Research and Application of a BIM-Based Virtual Construction Simulation System for Large-Scale Steel Structures (Postprint)

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Abstract

This paper investigates a BIM-based virtual construction simulation system for large-scale steel structures and its application in actual engineering projects. The system utilizes the Unity3d virtual reality development platform, effectively leverages BIM models to realistically present construction sites under various scenarios, and can be employed for construction site management and technical disclosure. Its successful implementation in the construction of large-span steel trusses at the Hangzhou Shangcheng District Sports Center has significantly improved construction efficiency while comprehensively ensuring quality and safety throughout the construction process.

Full Text

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Abstract: This paper researches and applies a BIM-based virtual construction simulation system for large-scale steel structures in an actual engineering project. The system utilizes the Unity3d virtual reality development platform and effectively leverages BIM models to realistically display construction sites under various scenarios, enabling applications in construction site management and technical disclosure. Its successful application in the large-span steel truss construction of Hangzhou Shangcheng District Sports Center significantly improved construction efficiency and fully guaranteed quality and safety throughout the construction process.

Keywords: Virtual Reality; Unity3d; BIM; Steel Structure; Construction Design

1. Introduction

With continuous advancements in information technology, the informatization level of construction management has become increasingly sophisticated, leading to substantial improvements in the control of construction cost, quality, schedule, and safety. Following the Ministry of Housing and Urban-Rural Development's explicit proposal in the "Opinions on Promoting the Development and Reform of the Construction Industry" to "promote the application of building information modeling (BIM) and other information technologies throughout the entire process of engineering design, construction, and operation and maintenance to improve comprehensive benefits," BIM technology has gradually matured in construction engineering applications. Its implementation in project information management [1], dynamic construction site layout [2], and construction cost control [3] has greatly enhanced construction management efficiency.

To further meet the demand for construction site visualization and assist project managers in making better decisions and site management while providing workers with efficient pre-job training and safety education, the integrated application of virtual reality (VR) and BIM technology has become a current research focus. Unity3d is a comprehensive VR development platform that enables efficient interfacing with BIM, allowing developers to implement different VR interactive experiences through C# scripting. Virtual simulation based on the Unity3d platform has been developed and applied in decoration [4], surveying [5], mining [6], and shipbuilding [7], achieving promising results.

However, VR applications in the construction field remain in their infancy, with most still relying on animation rendering or commercial templated VR software with fixed functions, resulting in insufficient interactive experiences and diminished application effectiveness. The large-span steel truss integral lifting project at Hangzhou Shangcheng District Sports Center features complex processes, high operational requirements, and numerous safety hazards, demanding high interactivity from the VR system. This paper investigates a BIM+Unity3D-based virtual construction simulation system for large steel structures specifically for this project and successfully implements it in practice, effectively improving construction efficiency and ensuring quality and safety during construction.

2. Project Overview

Hangzhou Shangcheng District Sports Center is a stacked sports complex located at the intersection of Hou Chao Road and Qianjiang Road in Hangzhou. The building has a total area of 55,681.2 square meters, with fourteen above-ground floors and four underground floors. The main structure employs a frame-shear wall system with partial steel structures. The sports center houses a water polo hall on the fifth floor and a basketball hall on the ninth floor, both featuring steel truss floor systems with concrete spectator stands below. The steel truss floor consists of six large-span steel trusses and connecting steel beams, spanning 39.2 meters in length, 33.2 meters in width, and 4.1 meters in height. After expert evaluation, the construction method involves first assembling the floor system on the concrete slab, then using a hydraulic lifting system to raise the entire steel truss floor into position, as shown in [Figure 1: see original paper].

The large-span steel truss weighs over 390 tons, and finite element analysis indicates a maximum mid-span deformation of approximately 8 mm. Twelve lifting points are arranged across the six trusses, with lifting platforms and hydraulic equipment installed on the floor above the installation location. Strict synchronization among different lifting points must be ensured during the hydraulic lifting process. Due to complex environmental factors, high operational requirements, and numerous safety hazards, it is essential to improve construction disclosure quality and systematically identify potential issues to ensure the smooth progress of the large-span steel truss hydraulic lifting operation.

3. BIM-Based Virtual Construction Simulation System for Large Steel Structures

The implementation of this virtual construction simulation system for large steel structures primarily involves five processes: 3D model import, scene element rendering, interaction command addition, user interface design, and system deployment, as shown in [Figure 2: see original paper].

3.1 3D Model Import

The existing BIM model of the sports center was retrieved, and considering the construction progress during steel truss lifting, only portions of the overall model up to and including the fifth floor were retained according to the completed construction schedule, as shown in Figure 3: see original paper. The model was exported from the Revit platform as an FBX file and imported into Unity3d, as shown in Figure 3: see original paper.

After import, physical properties must be added to the model to enhance its fidelity to the prototype. Collision volume is the most important property; without it, different objects would pass through each other during movement. Collision volumes are added by selecting the Physics-Collider property for the model, with Mesh Collider used for complex geometries. Additionally, to enable realistic physical effects under various forces, such as falling under gravity, rigidbody properties must be added by selecting the Physics-Rigidbody attribute.

3.2 Scene Element Rendering

To realistically simulate actual construction site conditions, various scene elements were added to the environment, including sound effects, sky, lighting, and weather.

At the Hangzhou Shangcheng District Sports Center construction site, four primary sound sources exist: overlapping construction operations, rain and wind during inclement weather, human footsteps, and hydraulic cylinder activation during steel truss lifting. The first three sounds maintain relatively constant volume regardless of the user's location, so audio properties were added to the character using Audio-Audio Source with corresponding audio files imported. Since hydraulic cylinders are fixed in position, their sound volume varies with distance from the user, requiring audio properties to be added directly to the cylinder objects.

The sky is controlled by Unity3d's built-in Skybox, configured as clear and cloudless, with the sun's position controllable along with the light source. All object rendering in the scene is achieved through lighting. The default light source is Directional Light, representing sunlight with directionality. By controlling the Rotation property values (x, y, z) of the light source, the illumination direction can be adjusted. When the light direction is parallel to the ground, dawn or dusk is simulated; when perpendicular to the ground with the source above the main building, midday is represented; when below the main building, late night is depicted. The Skybox and sun respond correspondingly to light source changes, as shown in Figure 4: see original paper and Figure 4: see original paper. Considering nighttime installation work, point light sources were arranged at appropriate locations for illumination, as shown in Figure 4: see original paper.

The weather system is represented using Particle Systems. Since the lifting operation occurs in summer, rain impact must be considered. Unity3d's particle effect control includes nearly a hundred parameters, but for rain simulation, the primary adjustments involve Duration, Start Speed, Max Particles, Shape, and Renderer to control raindrop lifecycle, falling speed, quantity, direction, and appearance. [Figure 5: see original paper] illustrates the simulated rainy construction scenario.

3.3 Interaction Command Addition

Interactions are implemented primarily through C# scripts attached to corresponding objects. In Unity3d, all character interactions are controlled by the Animator module combined with C# scripts. The Animator module provides character action animations; the logic for character action animations used in this project is shown in [Figure 6: see original paper]. Each character model includes an Avatar submodule that divides the human body into different parts by joints, such as hands, feet, arms, legs, shoulders, and neck. Action parameters can be defined to control movements of different body parts.

C# scripts serve two main functions in character control: (1) changing the character model's spatial position and orientation, and (2) setting key presses to modify action parameter values. For example, the following statements control character crouching when the "c" key is pressed:

```
Bool crouch = Input.GetKey (KeyCode.C);
m_{Character}.Move (crouch);
```

[Figure 7: see original paper] shows the character model used in this project, capable of standing, walking, running, jumping, and crouching for comprehensive site experience. Additionally, the system includes ThirdPerson Camera and FirstPerson Camera for third-person and first-person perspectives, with perspective switching implemented through C# scripting:

```
Void SwitchCamera (int index) {
    int i = 0;
    for (i = 0;i<cameras.Length;i++) {
        if (i! = index) {
            cameras[i].GetComponent<Camera>().enabled = false;
        } else {
            cameras[i].GetComponent<Camera>().enable = true;
        }
    }
}
```

Beyond character control, key processes in the steel truss lifting operation can also be simulated. Compared to the BIM model, the steel truss VR model was adjusted to rest on the concrete slab. Lower lifting points for hydraulic lifting were created at both ends of each truss, with lifting controlled by the "8" and "5" keys on the numeric keypad. The controlling C# statements are as follows:

```
float up = Input.GetAxis ("SteelTruss");
float risingHeight = 9.0f;
if (up > 0) {
    if (transform.position[1] < risingHeight) {
        transform.Translate (2 * Vector3.up * up * Time.deltaTime, Space.World);
    }
}
if (up < 0) {
    if (transform.position[1] > 0) {
        transform.Translate (2 * Vector3.up * up * Time.deltaTime, Space.World);
    }
}
```

Steel strands must also move with the steel truss to create a realistic lifting visualization. Unlike the truss, the strands undergo shortening and lengthening, requiring adjustment of both spatial position and Transform-Scale properties. Figure 8: see original paper shows the effect during truss lifting.

Wind effects were added during the lifting process, and slight asynchrony between different hydraulic lifting points was considered to comprehensively simulate various conditions during hydraulic lifting. To demonstrate construction scenarios under different weather and time conditions, corresponding interaction commands were added for weather and lighting control. Weather switching between sunny and rainy conditions is achieved by toggling the particle effect system:

```
if (Input.GetKeyDown (KeyCode.Tab)) {
    if (rain == 0) {
        objects.SetActive (false);
        rain = 1;
    } else {
        objects.SetActive (true);
        rain = 0;
    }
}
```

The particle effect system off (on) corresponds to sunny (rainy) conditions, with the "Tab" key toggling between them. Additionally, lighting intensity can be adjusted for further refinement. Lighting is controlled by adjusting the Rotation property values (x, y, z) in Directional Light (-180≤x,y,z$ $180), with x-value changes controlled as follows:

```
float up = Input.GetAxis ("SunLight");
transform.Rotate (Vector3.right Time.deltaTime, Space.World);
```

Pressing the numeric keypad "+" sets the "SunLight" value positive, corresponding to x-value changes in the positive direction (sun moving west to east), while pressing "-" sets a negative value (sun moving east to west).

3.4 User Interface Design

The user interface (UI) helps users quickly familiarize themselves with the virtual construction simulation system and simplifies operations. [Figure 9: see original paper] shows the start interface UI for this project, consisting primarily of a title, background texture, and instruction buttons. A new Scene was created in Unity3d, utilizing Unity3d's built-in MainMenuGUI C# script as a basic framework, with title elements added and adjusted according to requirements.

Transitioning from the start interface to the construction scene requires C# scripting for button actions. For example, the "Start VR Journey" button is assigned the following C# statement:

```
if (GUI.Button(new Rect(playButton), "开始 VR 之旅")) {
    StartCoroutine("ButtonAction", "Hengjia");
}
```

This indicates that pressing the "Start VR Journey" button transitions to the "Hengjia" scene (the virtual construction scene). Other buttons use similar C# scripts.

The icons in the upper-left and upper-right corners of [Figure 10: see original paper] are UI buttons in the construction scene, enabling restart and return-to-start-interface functions, respectively.

3.5 System Deployment

To enable project managers and workers to use the virtual construction simulation system anytime and anywhere without being limited by development software, system deployment is necessary. Selecting File-Build Settings opens the deployment interface to choose target Scenes and platforms. Unity3d supports multi-platform deployment, including Windows, Mac, Linux, iOS, and Android. Before deployment, all Scene files must be organized—typically two or more—with one Scene for the start interface UI design and others for various construction scenarios, as shown in [Figure 11: see original paper]. After organization, selecting Build completes system deployment, generating .exe files.

3.6 System Features

(1) **Efficiency**: The system effectively utilizes existing BIM models, closely integrating with the project to create virtual construction scenes based on actual models.

(2) **Realism**: The system authentically reproduces construction scenes with physical properties enabling collision and gravity simulation. The combination of sound effects, sky, weather, and lighting elements can display various possible construction scenarios.

(3) **High Interactivity**: Through C# scripting, diverse interaction forms can be designed, including character control, construction process control, and weather/time control, without software limitations.

4. Engineering Application Verification

The BIM-based virtual construction simulation system for large steel structures researched in this paper has been successfully applied to site management and worker training for the large-span steel truss integral lifting project at Shangcheng District Sports Center. The system comprehensively simulated realistic site conditions, considering environmental factors such as windy and rainy days, cloudy weather, and nighttime operations, as well as random factors like lifting asynchrony. The application achieved outstanding results:

1. Through the virtual simulation system's roaming experience function, the on-site layout scheme for hydraulic cylinders and hydraulic synchronous control equipment was comprehensively evaluated, as shown in [Figure 12: see original paper]. The final arrangement was selected on the north side of the steel truss assembly floor, where ample space and sufficient visibility allowed for complete control over the entire hydraulic lifting process.
2. By considering the effects of wind and slight asynchrony between hydraulic lifting points, potential contact jamming between the steel truss and steel column joints was identified during lifting, which could prevent further elevation. The virtual construction simulation preemptively identified steel column joints prone to contact jamming, allowing workers to monitor these locations on-site and resolve issues immediately upon occurrence, as shown in [Figure 13: see original paper]. This significantly improved construction efficiency.

Conclusion

Taking the large-span steel truss hydraulic integral lifting project at Hangzhou Shangcheng District Sports Center as the background, this paper researched a BIM-based virtual construction simulation system for large steel structures. The system effectively utilizes existing BIM models, enabling engineering managers to rapidly construct virtual construction simulation scenes. With characteristics of efficiency, realism, and high interactivity, the system's application in the steel truss hydraulic lifting construction at Shangcheng District Sports Center helped construction managers: (1) design more rational on-site layouts for hydraulic cylinders and synchronous control equipment, and (2) prepare in advance for potential contact jamming between steel trusses and steel column joints, substantially improving construction efficiency. Furthermore, the system can visually conduct pre-construction disclosure and training for workers, effectively ensuring construction quality and safety.

References

[1] Ye Haowen, Zou Jun, Sun Hui, Yang Wei. Research and application of BIM-based general contracting management system [J]. Construction Technology, 2016, 45(12): 29-33.

[2] Wang Tingkui, Zheng Jiao. Evaluation of dynamic layout schemes for construction sites based on BIM [J]. Construction Technology, 2014, 43(3): 72-76.

[3] Hu Bo. Research on construction phase cost control based on BIM [D]. Wuhan: School of Civil Engineering and Architecture, Hubei University of Technology, 2015: 1-57.

[4] Shao Zhengda, Song Tianren. Research and application of BIM-based building VR interaction technology [J]. Information Technology of Civil Engineering and Architecture, 2018, 10(3): 17-21.

[5] Ji Zheng, Xie Yuxing, Wang Yue. Virtual measurement experiment system based on Unity3D [J]. Bulletin of Surveying and Mapping, 2016, 10: 97-100.

[6] Xiu Chunhua, Sun Xiujuan, Miao Po. Design and implementation of virtual mine roaming simulation system based on Unity3D [J]. Metal Mine, 2015, 4: 262-266.

[7] Zang Rui. Research on optimization design and key technologies of ship virtual lifting system [D]. Hangzhou: College of Chemical and Biological Engineering, Zhejiang University, 2016: 1-73.

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