Evaluation of Construction Site Layout Using Virtual Reality Linked with 3D CAD and Body Tracking

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Abstract

Lately, virtual reality (VR) is being investigated for the field of construction. VR enables investigation from a stage where there is no actual object. The most common approach in VR is interaction with a controller. Therefore, the sense of body movements is often far from reality. Reflecting actual body movements is required for a more near-realistic experience in VR. In addition, VR linked to 3D CAD instantly enables the examination of design change. This paper proposes a method and framework for reflecting real body movements by tracking the body and real-time linkage of 3D CAD and VR. Azure Kinect and Leap Motion can track body movements and provide skeletal data. The VR body is linked to a real body by using a skeleton. The VR body enables to recognize how one's body moves in the VR space and its position in relation to other objects in the VR space. The ability to observe the distance between the body and VR space will expand the use of VR for this type of safety and buildability check. In addition, the tracked skeleton can be applied to measure the energy consumption of the body and extend the scope of analysis in VR. A real-time linkage between 3D CAD and VR was achieved by Rhinoceros and RhinoInside. In this study, steel-frame construction is used as an example of construction at heights and in confined spaces. The background behind the creation of this system is the liberalization of architectural shapes through 3D CAD. As the use of free shapes and dimensions in design and construction increases, the number of projects that cannot be handled by existing construction methods also increases. Therefore, a method for studying the implementation of each building should be developed to verify its buildability.

Keywords –
Virtual Reality; Construction Training; Tracking; Simulation; Parametric Modeling; Buildability

1 Introduction

Virtual reality (VR) has recently been investigated for construction purposes. VR enables training and examination in a completely safe environment [1]. Using head-mounted displays (HMDs), the environment created in the VR space can be viewed in three dimensions, which is an effective method for examination in construction where components are intricately linked. Furthermore, VR activities include reflections on real body movements, which are similar to real-life experiences [2]. Owing to these characteristics, VR can be considered as an effective tool for examining buildability. In this study, Unity was used to develop VR applications, and HTC VIVE Pro Eye was used for the HMDs.

This study presents a framework for evaluating parametric modeling using VR that incorporates body tracking. Parametric modeling creates a portion of the construction site and verifies buildability by searching for parameters. A steel-frame construction is used as an example of construction at heights and in confined spaces. 3D models created during design and construction studies are utilized in real time from 3D CAD and reflect real body movements. This enables verification of the relationship between the body and construction components in terms of buildability, for example, whether the envisioned site is sufficiently large for construction activity.

The liberalization of architectural shapes through 3D CAD is the background for the development of this system [3] [4]. It is possible to introduce programming into 3D CAD for parametric modeling. The use of parametric modeling is expanding, for example, in modeling small-scale buildings [5] and the construction of shield tunnels [6]. Therefore, the use of free shapes and dimensions in design and construction is expected to increase. However, some problems cannot be solved using existing construction methods. Therefore, it is important to confirm the buildability and safety of new construction methods.

2 Literature Review

2.1 Virtual Reality for Construction

Various studies have been conducted on VR technology, with VR in safety education being a typical example. Construction sites are considered dangerous environments, and safety education must be promoted; VR education is an alternative to passive learning methods [7]. Studies have been conducted in recent years to use VR not only for safety education but also for technical education. Adami et al. reported that training with VR improves knowledge, operating skills, and safety behaviors compared with face-to-face training [8]. They also cited cost as an advantage of VR, in addition to its superior safety features. Costs can be saved as real objects are no longer required and site constraints are eliminated. Furthermore, efforts to dynamically update VR environments also exist. Harichandran et al. proposed a framework for creating realistic and dynamically evolving VR training scenarios using digital twins [9]. In this study, we describe a method of linking 3D CAD and VR to speed up studies by reflecting changes in design and assumptions in real time, during construction studies.

2.2 Application of tracking technology

The tracking technology tracks the movements of real-world objects. An example of the use of tracking technology is to acquire data from remote local environments to operate robots remotely [10]. Tracking technology acquires the three-dimensional information of real objects. Commands can be transmitted based on three-dimensional data. Subsequently, a depth camera was used to acquire point cloud data as 3D data. Point cloud data can be used to record the shape of a building [11]. One of the advantages of using a depth camera is that there is no need to attach tracking equipment to the target object. Tracking technology can be applied to not only objects but also humans. In this study, tracking was targeted at human movement. When humans are the target of tracking, technology in the form of human skeletons is used to obtain information. Some construction projects have used tracked data of human skeletons, that is, acquiring the location of workers at a site using color-coded hard hats as tracking targets [12], and it has been suggested that the posture of workers can be analyzed. In this study, Azure Kinect [13] was used. Azure Kinect has a built-in depth camera and can acquire information about the human skeleton. There is a debate on whether the Azure Kinect is sufficiently accurate for use in energy consumption measurements. It has been suggested that the Azure Kinect could be used as an alternative to standard accelerometers [14]. In this study,

skeletal data acquired using the Azure Kinect were utilized to reproduce body movements in VR, by enabling the VR body model to follow the acquired skeletal information. Leap motion [15] is another technology for tracking parts of a body with high accuracy. Leap motion can track hand movements with a high accuracy. At construction sites, many operations involve hands. Therefore, tracking the movements of hands with high accuracy is important for reproducing the movements of the real body.

3 Reproduction of body movements in VR

3.1 Research Aim

This study presents a framework for evaluating parametric modeling using VR that incorporates body tracking. By reproducing body movements in VR, it is possible to evaluate the width and height of a construction site, based on one's own body. The model can also be evaluated by performing actions such as moving hands, stretching and contracting the body, and performing construction. This provides an experience similar to that of evaluating the size required for construction in a real mockup. Incorporating human behavior into a VR experience is an effective way to increase the level of detail in the reproduction of construction sites [16]. Furthermore, the parametric modeling transmitted to VR in real time enables the evaluation of dimensions with an efficiency that is not possible in reality because exporting objects from 3D CAD is not required. This system provides a method to examine, in an exercise format, whether construction work can be performed smoothly and safely in a prepared environment on a construction site, by visually checking the body and model of the job site.

3.2 The method of reproduction of body movements in VR

3.2.1 The elements for reproduction of body movements

Three main elements are required to reproduce the real body movements. The first is the use of HMDs, and there are various methods for using stationary monitors and HMDs to handle VR. However, when examining constructions using objects in a VR space, it is necessary to recognize the VR space as 3D. The second is to capture rough movements of reality. There are several techniques for this purpose, such as wearing a tracker on the body or using a camera. Considering the types of structures available in the construction industry and the large number of people involved, easy application is essential. To this end, tracking using a camera is considered an effective method, because people experiencing VR can

easily take turns. The third element is the tracking of individual body parts, which must be reproduced in detail. The operations performed by craftsmen at construction sites involve extensive detailed work. Therefore, when considering work in VR, it is necessary to reproduce movements in detail. For this it is necessary to track it separately from the rough movement tracking. In this study, rough movements were tracked using Azure Kinect, and detailed movements were tracked using Leap Motion.

3.2.2 Reproduction of whole-body movements using Azure Kinect

The Azure Kinect tracks whole-body movement. The information obtained through tracking is provided as a skeleton. The body model in VR moves as real movement using a skeleton. Movement control was performed using inverse kinematics (IK). We use the final IK [17] assets as a control method in Unity.

3.2.3 Reproduction of hands movements using Leap Motion

The Leap Motion tracks hand movements with high accuracy, and Azure Kinect also tracks hand movements. Therefore, when Leap Motion tracks the movements of the hands, the information transmitted to the IK is provided by the Leap Motion, and when it does not, the information transmitted to the IK is provided by the Azure Kinect. Furthermore, Leap Motion sends finger information that is directly reflected in the body model. Figure 1 shows the body movement reproduction system in a VR environment.
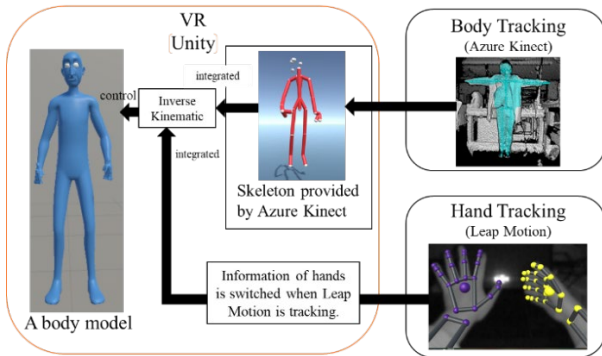

Fig.1 System of body movement reproduction in VR

4 Real-time linkage of 3D CAD and VR

4.1 Advantages of real-time linkage of 3D CAD and VR

By reflecting the 3D CAD model used in the VR design in real time, changes in the design plan can be immediately examined. Additionally, when a 3D model

is created such that the dimensions can be changed according to the parameters, the optimal values for the parameters can be determined without updating the 3D model. When a 3D model is used in VR, it must be exported as an object and then ported. However, by omitting this step, the time required can be shortened, and a speedy study can be achieved. In this study, Rhinoceros was used for 3D CAD, and RhinoInside [18] was used as an add-in to link Rhinoceros with Unity in real time.

4.2 Coordinate setting for 3D CAD

If the coordinates of the 3D model and HMD are incorrect, the positions of the models or HMD must be corrected after starting VR. This problem can be solved by setting the coordinates during the modeling stage. As the origin is shared between Rhinoceros and Unity, it is easy to handle the 3D model from the start of the interaction by setting the HMD as the origin in Unity and the center point of the location to be used in the 3D model as the origin in Rhinoceros. Ideally, the origin should be set at the start of modeling; however, if this is not the case, it is also effective to move the origin at the end of modeling. Furthermore, it is important to note that the scale varied between Rhinoceros and Unity. Unity was measured in meters, whereas rhinoceros was measured in millimeters. To smoothen the model for rhinoceros, we reduced the model transmitted to Unity by 1/1000.

4.3 Modeling of scaffold and steel-frame

Steel-frame 3D models were created using Rhinoceros software to evaluate the buildability of the scaffold. In this study, to examine the real-time reflection of changes in plan or design, 3D models were created using parametric modeling. Figure 2 and 3 show the parameters of the model. The parameters are as followss:

 (a) Width of scaffold
(b1) Handrail depth (below)
(b2) Handrail depth (above)
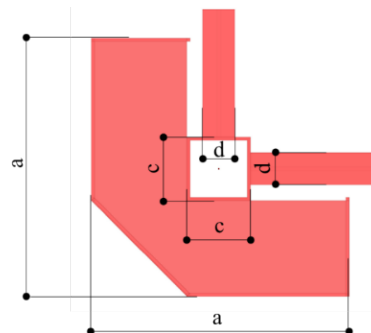(c) Width of pillar
(d) Width of beam
(e) Depth of beam
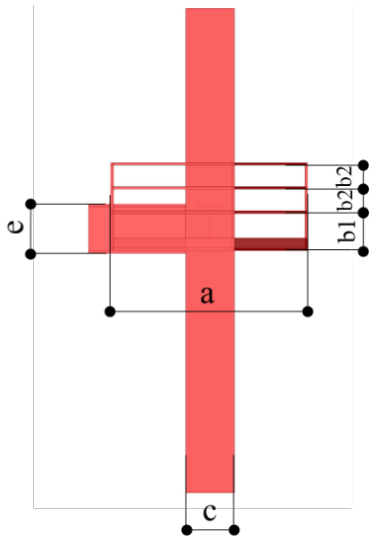

Fig.2 Top view of the steel-frame and scaffold models

Fig.3 Front view of the steel-frame and scaffold models

4.4 Transmitting 3D CAD data to VR

RhinoInside transmits the Rhinoceros mesh data to Unity through a C# script. In this study, the Rhinoceros mesh was used as the default. Three-dimensional (3D) models were created using Grasshopper, a visual programming feature of Rhinoceros. The mesh list was transmitted to Unity using C# script. The material information was not transmitted but was provided to Unity as soon as it was received. Figure 4 shows a photograph of the grasshopper model. The program consisted of three parts. The first part is modeling, the second is listing, and the third is transmission. Any number of meshes can be supported by inserting the components to be listed and by interspersing the process of counting the list.
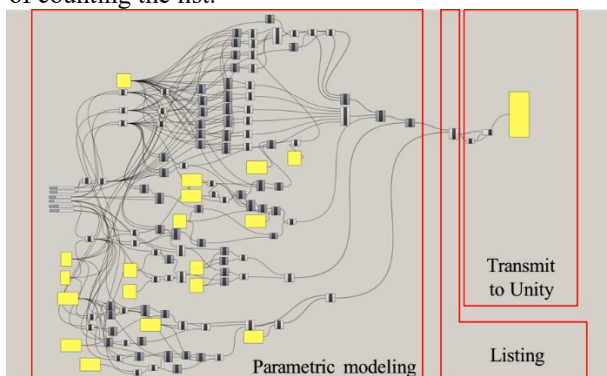

Fig.4 Composition of the grasshopper program

There are two advantages of transmitting each mesh individually. First, because mesh data are divided, hit detection is more likely to be reproduced for less complex shapes when a convex mesh collider is used. The higher the reproducibility of the hit decision, the more accurate the simulation. The second advantage is that each component can be assigned a function in VR. For example, when adding functions such as gravity judgment and hand tracking, if the meshes are integrated, all of them will be affected. However, if the meshes are transmitted individually, it is possible to add functions only to the desired parts. Figure 5 shows the models transmitted from Grasshopper to Unity.
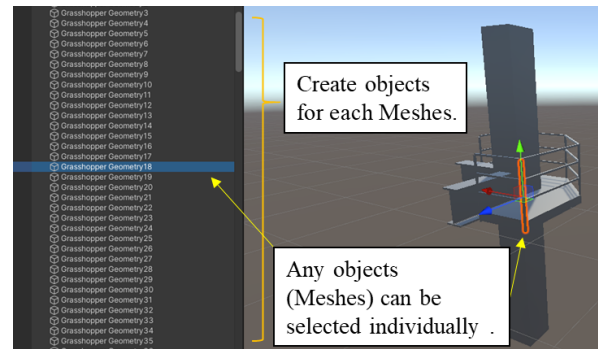

Fig.5 Models transmitted from grasshopper in Unity

4.5 Example of evaluation of construction site layout

First, we launched a VR device and then started linkage with 3D CAD. Once the linkage is initiated, the Rhinoceros model can be verified using VR. At this time, the 3D model is updated in real time, and changes to Rhinoceros can be immediately confirmed in VR. In the 3D model created in this study, the scaffold size, column height, handrail height, beam width, and beam height were set as parameters, and various dimensions were considered individually. In this study, the column height was fixed, and the width of the scaffold was varied to determine the necessary and sufficient width for safe construction. Additionally, when the construction area was fixed, the scaffold size was examined. The height of the scaffold railing can be determined to be safe and the appropriate height for construction can be determined. Figure 6 shows an example of checking the width of the scaffold. The most suitable width was determined by varying the width of the scaffold. Utilizing the reproduction of the body, the user performs movements such as turning the body and turning the hand, and examines whether the set parameters allow construction to be performed safely and constructively. Using various parameters, optimal scaffold dimensions were derived, and the use of the scaffold was envisioned to determine the actual temporary construction materials to be used. Without real-time linkage, the model must be exported every time this parameter is changed. However, this hassle was eliminated by sending mesh data in real time, allowing for a continuous study. The dimensions of the columns and beams can also be varied, which has the

advantage that multiple locations with different dimensions can be consecutively considered. Figure 7 shows examples from these studies. Even when examining multiple parameters, such as these, the 3D CAD model is immediately reflected, allowing for an examination with no time lag.   By observing the body, it is possible to examine the width that can be walked, the width needed to move, and to determine the necessary and sufficient parameters. While performing the construction operation, it is possible to examine whether the legs and body protrude from the scaffold, and whether there is excessive space.   For the handrail, a gripping motion can be used to determine whether it is sufficiently or excessively high. Thus, the plan can be examined in VR in real time while planning for changes and decisions.
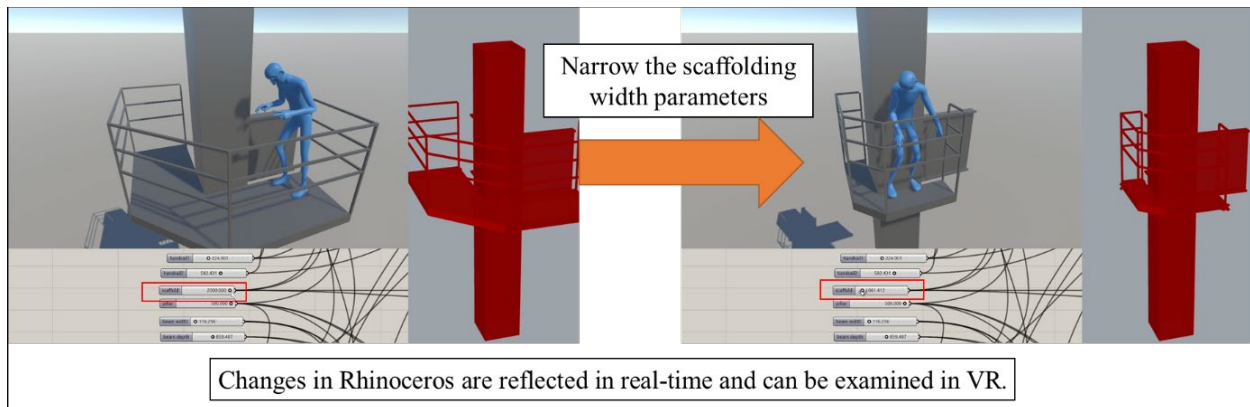

Fig.6 Checking the width of the scaffold

Fig.7 Example of differences in first- and third-person viewpoint because of changes in parameters

5   Discussion

Using this system, we can immediately review the plans after modeling, which enables the early expression of opinions in the process. Various people, such as construction workers, can easily express opinions, and they will connect to reflect workers' opinions on the

design.

One limitation of this system is that if the body is outside the range of the camera performing the tracking, real-life movements are not reflected in the VR. Therefore, it is difficult to study a wide range of areas. To improve this, it is necessary to set the means of movement in VR or attach a tracker to the body. In addition, this study confirms that only Rhinoceros and Unity can communicate in real-time. Therefore, if other applications are used, new means of communication will need to be developed, which is a limitation of this system. Large amounts of data may overload the computer and cause a lag, or may not be transmitted.

There are several possible developments for this system. Further information can be analyzed using the method of connecting applications. For example, by transmitting the data of skeletons tracked by Azure Kinect, the energy consumption of humans was analyzed. If Rhinoceros is used, a plugin such as Karamba 3D [19] can also be used. The advantage is that a single application can perform multiple modeling and analysis tasks simultaneously, and is simple to configure. Figure 8 shows the configuration of the system. 3D CAD, tracking systems, and VR were linked based on the VR platform. The system is composed of components that select the information to be used in VR and process it appropriately. In this study, the elements used in these functions were investigated. Therefore, if the necessary elements and data transmission methods are available, any application or platform can perform in a similar manner. In addition, as more functionality is required, similar discussions will enable the integration of additional systems into the development of VR applications.
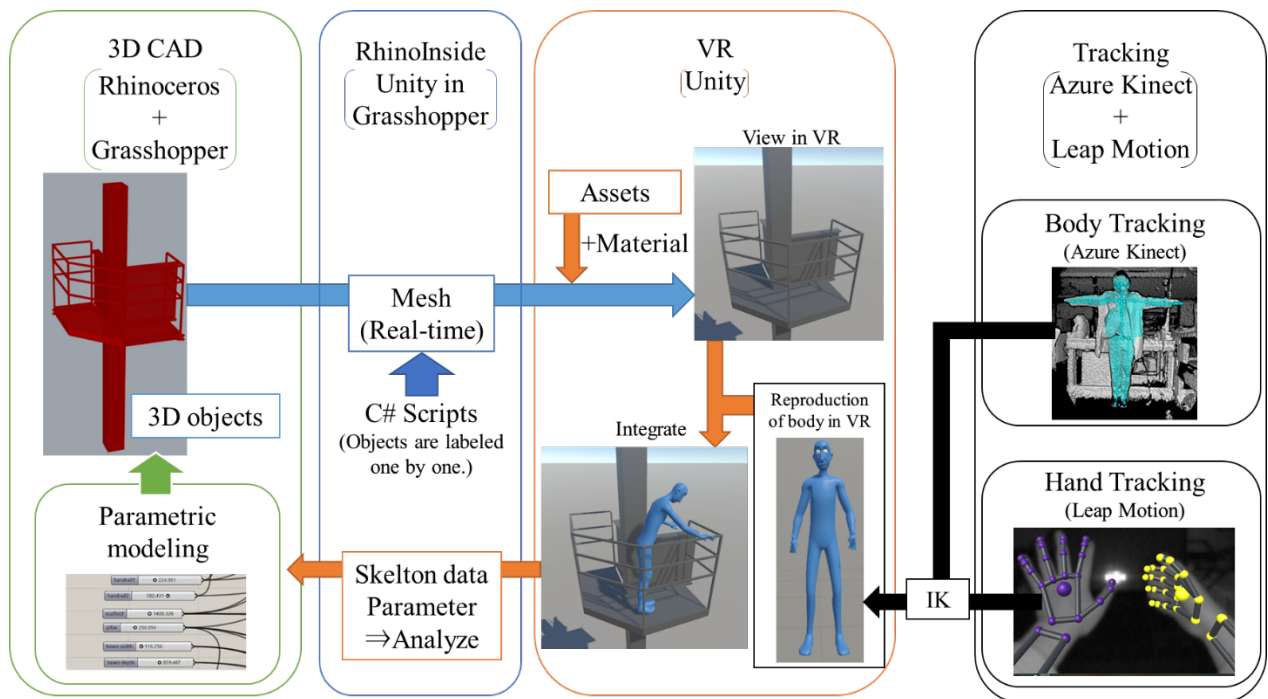

Fig.8 System configuration of VR system using tracking and 3D CAD

6 Conclusion

In this paper, the VR method connected to 3D CAD and the tracking system in real time were explained. The real-time tracking and reproduction of a body in VR can verify buildability by viewing the body and elements of a construction project. The real-time linkage of 3D CAD and VR enables us to view the plan and design changes instantly, as well as reflect the results of the study for planning. These linkages were achieved by examining the elements used in the functions. Rhinoceros was used for 3D CAD, Unity for the VR platform, Azure Kinect for body tracking, and Leap Motion for hand tracking. If these elements are in place, other 3D CAD, VR platforms, and tracking systems can be used. Furthermore, information from tracking and VR applications can be analyzed. Using this system, we can review the plans immediately after modeling, and express opinions. Various people will easily express opinions, and they will connect to reflect workers' opinions on design.

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