Simulating Wind Tower Construction Process for Virtual Construction Safety Training and Active Learning

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ABSTRACT

The growth of the wind energy industry in the United States has been remarkable; however, despite its significance and installation capacity, wind energy investments such as wind turbines and wind farms involve various safety risks. To increase awareness of construction workers regarding hazards associated, one needs to develop engaging training programs. Therefore, to address this emergent need, we develop a realistic simulation of the wind tower construction process in an immersive virtual reality environment aiming at informing workers of the general safety and health hazards associated with the critical processes used in constructing, maintaining, and demolishing wind towers.

Index Terms: Virtual Reality—Wind Tower—Procedural Animation—Construction Safety Training

1 INTRODUCTION

As the population is growing fast all over the world, the need for electricity is increasing dramatically. The rapidly developing wind energy sector is one of the most important renewable energy sources over the globe [10]. According to statistics published by the Global Wind Energy Council (GWEC) [1], the total installed wind capacity reached 591 gigawatts at the end of 2018, a growth of 9.6 percent compared to the end of 2017. Undoubtedly, the growth of the wind energy industry has been remarkable. However, despite its significance and installation capacity, wind energy investments such as wind turbines and wind farms involve various risks [10]. Because the construction and maintenance of wind turbines require highly specialized work, the need to pay close attention to worker safety in the industry is gaining importance.

The necessity for increased safety awareness in wind turbines is prompted by hazardous weather, working at heights, a potential for fires in the nacelle, and working around high voltages [5]. Many workers are exposed to hazards that could result in injuries, long-term damages, and even fatalities [3]. Technicians regularly climb towers that are usually 197 to 328 ft to the hub of the wind turbine to perform construction and maintenance activities [19]. This is usually done with ladders or hoists to workstations on the towers via base-mounted drum hoists. Workers are put at risk when working on these elevated structures. One of the risks associated with working at such a height is the potential for lightning strikes that can trigger a fire [5]. Moreover, workers are exposed to a variety of serious hazards, including structural collapses, struck-by, fatigue, radiofrequency, inclement weather (including extreme heat and cold), electrical shocks, and cut and laceration due to the use of sharp, heavy tools and materials [2]. It is therefore of paramount importance that preventive measures be taken to reduce the risk of injuries and fatalities associated with working on wind turbines.

To address the safety issues, workers must be properly trained to ensure that their knowledge and awareness of hazards are constantly updated while staying safe on-site at all times. Although Occupational Safety and Health Administration (OSHA) requires employers to provide training to their employees, many workers still fail to identify hazards, assess their significance, or use protection appropriately. There are several factors that contribute to such poor performance: poorly designed training programs, time constraints in schedule-intensive projects, and lack of interest or commitment among workers. In addition, while the backbone of any occupational health and safety discussion is hazard identification, current methods of teaching hazard identification focus on lectures and passive education (e.g., training manuals), which result in decreasingly relevant training options.

Compounding this training limitation is the reality that the demographics of construction workers are changing. The emergence of the Net Generation—those who have grown up with information technology and who expect faster, more hands-on educational experiences—means that trainers must find more active-learning approaches to educate these workers. Additionally, the large number of immigrant workers in the construction labor force is another serious issue. For example, according to the U.S. Census Bureau, foreign-born workers composed almost 22.4 percent of all construction workers in the United States [4]. Many of these workers are illiterate even in their native language, a fact that renders written manuals less effective and contributes to a higher number of injuries among immigrant workers. Combined, these factors mean there is increasing attention to developing training materials based upon active or visual cues.

As advanced technologies in the computer graphics and virtual reality industry are emerging, novel pedagogy for combining education and entertainment, also called edutainment, prevailed in recent years. Therefore, developing active-learning exercise programs and augmenting them with virtual-reality environments represent a valuable opportunity for teaching hazard identification to at-risk construction workers involved in wind tower construction and maintenance. Active learning opens a valuable channel for visual-cue-based education, and virtual reality-based safety training programs signify a particularly notable option for addressing these emergent audience-oriented issues. Specifically, data-driven virtual modeling methods such as Building Information Modeling (BIM) provide media to visualize components, manage and coordinate associated construction management activities. These virtual models simulate full, real-world conditions across time, physical space, and material properties. Such spatiotemporal granularity represents an engaging, dynamic replacement for physical sites and is thus adaptable and robust for various training situations.

To respond to the health risks resulting from the construction and maintenance of wind towers, in this project we develop a thorough training and educational program on virtual reality platform for at-risk construction laborers, operating engineers, wind turbine service technicians, crane and tower operators, and electricians who are involved in these operations. Existing research works show that this targeted population often faces higher risks due to their construction roles, their language skills, and their cultural differences. This project focus on informing workers of these vital options for ensuring jobsite safety and testing their awareness of construction safety through realistic simulation of wind tower construction process and immersive virtual reality environments.

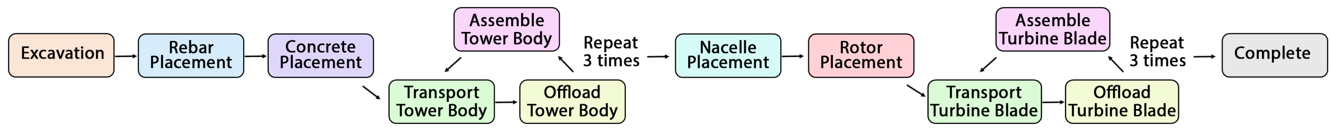


Figure 1: Overview of our wind tower construction simulator.

2 Related Works

Wind Turbine Tower Construction. Wind turbine towers are devices that convert the wind's kinetic energy into electrical energy that is becoming an increasingly important source of intermittent renewable energy and are used in many countries to lower energy costs and reduce reliance on fossil fuels [12]. Therefore, how to construct wind towers in a time and cost-saving manner becomes a popular topic for the wind energy industry. As one key observation that lots of time and cost overruns are caused by construction safety issues, construction workers must be trained effectively with respect to safety awareness in the jobsite. Besides, analyzing the wind tower dynamics [6], analyzing the wind tower fragility [16] and optimizing the wind tower structure [15] become extremely interesting for researchers. In the meanwhile, the construction process of wind turbine towers is another hot topic among the wind energy industries. For example, Hu et al. [13] have analyzed the dynamics of offshore steel wind turbine towers subjected to wind, wave, and current loading during the construction process. Stavridou et al. [20] conducted the finite element analysis and comparative study on the welded connections of wind turbine towers under fatigue loading during the construction process. Simulation on the construction process of wind turbine towers can also be applied to optimize the wind turbine towers' construction plan. For example, Atef et al. [7] devised a simulation-based system to aid in the construction planning of wind turbines. However, unlike their work, our work focuses on procedurally animating construction process of wind towers, rather than focusing on optimizing construction plan.

Construction Safety Simulations in VR. As Virtual Reality (VR) technologies have become popular among the research communities, simulations on VR platforms have been hot research topics within the construction engineering education and training industries [22]. For example, a virtual reality safety-training system for construction workers was developed by Xie et al. [23] and an effective human-machine interface was devised by Rezazadeh et al. [17] through a novel approach to increase trainees' operation performance in virtual construction crane training systems. The success of these works inspires us to simulate the construction process in immersive environments. Our research is not the first work that employs immersive virtual reality technologies, similar technologies have been employed by Sacks et al. [18] to develop an effective training program for construction safety training, their work indicates that virtual construction safety training is feasible and effective, especially in terms of workers' learning, identifying and assessing construction safety risks. Inspired by the simulation that has been developed by Zhao et al. [24] for a VR-based safety training program indicating that users can effectively promote their abilities for hazard cognition through virtual training, we develop our wind tower construction simulator on an immersive VR platform to enhance the user experience during the training process. Similar to our work, a virtual construction simulator was developed by Lu et al. [14] for examining the priming effects on safety decisions. Recently, the potential of the virtual construction site as a tool of knowledge management on technological processes of construction products has been examined by Terentyeva et al. [21]. At the same time, stereo-panoramic environments were considered by Eiris et al. [9] for construction safety training. All positive conclusions drawn on taking VR as the training environment for active learning confirm our confidence in suggesting a VR platform for wind tower construction simulations.

3 Overview.

Figure 1 shows the overview of our wind tower construction process simulator. According to the modern standard wind turbine construction process [8, 11], the main pipeline of constructing a wind tower typically includes excavation of the ground, rebar placement, concrete placement, casting of concrete, transporting, off-loading, and assembling the wind tower parts. Typically, wind tower parts include a tower body (three sections), nacelle, rotor, and turbine blades (three pieces), etc. The flow chart of the construction process is presented in Figure 1 where different colored boxes depict different stages during the construction process.

4 Simulation Approach.

We simulate the wind tower construction process using a mathematical procedural animation approach. During each stage, we applied the robotic dynamics calculations to each moving part of the constructions tools. For simplifying the implementation, we use different grammas to represent the procedural animations. This section illustrates the mathematics behind our simulation approach.

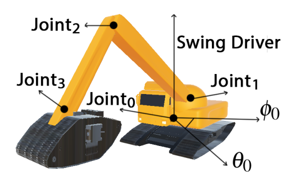


Figure 2: Excavator.

Excavator. Excavator is a construction tool used during the excavation process. The gramma for an excavator is "$01231.02<3>$", each character in the gramma string represents an operation in animation. At here, dot "." represents the update of the cave (e.g. the elevation of the ground plane within the cave decreases over time). "$<$" and "$>$" represent the initialization and the termination of the dust particle system's animation respectively. There are four joints in the excavator, the starting angles of the joints are $\Theta = \{\theta_0, \theta_1, \theta_2, \theta_3\}$, the ending angles of the joints are $\Phi = \{\phi_0, \phi_1, \phi_2, \phi_3\}$. Therefore, the numbers in the gramma are the joint indices. For example, the first number in the grama is 0, therefore, at the first stage, only the first joint (swing driver) is rotating (from θ_0 to ϕ_0). After rotating each joint, the rotation direction of that joint will reverse. This means, the second time when it meets the 0, the first joint will rotate from the ϕ_0 to θ_0. After the whole gramma string is executed, the joint angles will be reset and the whole process will repeat several times according to the user's setting. In our simulation, $\Theta = \{-60, 15, 90, -90\}$ and $\Phi = \{0, -30, 45, -180\}$.

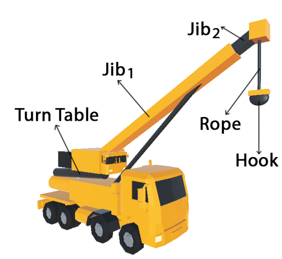
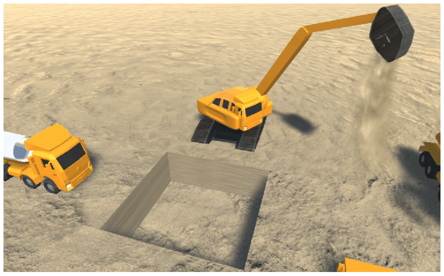
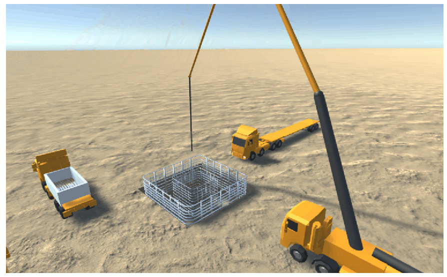


Figure 4: Truck Crane.

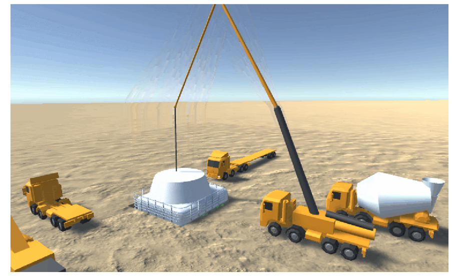
Truck Crane. We use the truck cranes to finish those offloading and assembling tasks during the wind tower construction process. During these tasks, there is an arbitrary number of target positions that need the truck crane's hook to move to. Those targets positions are represented as a vector array: $\mathbf{P} = \{\mathbf{p}_0, \mathbf{p}_1, \mathbf{p}_2, ...\}$. Now, according to $\mathbf{P}$, we generate a string of action sequences using the following grammar: "$(.RTE)^*$". Where the dot "." represents the update of target positions, letter "R" represents the rotation of turn table from the current target position $\mathbf{p}_i$ towards the next target position $\mathbf{p}_{i+1}$, letter "T" represents the telescopic motion of jib$_2$, and letter "E" represents the vertical (elevation) motion of the rope (along with the hook). All motion speeds



(1) Ground excavation .

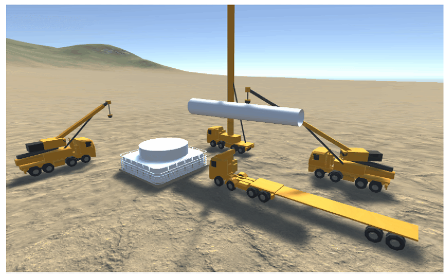


(2) Rebar placement.

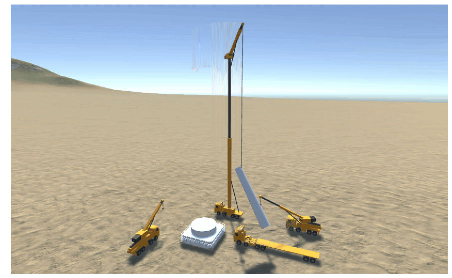


(3) Casting of concrete.

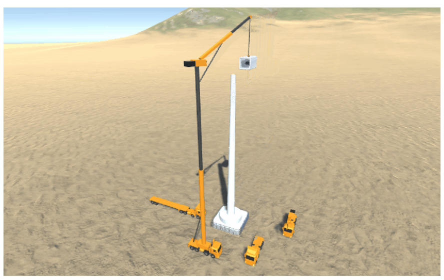
(4) Tower body transportation.



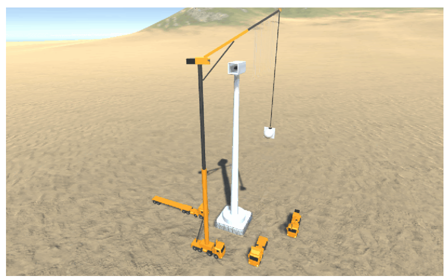
(5) Off-loading tower body.



(6) Assemble the tower body.



(7) Assemble the nacelle.



(8) Assemble the rotor.

(9) Assemble the blades.

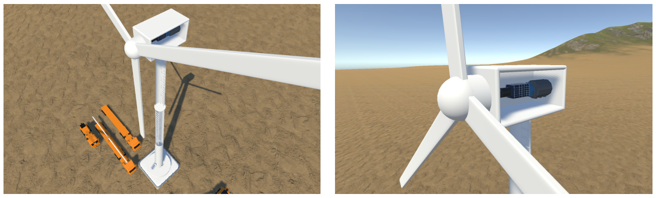
Figure 3: A running example of our wind tower construction simulator.

are calculated according to the Euclidean distance and the angular distance between $\mathbf{p}_i$ and $\mathbf{p}_{i+1}$. Note that, there will be no letter "R" appearing in the grammar when there is no rotation action needed to be taken for the hook to move from $\mathbf{p}_i$ towards $\mathbf{p}_{i+1}$ when $\mathbf{p}_i$ and $\mathbf{p}_{i+1}$ are on the same direction facing towards the turn table. Similarly, the letter "E" and the "T" may be missing as well. Specifically, the scale of the rope (represented with a cylinder) will stretch or shrink to achieve a realistic effect of changing the hook's elevation.

5 Simulation Result

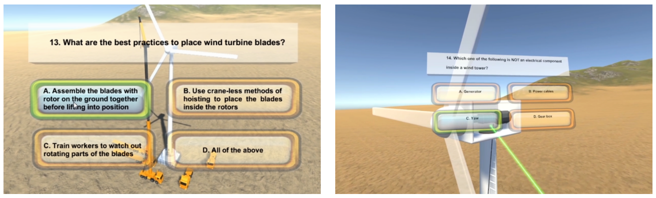
Figure 3 shows the simulation result of our wind tower construction simulator. Different subfigures show the different stages during the construction process of a wind tower. Figure 3 (1) shows the Excavation Process. The first step in the excavation process for the wind turbines is to remove and stockpile topsoil and subsoils. The excavated area is leveled and prepared for placing the foundation. The next step will be placing the steel-wire framework to stabilize the foundation of the wind tower as shown in Figure 3 (2). After then, the concrete will be along with the framework to get the foundation being built up as shown in Figure 3 (3). After the foundation is built up completely, the tower body will be transported by truck as shown in Figure 3 (4), then the truck crane is ready to offload the tower bodies as shown in Figure 3 (5). During the off-loading process, the training program emphasizes the worker's inspection of the crane before lifting, and avoiding overloading is vital for the safety of workers. Figure 3 (6) shows the process of assembling the tower body. The wind tower usually contains three sections which are very heavy and hollow steel sections. We simulate the process that the sections are bolted together and lifted into position by a truck crane. In our simulator, upon completion of the tightening of the bolts, stability is achieved through an auto-alignment calculation between sections. After the tower body is assembled correctly, the nacelle will be placed on the top of the tower body. Figure 3 (7) shows the process of assembling the nacelle. The nacelle usually includes the gearbox and main drive shaft. This is where most of the electrical components are located. As shown in our simulator, the nacelle is lifted on the completed tower and fixed in position. The next step is being the rotor assembly stable attached to the nacelle. Figure 3 (8) shows the process of assembling the rotor. A good practice is to fully assemble the rotor on the ground before it is lifted into position. We simulate in another way that assembles the blades after the rotor is fixed. Similar to the assembling of the tower body, the turbine blades will be assembled in three steps as there are three separate blades as shown in Figure 3 (9). After the blades are assembled correctly, the trainee is asked to connect the electrical cables inside the nacelle, if the electrical components are integrated correctly, the wind tower will be animated with the wind turbines rotating steadily. In our simulator, the blades are connected to a central cone called the hub, which is connected to a shaft that passes into the nacelle.

Besides the animations, our simulator provides details inside the wind tower as well. For example, as shown in Figure 5 (a), the inside view of the wind tower in our simulator is presented. As we can see, the ladders are placed in alternating directions, and the power cables are hanging freely at the top of the wind tower. We also present the details of the yaw system in Figure 5 (b). Yaw system of wind turbines is the component responsible for rotating the nacelle around



(a) Inside the tower. (b) Yaw system.

Figure 5: Details of the wind tower in our simulator.



(a) Quiz on PC. (b) Quiz in VR.

Figure 6: Quiz system within our wind tower construction simulator.

the tower axis. The yaw system aids in pointing the rotor swept area towards the wind direction for optimal power input, and conversely, it can also be used for power regulation above rated wind speeds by reducing the rotor swept area directed to the oncoming wind. As another advantage of our simulation system, we embed a set of quizzes during our simulation. In such a way, trainees can be both trained and evaluated at the same time. We provide two modes of the quiz, one is the PC version as shown in Figure 6 (a), another one is the VR version as shown in Figure 6 (b). In our experiments, we test our simulator on Oculus Quest 1.

6 Conclusion

In order to make trainees familiar with the processes in wind tower construction and get the trainees capable of identifying the safety and health hazards associated with the construction process, we devised a novel system for simulating the wind tower construction process for virtual construction safety training and active learning. As shown in the experimental, the animation of the truck crane is achieved by three DOF mechanical movements, including rotation, telescopic motion, and elevation. Through the procedural animation synthesis approach proposed by us, the truck crane is able to reach and move any object within its reaching area (a column space within the radius of the jib) through our mechanical simulation. This results in a realistic animation of our wind tower construction simulator. Besides, both PC and VR quizzes are performed along with the simulation process proposed above. This provides the trainee with more flexibility in active learning and effective training.

In future work, we will include the human factors and environmental factors that cause unpredictable events which are namely the accidents. Such uncertainty will simulate the accidental cases that happened in reality. Hereby, a virtual character will be included to represent the trainee. Besides, during each stage, the trainee will be assigned different types of tasks. We believe our realistic simulator will inspire more innovative and effective virtual training programs on wind tower construction safety training.

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