

BIM-based Virtual Construction Simulation System for Large Steel Structures: Research and Application (Postprint)

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Abstract

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

Full Text

Preamble

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

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Abstract: This paper presents the research and practical application of a BIM-based virtual construction simulation system for large steel structures. The system employs the Unity3d virtual reality development platform to effectively utilize BIM models, enabling realistic visualization of construction sites under various scenarios for 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 while fully ensuring quality and safety throughout the construction process.

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

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With continuous advancements in information technology, construction management has become increasingly informatized, 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 call 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, significantly enhancing construction management efficiency in areas such as engineering information management [1], dynamic site layout [2], and construction cost control [3].

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

In the construction field, however, VR applications 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 lifting project at Hangzhou Shangcheng District Sports Center features complex procedures, high operational requirements, and numerous safety hazards, necessitating 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, successfully implementing it in practice to effectively improve construction efficiency and ensure quality and safety during construction.

2. Project Overview

The Hangzhou Shangcheng District Sports Center is a multi-purpose sports complex located at the intersection of Hou Chao Road and Qianjiang Road in Hangzhou, with a total building area of 55,681.2 square meters. The structure consists of 14 above-ground floors and 4 underground floors, featuring a frame-

shear wall structural system with partial steel construction. The sports center houses a water polo hall on the fifth floor and a basketball hall on the ninth floor, both utilizing a steel truss floor system supported by concrete stands below. The steel truss floor comprises six large-span steel trusses and connecting steel beams, with a span of 39.2 meters, width of 33.2 meters, and height of 4.1 meters. Following expert evaluation, the construction method involves assembling the floor system on the concrete slab before lifting the entire steel truss floor into position using a hydraulic lifting system, as shown in [Figure 1: see original paper].

The large-span steel truss weighs over 390 tons, with finite element analysis indicating 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 is required during the hydraulic lifting process. Due to complex environmental factors, high operational demands, and numerous safety hazards, it is essential to improve construction disclosure quality and systematically identify potential issues to ensure the smooth lifting of this large-span steel truss structure.

3. BIM-Based Virtual Construction 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, UI design, and system deployment, as illustrated 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 the steel truss lifting phase, only portions of the overall model up to and including the fifth floor that had been completed according to schedule were retained, 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 were added to enhance the model's fidelity to the prototype. Collision volume represents the most critical property; without it, objects would intersect during movement. Collision volumes were added by assigning the Physics-Collider property to models, with Mesh Collider selected for complex geometries. Additionally, to enable models to exhibit realistic physical effects under various forces, such as falling under gravity, rigid body properties were added by assigning the Physics-Rigidbody attribute.

3.2 Scene Element Rendering

To realistically simulate actual construction site conditions, various scene elements were rendered, 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 sounds during inclement weather, human footsteps, and hydraulic cylinder activation sounds during steel truss lifting. The first three sounds maintain relatively constant volume regardless of the character's position, so an Audio-Source property was added to the character with corresponding audio files imported. Since hydraulic cylinders are fixed in position, their activation sound volume varies with the character's distance, so the audio property was added directly to the hydraulic cylinders.

The sky is controlled by Unity3d's built-in Skybox, configured as a clear, cloudless sky with sun position synchronized to the light source. All object rendering is achieved through lighting, with the default source being Directional Light representing sunlight. By controlling the x, y, and z values in the light source's Rotation property, 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 structure, midday is represented; and when positioned below the structure, nighttime is depicted. The scene's 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 operations, point lights were arranged at appropriate locations for illumination, as shown in Figure 4: see original paper.

Weather systems are represented through Particle Systems. Since the lifting operations occur during summer, rain impact on construction must be considered. Unity3d offers nearly a hundred parameters for particle effects control, but for rain simulation, the primary adjustable parameters include 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-day construction scenario.

3.3 Interaction Command Implementation

Interactions are implemented primarily through C# scripts bound to corresponding objects. In Unity3d, all character interactions are controlled jointly by the Animator module and C# scripts. The Animator module provides character action animations, with the animation logic for this project shown in [Figure 6: see original paper]. Each character model includes an Avatar submodule that divides the body into different parts such as hands, feet, arms, legs, shoulders, and neck, enabling actions to be defined for specific 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.

The following C# 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, critical procedures in the steel truss lifting process can also be operationally simulated. Compared to the BIM model, the steel truss VR model was adjusted to rest on the concrete floor slab. Lower lifting points for hydraulic lifting were created at both ends of each truss, with lifting controlled by the numpad “8” and “5” keys. Sample C# control 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 achieve a realistic lifting visualization. Unlike the truss, the strands undergo length changes, requiring adjustment of both their spatial position and Transform-Scale properties. Figure 8: see original paper shows the effect during truss lifting.

Wind effects were added during lifting, and slight asynchrony between different

hydraulic lifting points was considered to comprehensively simulate various conditions during hydraulic lifting. To simultaneously demonstrate construction scenarios under different weather and time conditions, interactive commands for weather and lighting were implemented. Weather toggling between sunny and rainy conditions is achieved by controlling the particle effects system:

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

The particle effects system off (on) corresponds to sunny (rainy) weather, with the “Tab” key toggling between them. Lighting is controlled by adjusting the x, y, and z values (-180 x,y,z 180) in the Directional Light’ s Rotation property, with x-value modification implemented as:

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

Pressing numpad “+” sets “SunLight” to a positive value, corresponding to x-value change in the positive direction (sun moving west to east), while numpad “-” sets a negative value for east-to-west sun movement.

3.4 UI Design

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

Transitioning from the start interface to the scene requires C# scripting for buttons. For instance, the “Start VR Journey” button is assigned:

```
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), with similar scripts for other buttons. [Figure 10: see original paper] shows the UI buttons in the construction scene, with icons in the upper-left and upper-right corners enabling restart and return-to-start functions, respectively.

3.5 System Release

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

3.6 System Features

- (1) **Efficiency:** The system effectively leverages existing BIM models, closely integrating with the project to create virtual construction scenes based on actual models.
- (2) **Realism:** The system authentically restores construction scenes by introducing physical properties to simulate collisions and gravity, while combining sound effects, sky, weather, and lighting elements to 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 developed in this paper has been successfully applied to site management and worker training for the large-span steel truss lifting project at Shangcheng District Sports Center. The system comprehensively simulated authentic site conditions, considering environmental factors such as wind, rain, overcast conditions, and nighttime operations, along with random factors like lifting asynchrony, achieving outstanding results in practical application:

1. Through the virtual simulation system's roaming function, the on-site layout scheme for hydraulic cylinders and hydraulic synchronization control equipment was comprehensively evaluated, as shown in [Figure 12: see original paper]. The final placement on the north side of the steel truss assembly floor was selected, providing both ample space and sufficient visibility to oversee the entire hydraulic lifting process.
2. By considering wind effects and slight asynchrony between lifting points, potential jamming between the steel truss and steel column nodes was identified during lifting, which could halt the lifting operation. The virtual construction simulation preemptively identified steel column nodes prone

to jamming, enabling workers to monitor these locations and resolve issues immediately upon occurrence, as shown in [Figure 13: see original paper], thereby substantially improving construction efficiency.

In summary, the BIM-based virtual construction simulation system for large steel structures, characterized by its efficiency, realism, and high interactivity, facilitated more rational design of hydraulic cylinder and synchronization control equipment layouts and prepared the team for potential node jamming issues during the large-span steel truss lifting project at Hangzhou Shangcheng District Sports Center, markedly enhancing construction efficiency. Additionally, the system provided visual pre-construction disclosure and training for workers, effectively ensuring construction quality and safety.

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Note: Figure translations are in progress. See original paper for figures.

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