process was implemented. The datasets used in the proposed learning model were divided into two categories and used for more-realistic white cane walking interaction.

a) Dataset comprising only normal braille blocks: Designed to handle situations that may occur if the visually impaired users using a white cane cannot accurately recognize damaged braille blocks in a natural way that is similar to that in a real environment.
b) Dataset comprising various conditions of braille blocks of the real world: Designed to present a novel walking interaction technique applicable to reality in addition to VR by enhancing the recognition of damaged braille block as well as normal braille block.

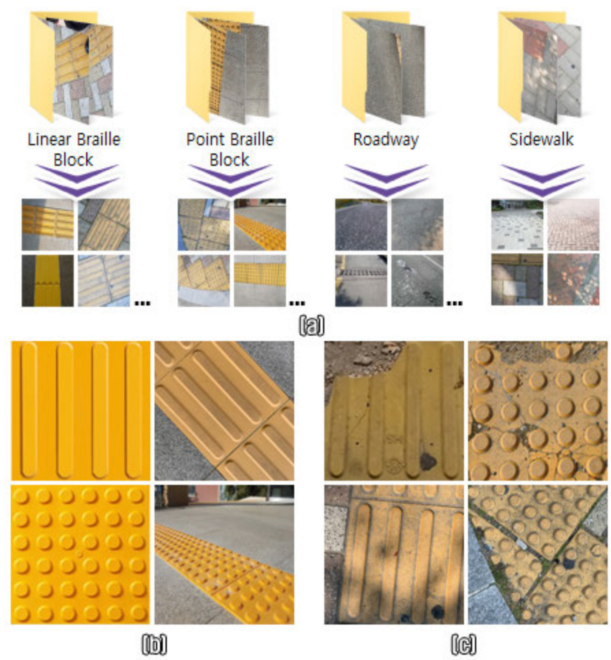

FIGURE 4. **Datasets for walking interaction: (a) dataset composed of braille block, sidewalks, and roadways, (b) normal braille blocks, and (c) braille blocks damaged by environmental (aging, weathering, etc.) and management issues.**

1) TRANSFER LEARNING THROUGH DEEP LEARNING: INCEPTION v3

The proposed VIVR uses a convolutional neural network (CNN) model, which is one of the most widely used image classification methods among the deep-learning methods. For the CNN model, this study employed a transfer learning method. The structure and parameters of Google's Inception v3 model [31], which features an efficient structure for image recognition and inference, were used to retrain the model with the braille block and road (or sidewalk) datasets in this study. Figure 5 shows the learning process using the Inception v3 model structure based on the basic datasets prepared as shown in Figure 4. The basic datasets and the final dataset derived by augmentation (movement, rotation, size, brightness, etc.) were constructed, and training for braille block classification was conducted.

In the process, the braille block among the datasets used for training was divided into normal braille blocks and all types of braille blocks present in the real world, as defined earlier, and the training process was conducted twice.

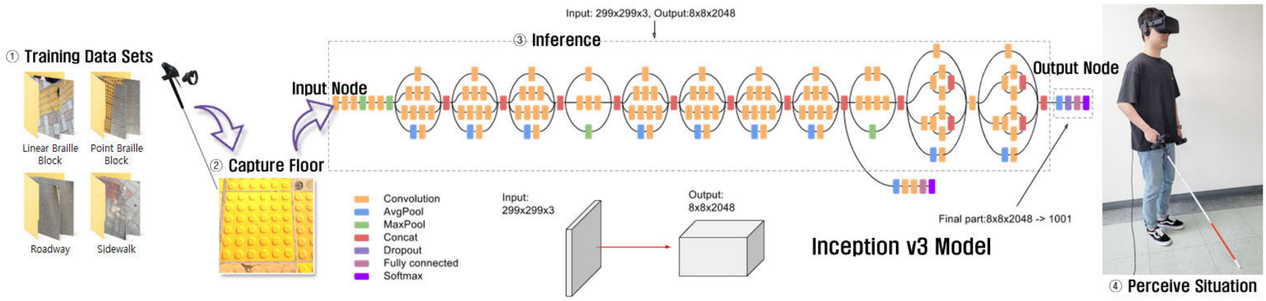

FIGURE 5. Process of inferring braille blocks and judging the situation through VR white cane based on inception v3.

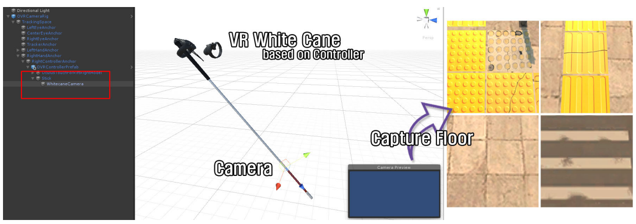

FIGURE 6. Setting up a capture camera on a VR white cane in the Unity engine development environment.

2) VR APPLICATION

To configure the format suitable for the input image format and inference result value derived based on the trained data file in the Unity engine development environment, the input and output nodes were adjusted. During this process, the final data were generated by using the optimize_for_finference library available in Python's TensorFlow tool [32].

In the immersive VR environment, a capture camera, which has a hierarchical relationship with the VR white cane configured in the HMD user's hand (either left or right), is used to capture the ground (roadways, sidewalks, and braille block) from the VR white cane and store the captured image as an input image. The ground image captured through the camera is stored in the image buffer of the input node format, and the image result is inferred from one of the labeled images. Figure 6 illustrates the result of constructing the capture camera on the VR white cane in the Unity engine development environment.

Once the VR white cane recognizes the braille blocks, a vibration and appropriate sound are transmitted to the Touch controller so that the user can identify the blocks in a natural way.

IV. APPLICATION

The immersive walking experience of users with visual impairments is designed to be implemented in the real world in addition to presenting unpredictable situations in VR considering realistic walking adaptation. Accordingly, in this study, the proposed VR white cane was used to develop a VR application in which the visually impaired users walk along a road by recognizing braille block.

The application presents two scenes. One was created based on the data trained with only normal braille block to express situations that may occur in the real world because of failure to accurately recognize the damaged braille blocks. The other was created based on the data trained with various braille blocks (normal, damaged, aging, weathering, etc.) found in the real world to examine the applicability of the learning model of the proposed VR white cane in real situations. Additionally, the level of visual impairment was implemented through various situations as follows: a situation in which the visually impaired users cannot see anything ahead because of complete vision loss, a situation in which the users have blurry vision and face difficulties in recognizing objects because of cataracts, and a situation in which the users have a reduced field of vision and face difficulties in making judgements because of glaucoma. However, since it is difficult to generalize and express situations for various visual impairments, the scenes are composed only of representative symptoms.

The background of the application features an outdoor walking experience environment. It is simply configured with start and end points, along with braille block arrangements on walkable sidewalks. The user moves through the area using the proposed VR white cane. Additionally, various terrain features, such as roadways and humans, that may interfere with walking and cause safety risks are arranged. In particular, roadway situations are included to enable users to recognize the difference between linear and point braille blocks. Figure 7 shows the execution process of the application developed in this study. In the figure, two scenes and three situations are depicted.

V. EXPERIMENTAL RESULTS AND ANALYSIS

The deep-learning model applied to the VR white cane of the proposed immersive walking experience environment was implemented through Anaconda 3, conda 4.6.12, and TensorFlow 1.13.0. Furthermore, the experiment on the learning model in the Unity 3D engine was implemented using the TensorFlowSharp 1.15.1 plugin. The application for the user survey experiment and evaluation was developed using Unity 3D 2019.2.3f1 (64 bit) and Oculus SDK. The PC environment used for the system implementation and experiment was composed of Intel Core i7-6700, 16 GB RAM, and GeForce GTX 1070 GPU. Figure 8 shows the experimental environment where the user can experience the proposed immersive

FIGURE 7. Result of application creation in consideration of each of the real and virtual worlds and the user's experience environment (vision loss, glaucoma, cataracts, etc.).

FIGURE 8. Configuration of immersive walking experience environment using VR white cane.

walking by wearing the Oculus HMD and holding a white cane attached to a touch controller. The experimental environment consisted of a space (1.5 × 1.5 m) that was sufficient to stand comfortably in and perform walking in place.

To objectively verify the user satisfaction level on the proposed interface and examine the presence of the experience environment shown in Figure 7, a survey experiment was performed. The survey participants comprised 15 males and 5 females between 20 and 38 years of age. The purpose of the survey experiment was to confirm whether the proposed VR white cane and braille block recognition interface using deep learning provide a satisfactory walking experience for the visually impaired and to verify whether the experience plays a positive role in providing a satisfactory presence in immersive VR. Therefore, the participants responded to all questionnaires (satisfaction, presence) after experiencing all of the two scenes and three situations of the produced application.

The first survey experiment was conducted to analyze satisfaction with the VR white cane interface of the proposed immersive interaction. To evaluate usefulness, satisfaction,

TABLE 1. Satisfaction analysis result of the proposed interface of immersive walking interaction using VR white cane.

	Proposed interface
Mean(SD)	
usefulness	6.323 (0.785)
ease of use	5.828 (0.884)
ease of learning	6.117 (0.924)
satisfaction	6.544 (0.486)

and ease of use (i.e., ease of learning and using), the survey experiment was carried out using the usefulness, satisfaction, and ease of use (USE) questionnaire suggested by Arnold Lund [33]. The responses were recorded on a seven-point scale for 30 items on four dimensions of usability. Table 1 summarizes statistical data based on the survey results. As shown, overall averages of approximately 6.0 were observed in all four usability dimensions—usefulness, ease of use, ease of learning, and satisfaction—indicating a high user satisfaction. The process of navigating along the braille block was somewhat difficult for participants because they had no prior experience with the white cane. However, they easily familiarized themselves with the process of recognizing the braille block and inferring the path through appropriate feedback (vibration and sound). Moreover, because the environment used VR rather than the real world, the participants could actively participate instead of feeling fear and acting passively.

The second survey experiment was conducted to analyze the presence. The objective was to reflect the real-world process of finding a walking path by recognizing braille block using a white cane in a VR environment as realistically as possible. Hence, to perform the evaluation, the process of identifying the braille block by making contact with it via a white cane in the real world was observed first. Based on this, a survey experiment was conducted on the proposed interaction. For the questionnaire regarding presence, reducing the difference between the real world and VR was also an important objective; thus, a model trained using a dataset composed of various braille blocks in the real world was used.

TABLE 2. Presence analysis results of the proposed VIVR experience environment.

	Proposed interface
Mean(SD)	
realism	5.772 (0.819)
possibility to act	5.844 (0.529)
quality of interface	5.445 (0.895)
possibility to examine	5.511 (0.887)
self-evaluation of performance	5.417 (1.201)

The survey participants were instructed to provide responses for 19 items of the presence questionnaire suggested by Witmer *et al.* [34] on a seven-point scale. The items were analyzed in detail based on the recorded responses. Table 2 summarizes the analysis results. With a score of 7 indicating an experience close to that of the real world, the results listed in Table 2 can be deemed satisfactory for all items. In particular, high presence result values were observed in the items of realism and possibility to act, which are directly related to motion. In addition, similar to the interface satisfaction analysis results, a high satisfaction level was observed in the interface combined with the white cane and feedback.

A performance analysis experiment was conducted to evaluate whether the proposed immersive interaction can be implemented as a walking interaction technology applicable to the real world, instead of being limited to the VR. In this experiment, the recognition rates were compared and analyzed based on a model that was trained by classifying a dataset composed of only normal braille blocks and a dataset composed of various real-world conditions of braille blocks (aging, weathering, damaged, etc.). The recognition result of the ground image captured from the VR white cane was recorded in the process of the experiment participants going from the configured start point to the end point. On average, the model trained with a dataset composed of only normal braille blocks yielded 92.23% recognition accuracy for linear braille blocks, 81.57% accuracy for point braille blocks, 91.04% accuracy for sidewalks, and 86.13% accuracy for roadways. Because the point braille blocks were located adjacent to the roadway, the recognition accuracy decreased depending on the image capturing angle. Furthermore, as a result of constructing the dataset by adding real-world textures, accuracies were obtained as follows: 85.11% for linear braille blocks, 75.51% for point braille blocks, 89.12% for sidewalks, and 85.67% for roadways. The overall recognition accuracy decreased as images of various irregular patterns found in the real world were added. However, it was not deemed to be a problem because such accuracy results did not interfere with or lead users to a dangerous situation by delivering inaccurate information during the walking process. The proposed immersive interaction was found to be applicable not only in the VR experience environment but also in the real world.

Finally, the time required for the proposed model to capture the ground image and provide recognition result feedback to the user was measured. In the case of a VR application, the frame rate, such as frames per second (fps), is an important factor that affects the user's immersion, such as VR motion sickness. Hence, it is necessary for the recognition process not to affect the frame rate. First, an average frame rate of 65 fps or higher, which is the recommended number for VR applications, was observed. Subsequently, the fps of the basic scene before the recognition process and the fps difference at the time when the braille block recognition result was obtained after identifying the ground from the VR white cane were measured. As a result, a maximum difference of approximately 5 to 6 fps was observed between the two scenes. The recognition time was also less than 0.000001, suggesting that the recognition and inference processes do not affect the system performance.

VI. LIMITATION AND DISCUSSION

The deep-learning model applied to the VR white cane was developed based on a CNN and employed a transfer learning method using Inception v3, which is an efficient model for image classification and inference. This study was carried out by applying the existing deep-learning model to the immersive VR interaction rather than designing a separate learning model optimized for braille block image recognition. Thus, if further studies on designing an optimized learning model while eliminating unnecessary processing in an environment composed of a dataset with a small number of labels are conducted, various immersive VR applications can be implemented more effectively.

For the proposed immersive interaction of this study, the white cane was designed in a manner that is suitable for VR. However, simulating walking through walking in place was found to be the factor that lowers the sense of immersion compared with identifying actual braille block using a white cane. This limitation can be addressed by implementing natural walking through full body tracking by using equipment such as a treadmill and motion capture system, or even a Kinect device. In addition, there is a need to expand the experience environment of the application, which currently only supports a simple outdoor walking experience, to special indoor environments, such as a subway or a building, or to complex outdoor environments, such as stairs.

Finally, the survey participants conducted an experiment in an experiential environment in which visual impairments were applied only for general users without visual impairments. In the future, we plan to analyze the proposed interaction by comparing users with visual impairments together.

VII. CONCLUSION

A deep-learning-based VR white cane was proposed for immersive interaction to provide a realistic walking experience for the visually impaired in immersive VR. In the proposed immersive interaction, a white cane, a walking aid, and a VR controller were combined to create a realistic experience environment. Additionally, a learning model based on deep learning was designed to express the braille block recognition and inference processes, which are difficult to predict from a VR white cane. The goal was to design interactions that can be applied to the real world in addition to experiences in virtual environments. To achieve this, the datasets were divided into two categories to train the model and utilize it for the experience. For the analysis, survey experiments were conducted to compare the presence in VR based on the USE questionnaire for the satisfaction level of the proposed VR white cane interface interaction and the process of recognizing and inferring braille block using a white cane in the real world. The results of the survey experiment confirmed that the proposed VIVR provided a satisfactory presence in the interface experience. Furthermore, it was verified that there are no problems in implementing the braille block recognition process using deep learning in a VR system and that it yields an acceptable recognition rate, even for real-life applications.

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