Development of the Simulator for Carrying a Lifted Load in Large Plant Construction

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Abstract –

Large plant construction has numerous works, and the proportion of hoisting operations in the total construction work is high. In the hoisting operations, many things should be considered to keep the operations safe, and the work steps of the hoisting operations are planned by considering them. However, it is difficult for novice construction workers to understand the work steps with conventional two-dimensional drawings. Thus, to have those workers understand it well, we developed the hoisting-operation simulator considering the physical behavior of a load in conjunction with 3D viewer and physics engine. The simulator can visualize the work steps as three-dimensional animation. Moreover, by associating the simulator with mixed reality technology, we developed the system superimposing the 3D animation on reality space via head mount display. Experiments verify that the 3D animation of a load moves with the vibration due to the inertial force and that the 3D animation generated by the simulator is superimposed in the work site.

Keywords –

Simulator; Mixed reality; three-dimensional measurement

1 Introduction

Large plant construction has numerous works, and in particular, the proportion of hoisting operations in the total construction work is high. In the hoisting operations, many things should be considered to keep the operations safe. When a load is hoisted in a narrow work site, the clearance between the load and the surrounding equipment should be considered. In addition, considering the forces of each lifting point (i.e., the placement of lifting tools) is also important. According to those information, the work steps of the hoisting operations are planned. In conventional planning, work steps were determined with two-dimensional drawings. However, novice construction workers take time to understand the details in the 2D drawings. In fact, the proportion of the novice construction workers in the total workers increases due to the decrease of skilled construction workers. For the reason, it is imperative to develop the system that make the novice construction workers understand the work steps of hoisting operations.

In recent years, some examples of using three-dimensional design software and 3D viewer have been reported to make construction workers understand their works. In particular, Building Information Modeling (BIM) associating information of design, construction and maintenance with the 3D model of buildings is used to various construction works [1]. As examples of recent BIM, Zhang et al. developed safety checking platform that detects the opening in a 3D model and automatically places guardrails for preventing fall-related accidents [2]. Sugimoto et al. developed a simulation system for quantitatively evaluating the validity of crane-deployment plans by integrating 3D models and a time dimension [3].

Moreover, Augmented Reality (AR) and Mixed Reality (MR) (i.e., a technology superimposing computer-generated objects on a reality space) has been promoted to use in construction works. Singh et al. indicated that AR has the important role in automating the site layout planning on construction projects [4]. Yeh et al. proposed a wearable device that can project the construction drawings and related information to on-site space [5]. Riera et al. reported the implementation and evaluation of an AR application to the education of building engineering [6]. On the other hand, as examples of recent MR, Ammari and Hammad developed a BIM-based system to facilitate on-site data collection and to support inspectors in evaluating building elements via MR [7]. Chalhoub and Ayer reported that using MR reduced the time required to understand the design of electrical conduit and led to fewer errors during the assembly process as compared to using traditional 2D drawings [8].

As above, many BIM and AR/MR technologies have been developed in order to make construction workers

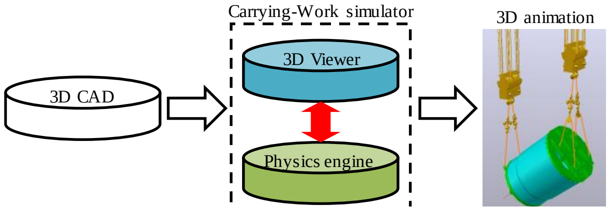


Figure 1. System flowchart of the animation application

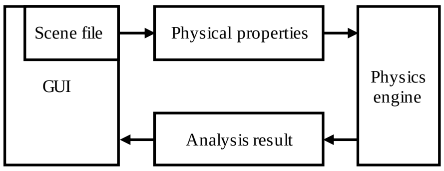


Figure 2. System diagram of the 3D viewer and the physics engine

understand their works. However, Most of them are not specialized in hoisting operations. Specifically, the physical behavior such as the vibration of a lifted load are not considered in the conventional BIM and a computer-generated lifted load including the physical behavior are not superimposed in conventional AR/MR. Hence, we have developed applications focusing on hoisting operations.. The features of the applications are as follows.

1) It creates 3D animations considering the physical behavior of a lifted load in conjunction with 3D viewers and physics engines.

2) It calculates forces applied to lifting points to define the position of lifting points and lifting tools.

Furthermore, we devised a system associating the above applications with MR technology. The features of this system are as follows.

3) It superimposes the 3D animation created by 1) to the reality space.

This paper is structured as follows. Chapter 2 gives the overview and method diagram of 1) and 2). Chapter 3 explains the overview and method diagram of 3). Chapter 4 presents the results of experiments to verify some proposed applications and systems. Finally, Chapter 5 concludes the paper.

2 Applications for Hoisting Operations

2.1 Animation Application Considering the Physical Behavior of a Lifted Load

In order to plan the hoisting operations for a lifted load considering physical behavior, we have developed the application that cooperates physics engines with by using the Application Programming Interface (API) of 3D viewers. Figure 1 shows the system flowchart of the application. Herein, this application is Hoisting Operation simulator (HO simulator).

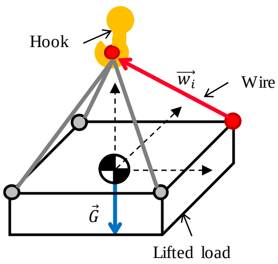


Figure 3. Configuration diagram of multi-point

First, the 3D model of a lifted load is made by 3D CAD. In order to perform the physical calculation on the 3D viewers, the center of gravity (the pink cube in Fig. 1) and the lifting points (the orange cube in Fig. 1) are incorporated in the 3D model.

Next, the 3D hoisting-operation animation is generated by using physics engines. Figure 2 shows the system diagram of the 3D viewer and the physics engine. The scene file is loaded into the 3D viewer's graphical user interface (GUI). Then, physical properties (e.g., the mass of each element in the model, friction coefficient and restitution coefficient) and the constraint condition are defined in the scene file. The defined file is handed over to the physics engine, and the analysis result is feedback to the GUI. These systems make it possible to generate the 3D animation considering the physical behavior and the planning of hoisting operation is performed more efficiently.

2.2 Force-Calculation Algorithm of Each Lifting Point

In the hoisting operation of large equipment into a work site, "multi-point lifting" is often used. The multi-point lifting is the method that carries a lifted load with many lifting tools. By using the multi-point lifting, the forces of lifting tools decrease and the attitude of the lifted load is more stable than single-point lifting. When using this method, the calculation of accurate forces of each lifting point and the selection of proper lifting tools are important.

Figure 3 shows the configuration diagram of multi-point lifting. Herein, F_i is the force of the lifting point, $\vec{w_i}$ is the three-dimensional vector from the lifting point to the hook, m is the mass of the lifted load, and g is the gravitational acceleration. The number i is numbered from No. 1 to No. n counterclockwise. The equation of motion of Fig. 3 is given as

$$[\vec{w_1} \quad \cdots \quad \vec{w_n}] \cdot [F_1 \quad \cdots \quad F_n]^T = [0 \quad 0 \quad mg]^T \qquad (1)$$

$$\Rightarrow \vec{W} \cdot \vec{F} = \vec{G},$$

where the size of $\vec{W}$ is 3 × n, the size of $\vec{G}$ is 3 × 1, and

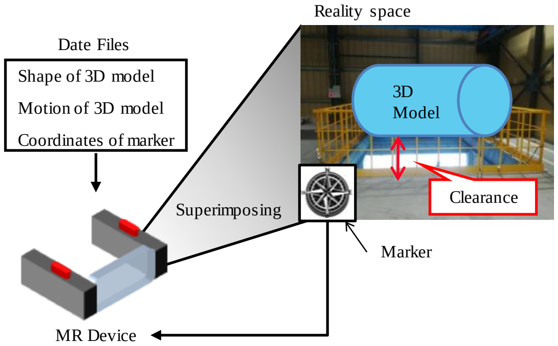


Figure 4. System diagram to superimpose 3D animations

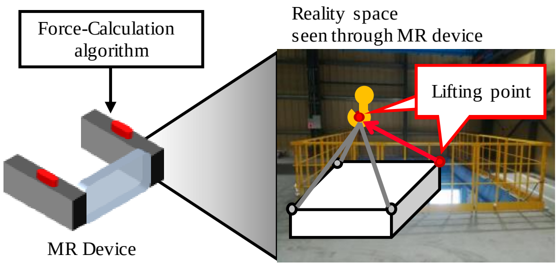


Figure 5. System diagram to calculate the forces of each lifting point

the size of $\vec{F}$ is 1 × n. Thus, when n is larger than 3, Eq. (1) is defined as an overdetermined equation system and general physics engines cannot calculate solutions accurately.

Therefore, we developed an algorithm that can calculate the forces of each lifting point even equations are overdetermined. Herein, this application is the Force-Calculation algorithm (FC algorithm). In the algorithm, a redundant equation is solved by regarding when the sum of root square of $\vec{F}$ is the minimum as the solution of Eq. (1). The solution of Eq. (1) is derived as

$$\vec{F} = \vec{W}^T \cdot \left(\vec{W} \cdot \vec{W}^T\right)^{-1} \cdot \vec{G} \qquad (2)$$

By Eq. (2), the forces of each lifting point in the multi-point lifting are calculated.

3 System Combining the Applications with MR Technology

As noted in Chapter 2, the HO simulator can generate 3D hoisting operations animations. However, it is desirable to explain how the hoisting operations is performed at a work site to managers and workers in order for them to appreciate the hoisting operation. In addition, the 3D animations are likely to interfere with the equipment in the plant because the work site does not always correspond with a map of that. Taking these matters into consideration, the application that can display the 3D animations in realty space is indispensable. Thus, the system that superimposes 3D animation on reality space by utilizing Mixed Reality (MR) technology is developed. Figure 4 shows the diagram of the proposed system.

First, the shape date of the 3D model, the motion date of the 3D animation generated by the HO simulator, and the coordinate date of a two-dimension marker model on the 3D viewer are stored in a HMD.

Next, a marker is set at the coordinate position defined in the 3D viewer. The marker is photographed by the RGB camera mounted on the HMD, and is recognized in the device. The initial position and direction to superimpose the 3D animation is defined. After recognizing the marker, the position of HMD itself in the reality space is defined by using the image data acquired by the monocular camera, and the animation is accurately superimposed according to the relative position between the marker and the device itself. At the same time, the surrounding environment seen through the HMD is meshed. Therefore, the 3D animation can be superimposed at an initial position in the reality space even a HMD wearer moves in the reality space. Moreover, in order to review the same scene as necessary, the system supports rewind, temporary stop, and frame-by-frame playback (rewind). Furthermore, the system supports measuring the distance between the 3D animation and the surrounding object (e.g., floor surface and wall) in the real space since the three-dimensional reality space where the HMD exists is meshed.

In addition, by combining the FC algorithm in Section 2.2 with the MR technology, the system that grasp the forces of each lifting point in a work site can be realized as shown in figure 5. Since the distance from a lifting point to a hook can be measured, the vector $\vec{w_i}$ is determined. Therefore, the forces are calculated by the equations (1) and (2).

4 Verification Testing

4.1 Verification of Animation Application and Superimposition System

Experiments were performed to verify the HO simulator and the superimposition system. Figure 6 shows a 3D work site model of the experiments. The beam (length: 8.0 m, weight: 1.8 t) was lifted by an overhead crane and carried from the first floor to the second floor through the aperture (dimension: 6.0 m×4.0 m). The beam and the overhead crane were connected by chain blocks and the attitude of the beam can be arbitrarily changed by hoisting the chain blocks. In the carrying experiments, the following things should be considered.

1) The attitude and the carrying path of the beam for

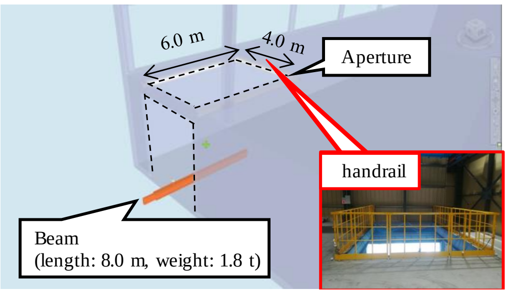


Figure 6. 3D work site model of the experiments

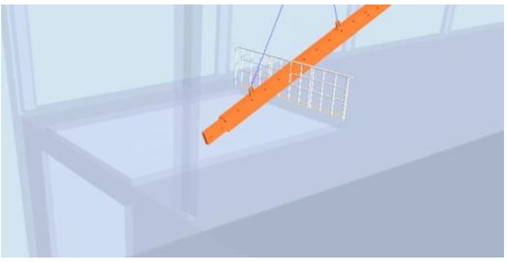


Figure 7. One scene cut out from the 3D animation

Fig. 8 3D animation superimposed on the work site

it to pass through the narrow aperture.

2) The clearance between the handrail (dimension: 4.0 m×1.3 m) around the aperture and the beam.

3) The collision between the second floor and the beam due to the vibration of the beam while carrying.

In order to examine these matters, the hoisting operations was planned with the HO simulator by using a beam model and the work site model. In addition, the 3D animation of the work was superimposed on the work site. Herein, in order to check the superimposed animation either on the 1st floor or the 2nd floor, markers were set at the positions indicated by the red letters in Fig. 6.

Figure 7 shows one scene cut out from the 3D animation. The 3D animation shows that the beam moves with the vibration due to the inertial force. Moreover, the 3D animation also shows that the magnitude of the vibration is changed by the influence of the length of the chain block. By realizing this vibration, checking the

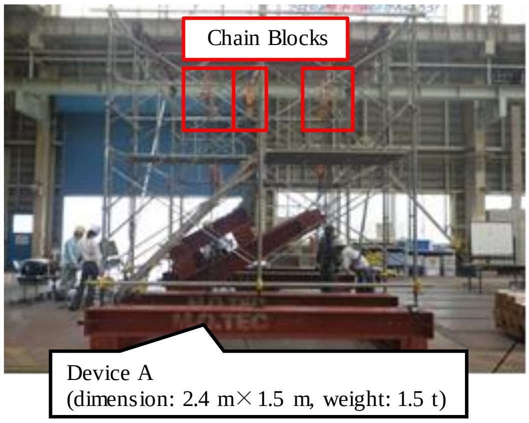


Figure 9. Equipment for the verification experiment of the Force-Calculation

collision between the beam and the second floor is performed more realistically.

The result of superimposing the 3D animation on the work site is shown in Figure 8. The RGB camera of the HMD successfully authenticated the marker and the 3D model of the beam is superimposed on the 1st floor. Then, it was confirmed that the 3D animation was superimposed at the initial position even when the HMD wearer moved due to the self-localization function of the HMD. Also, the same motion as the motion created on the HO simulator was superimposed in the work site.

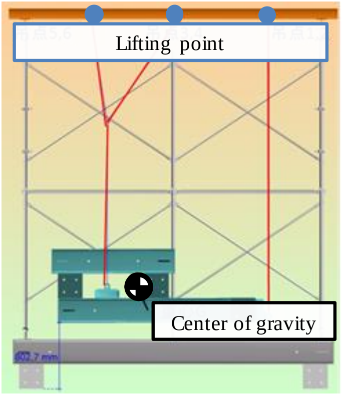
4.2 Verification of Force-Calculation Algorithm

An equipment for a verification experiment is shown in Figure 9. The attitude of a device A (dimension: 2.4 m × 1.5 m, weight: 1.5 t) was changed by operating the length of six chain blocks. The angle between the bottom surface of the device A and the ground surface was changed from 0 degree to 60 degree. Forces of each lifting point were measured with load cells (i.e. total number of load cells is 6) and the angle was measured with a digital angle sensor attached on the bottom surface of the device A. The measured results were compared with analyzed results from the algorithm in Section 2.2. The analysis was conducted under same conditions as the ones in the experiment.

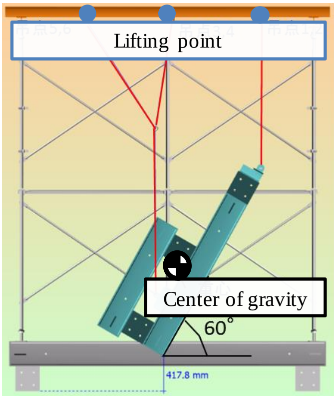
Figure 10 is a side view of the device A at 0 degree and 60 degree, and Table 1 and 2 show measured results and analyzed results under each degree. Table 1 and 2 also include relative errors based on the analysis values. The difference between the measured results and the analyzed results is ± 10% or less at each hanging point. Therefore, the effectiveness of the algorithm is verified.

5 Conclusion

In order to improve secure the safety of hoisting



1) 0 degree.



2) 60 degree.

Figure 10. Attitude of a device A at each degree

operations, the paper proposed an application for planning a hoisting operations. Furthermore, in order to have construction workers understand the plan of hoisting operations, the paper proposed a system associating the applications with MR technology. From the results of verification testing, we got the following conclusion.

1) The application that creates 3D animations considering the physical behavior of a lifted load was developed. The application was realized by cooperating physics engines with Application Programming Interface (API) of 3D viewers. The application make it easy to check the clearance between a lifted load and the equipment in a plant and to plan an appropriate hoisting operation procedure.

2) The system that superimposes 3D animations to reality space was developed. The system was realized by using MR HMD that includes many sensors. The system make it possible to predict the dangerousness of a hoisting operations at a work site.

3) The application that calculates forces applied to each lifting point was developed. The application can calculate the forces of each lifting point even a simultaneous equation is redundant. The application make it easy to define the position of each lifting point and lifting tools.

Table 1. Comparison of measured forces and calculated forces at 0 degree

Number of Lifting point	Measured Force [N]	Calculated Force [N]	Error [%]
1	1200	1300	8
2	1200	1300	8
3	205	220	7
4	205	220	7
5	5200	5030	3
6	5200	5030	3

Table 2. Comparison of measured forces and calculated forces at 60 degree

Number of Lifting point	Measured Force [N]	Calculated Force [N]	Error [%]
1	1175	1297	10
2	1175	1297	10
3	1550	1430	8
4	1550	1430	8
5	4000	3866	3
6	4000	3866	3

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