REAL-TIME VISUALIZATION OF CRANE LIFTING OPERATION IN VIRTUAL REALITY

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ABSTRACT: *In the construction domain, previous efforts in utilizing Virtual Reality (VR) mainly focused on training and education, pre-planning, and simulation. The understanding of their benefits in real-time applications during the construction phase is scarce. This research presents an approach to leverage VR for real-time sensor data visualization for the monitoring of equipment operations. Two critical components in this approach, 1) equipment motion visualization and 2) workspace condition visualization, are explained in detail. The effectiveness of the proposed real-time visualization approach is presented by a case study of crane lifting operations. The pipeline for developing real-time crane operation visualization is presented by the steps of sensor data visualization, point cloud processing and visualization, and the design of a graphical user interface. Results of a field test show that with the proposed approach, crane motion and workspace condition can be effectively visualized in real-time during the lifting operation, which has a positive impact on supporting timely decision-making of crane operators.*

KEYWORDS: *Virtual Reality; Crane Lifting Operation; Real-time; Point Cloud; Graphical User Interface*

1. INTRODUCTION

Construction equipment plays a critical role in the efficient and safe execution of a construction project. The location, motion, and status of a piece of equipment are essential information for tasks such as safety management, asset inventory and maintenance, and progress monitoring. Visualizing equipment activity provides the stakeholders intuitive understanding of equipment operations on a construction site which will assist them in decision-making. Despite much research in utilizing Virtual Reality (VR) for construction applications, they mainly focus on training and education, pre-planning, and simulation. Very few explore the benefits of VR in real-time applications during the construction phase, such as equipment motion visualization, workspace condition modeling, and real-time operation assistance.

This research presents an approach to leverage VR technology for real-time sensor data visualization for the monitoring of equipment operations. The methodology contains two critical components, 1) equipment motion visualization and 2) workspace condition visualization. The effectiveness of the proposed real-time visualization approach is presented by a case study of crane lifting operations. Test results are presented by comparing the virtually reconstructed crane motion and workspace condition to the actual ones. With the proposed approach, crane motion and constraints in the workspace can be visualized in real-time during the lifting operation, which has a positive impact on supporting the decision making of crane operators.

2. RELATED WORK

2.1 Virtual Reality and Game Engine

Virtual reality (VR) is a multi-disciplinary field of computing technology that emerged from research on three-dimensional (3D) interactive graphics and pilot simulations in the 1960s. Rather than a single technology, virtual reality is a combination of a set of technology that keeps evolving over time. These technologies are essentially computer graphics/displays, human-computer interfaces, and simulation. They are used to create a 3D computer-generated simulation in which the user can navigate around, interact with, and be immersed in a virtual environment (VE).

A game engine is software to create and develop VR content, such as video games or serious games for professional training. The core functionality of a game engine typically includes a rendering engine, a physics engine, and other critical components including sound, scripting, animation, artificial intelligence, networking, and streaming. Due to the close-to-reality simulation and flexibility in customizing the script, game engines are replacing traditional VR platforms and have been extensively used in the development of VR content for various construction applications.

2.2 Virtual Reality for Construction Applications

In the field of construction, VR has been extensively utilized for design verification (Yan et al. 2011), education and training (Albert et al. 2014), equipment simulation (Kamat and Martinez 2005), and occupant/worker behavior analysis (Zou et al. 2016). Inspired by the application of VR in pilot and surgery training, the construction industry has been exploring how VR can enhance the education and training of construction operations. Several risk-free virtual training systems are developed to expose users to a virtual construction site with potential hazards (Lin et al. 2011; Li et al. 2012). Virtually walking on the site, users will learn how to identify the hazardous situations and how to mitigate them properly. To improve the collaboration among crane lifting crew members (e.g., crane operator, riggers, signal person), Fang and Teizer (2014) presented a virtual training environment where the entire lift crew can participate in virtual lift tasks cooperatively.

Compared to visualizing static objects, simulating the dynamic operation of construction equipment is more challenging as the kinematics of each kind of equipment are different. Cho et al. (2002) proposed a framework for rapid local area sensing and 3D modeling for the planning and visualization of equipment operation. Using the principles of forward and inverse kinematics, Kamat & Martinez (2005) developed an approach for dynamic 3D visualization and simulation of articulated construction equipment. With a specific focus on cranes, Kang & Miranda (2006) developed a computer system that provides detailed simulation and visualization of crane operations. Al-Hussein et al. (2006) integrated 3D visualization and simulation for modeling the lifting operation of tower cranes.

Emerging remote sensing technology has greatly expended the sources of field information and the way they are collected on construction sites. The potential of visualizing real-time field data in a virtual environment is investigated by Xie et al. (2011). They implemented Radio Frequency Identification (RFID) and real-time VR simulation in construction processes to improve the control and monitoring of construction projects. Fang et al. (2014) proposed a framework for visualizing real-time location data in an as-built virtual environment. They visualized the worker's location in a BIM-enabled virtual construction site based on the location data collected by Ultra-Wide Band (UWB) technology. However, the real location data of construction workers were only used for crane operator training, instead of real-time applications.

In addition to visualizing the location of construction equipment and workers, visualizing the workspace around the equipment is critical for a more comprehensive awareness of the equipment operation. Cho and Haas (2003) reported a 3D visualization method for modeling unstructured construction workspace. This method uses simple sensors combined with human perception and highly descriptive CAD models to rapidly model and visualize geometric information of entities such as equipment and materials in the construction workspace. To help the heavy equipment operators rapidly perceive the surrounding environment, Cho and Gai (2014) introduced a dynamic object recognition and registration methods using computer vision and laser scanning technologies. Wang and Cho (2015) proposed a smart scanning technique for tracking the location of construction equipment and modeling the dynamic workspace. Although their approach significantly accelerates the 3D modeling process of dynamic equipment, the model update rate is not fast enough for an operator to make a timely decision due to the slow laser scanning rate.

3. METHODOLOGY

3.1 Framework

This research proposes a framework for real-time visualization of crane motion and site condition. As shown in Figure 1, this framework is comprised of three parts: 1) crane motion capturing, 2) site condition modeling, and 3) user interface and interaction. First, crane motion is captured by multiple sensors and transmitted to a processing unit in real-time. Then, site conditions (e.g., existing buildings, trees, powerlines) are represented by laser-scanned point clouds and the bounding boxes constructed based on the point clouds. The following sections will explain the two key components of the framework that are enabled by game engine technology: 1) sensor data visualization and 2) point cloud visualization. Details of other components in this framework can be found in (Fang et al. 2016).

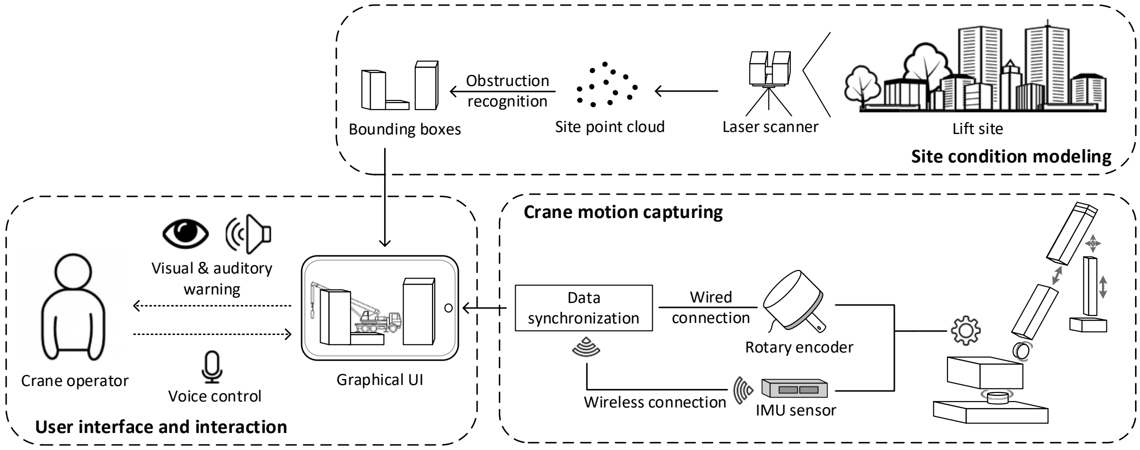

Figure 1: A framework for real-time visualization of crane motion and site condition

3.2 Sensor Data Visualization for Real-time Crane Motion Reconstruction

To capture the crane motion in real-time, multiple sensors are deployed on a crane to measure critical crane motions, including boom swing, lift, and extension, and load sway based on a kinematics analysis (Figure 2).

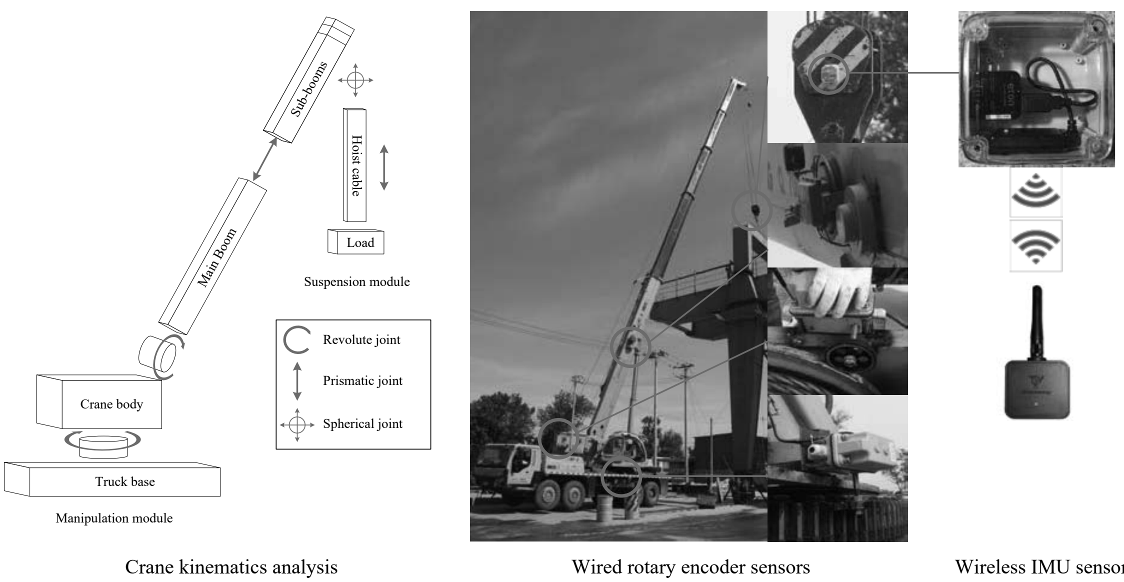

Figure 2: Sensor deployment for critical motion capturing

These sensor data are synchronized and transmitted to a computer through a serial port. In the game engine, the crane motion data are read from the serial port and linked to different parts of a virtual crane model (e.g., cabin, boom, load) represented by multiple rigid bodies (see Figure 3).

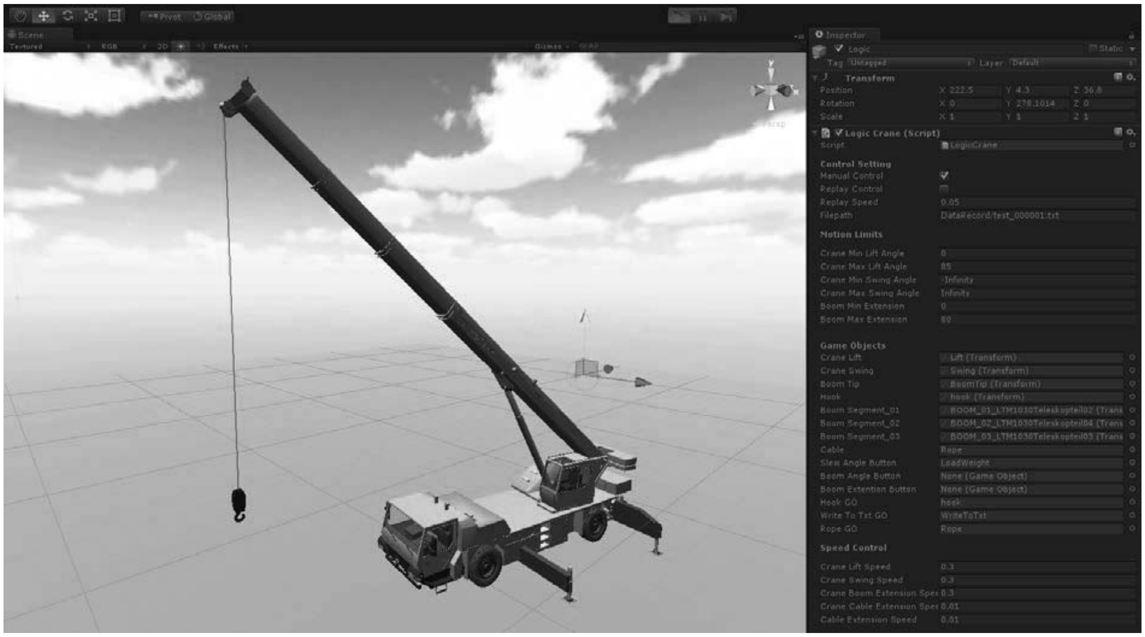

Figure 3: Sensor data visualization in a game engine for real-time crane motion reconstruction

3.3 Point Cloud Visualization for Site Condition Modeling

The goal of site condition modeling is to model a lift site with as-is conditions, especially the presence of obstructions such as vehicles, trees, and powerlines. 3D point clouds acquired by a laser scanner can correctly reflect the as-is condition of a lift site with comprehensive 3D geometric information. However, continuously computing the distance between each point and the crane parts is too computationally heavy. Therefore, the site point cloud needs to be converted into bounding box objects to represent the location and dimension of all the obstructions in presence. As illustrated in Figure 4, the pipeline to obtain an oriented bounding box from a point cloud involves the steps of segmentation, clustering, and orientation estimation. The input point cloud is first down-sampled from its original number of points to around 10,000 points by performing voxel grid filtering. Next, ground plane segmentation is performed using Random Sample Consensus (RANSAC) (Schnabel et al. 2007). Finally, an oriented bounding box is computed for each point cluster by considering the physical spread of points in the z-axis (vertical axis) and the x-y-plane. Once the bounding boxes for obstructions are automatically created, they are prepared for visualization with the adjustment of surface transparency level and being labeled as obstructions in the game engine. Furthermore, the crane model is placed at the planned position and specific pick and place locations can be manually positioned in the virtual lift site.

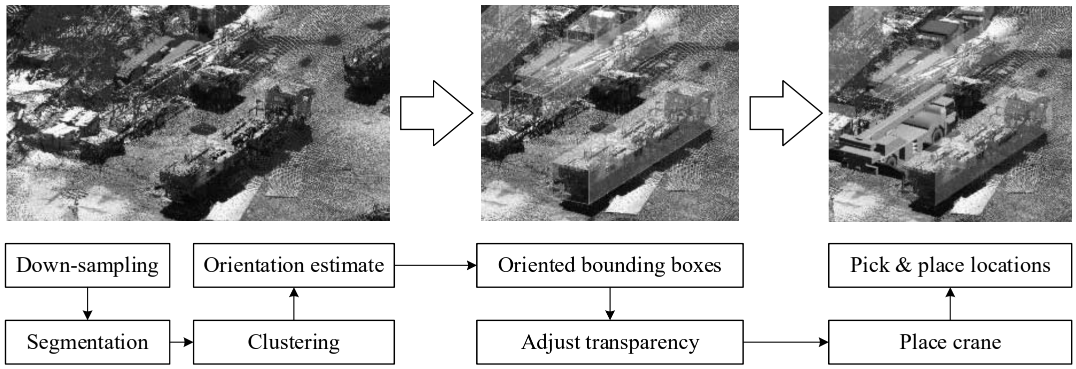

Figure 4: Pipeline for point cloud visualization

3.4 Graphical User Interface

A user interface (UI) is the main channel of the communication between the operator and the system. The information presented by the UI must be concise and easily understandable so that the operator can perceive the information with minimal cognitive workload. The UI of the developed system consists of three main views of the virtually reconstructed lift scene: a voice control free view, an elevation view and a top view. All views simultaneously show the virtually reconstruction lift scene in real-time that consists of the crane movement and the environment conditions (see Figure 5). The main free view is controlled by the voice commands from the operator (e.g., zoom in/out, left/right, up/down, reset) so that the operator can easily focus on the objects of interest from an occlusion-free angle. The elevation view and the top view are useful to understand the elevation and position of crane load and parts. In addition to the three views, the UI is augmented by information including 1) visual warnings for collision hazard and excess load sway, 2) highlighted obstructions in proximity to the load or crane parts, 3) previous lift path, and 4) a voice control panel.

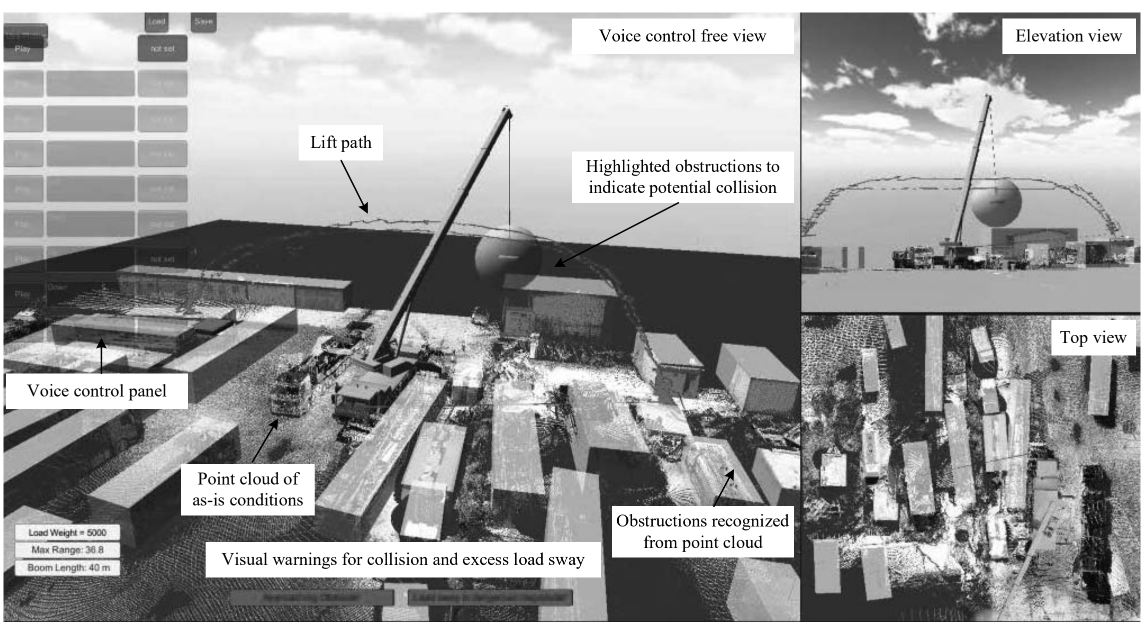

Figure 5: User interface (UI) shows virtually reconstructed lift scene and critical information in real-time

4. FIELD TEST RESULTS

The proposed method was implemented in an actual crane lifting operation. The site point cloud was processed prior to the operation and the sensor data was processed and visualized in a game engine by a tablet computer installed in the crane cabin. The results of real-time visualization were validated by comparing the virtually visualized crane operation to site camera recordings from two view angles: site overview and top view from the crane boom tip. The site overview comparison demonstrates the visualization results in reconstructing crane boom motions (see Figure 6) and the top view from boom head comparison demonstrates the accuracy in visualizing crane load position (see Figure 7). From the comparison, it can be seen that visually, the virtually reconstructed crane motion and the site condition match with the actual scenarios closely. In addition, the delay between actual and reconstruction crane motion is almost unnoticeable.

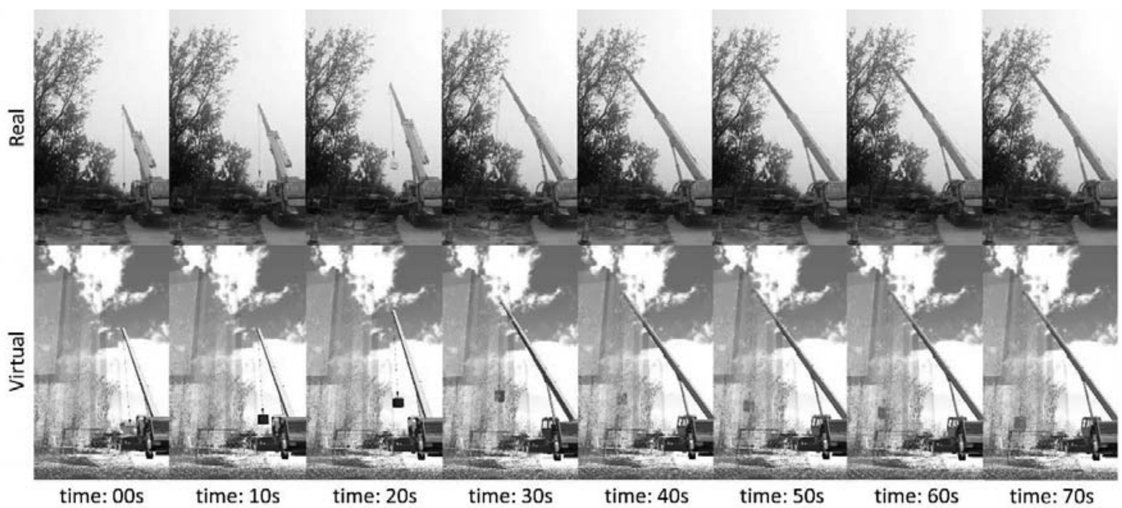

Figure 6: Comparison between actual load sway motion (upper) and reconstructed load sway motion (lower) from the boom's top view.

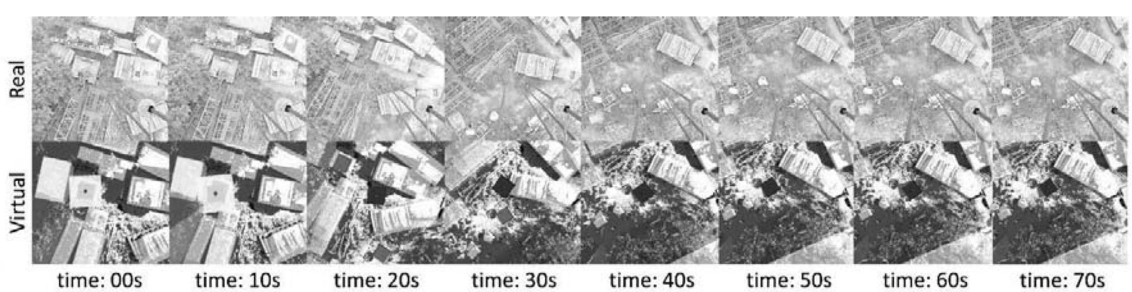

Figure 7: Comparison between actual lifting (upper) and reconstructed lifting process (lower) in site overview

5. DISCUSSION

This research demonstrates the feasibility of using VR technology for real-time visualization of crane operation.

However, several limitations have to be overcome before this method can be applied in daily equipment operations. First, certain steps in the proposed approach remain as semi-automated processes, including setting up crane rigid bodies in the game engine for motion visualization and importing site point cloud to game engine. These steps will be automated in future work by creating a standard format in the game engine for model setup and import. Another limitation of the presented work is that site point cloud is currently collected using a laser scanner. The scanning process must be completed prior to the operation, which can be laborious and time-consuming. This is out of the scope of this research but automated point cloud collection methods, for example using drones, will be explored in the future to minimize the efforts in data collection.

6. CONCLUSION

This research proposes a method for real-time visualization of crane operation using VR technology. It specifically addresses the challenges in real-time equipment motion visualization and site condition modeling. This approach is demonstrated by a case study of crane lifting operation visualization. The proposed method was implemented in an actual crane lifting operation and the results show that the crane motion and lift site condition can be closely visualized in real-time with minimal delay. User feedback indicated that visualizing the crane operation in real-time have positive impacts on improving the efficient and safety performance of crane operators, and supporting the decision making of the lift supervisor.

7. ACKNOWLEDGEMENT

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