Leadership in Sustainable Infrastructure

Leadership en Infrastructures Durables

Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

DATA-DRIVEN SCENARIO GENERATION FOR ENHANCED REALISM OF EQUIPMENT TRAINING SIMULATORS

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Abstract: Improving the training of heavy equipment operators can make a significant contribution to improving the safety of construction sites. In recent years, Virtual Reality (VR)-based simulators have gained increased popularity for the use in equipment training programs. While VR training simulators for heavy equipment are less mature than those used in the aviation industry, these simulators are gradually carving their ways into the training programs for construction equipment operators as well. Presently, the majority of the existing VR scenes are based on hypothetical scenarios and more focused on developing motor skills. However, on real construction sites, the decisions an operator makes to operate the equipment safely and efficiently depend on the decisions made by other operators or workers in addition to the type and location of the work. In the current situation, the training simulators do not capture the dynamism of the construction site and the uncertainties involved in the project as a result of human factors. One way to address this issue is to generate realistic training simulators based on the actual construction operations. In these VR scenes, the data from actual equipment will be used to generate a scene where the trainee is supposed to operate the equipment in face of the movements of many other pieces of surrounding equipment. For this purpose, sensor data needs to be integrated with a multi-agent system to capture the behaviour of many equipment and workers. Nonetheless, the first step towards the generation of such a scene is to reconstruct the actual construction site in the VR environment. This research builds upon the previous work of the authors and the advancements in geo-informatics to propose a method for the reconstruction of actual sites using GIS and cadastral data. Two different approaches for the generation of these scenes are compared and a prototype is developed to show how sensor data can be integrated with the VR scene for the construction of the realistic training simulators. The feasibility of the approach is demonstrated by means of a case study where GPS data from an actual construction project is replayed in the VR model of the site where the project took place.

Keywords: Training, Simulation, Visualization, Virtual Reality

1 INTRODUCTION

Construction equipment accounts for a great number of fatal incidents on the construction sites (Hinze & Teizer 2011). Therefore, enhancing the productivity and safety of construction operations has been an area of great interest for practitioners in the industry. In recent years, various systems have been developed to improve the productivity and safety of construction operations based on the application of Real-time Location Tracking Systems (RTLS) (Vahdatikhaki and Hammad 2015a, Vahdatikhaki and Hammad 2015b). While efficient, these systems are utilized in an assistive capacity (i.e., providing guidance to the operators rather than making autonomous decisions), and therefore operators decision still plays a significant role in avoiding accidents and coordinating the work in an efficient way. Therefore, it is important to ensure that the operators are properly sensitized to the factors that affect the safe operation of the heavy construction equipment.

Despite the fact that operators of these pieces of equipment go through stringent training programs, a considerable proportion of decisions made by the operators remains intuitive. Part of this can be attributed to the fact that a great part of the training programs is dedicated to the technical aspect of steering equipment. This approach limits the extent to which the operators' training programs are conducive to a proper acquisition of coordination skills required to excel at operating the equipment. On a construction site, an operator needs to constantly coordinate with other operators and workers to be able to navigate in the construction site safely and efficiently. Therefore, it is of a cardinal importance to incorporate the coordination and human factors in the equipment training program more effectively. However, the cost and risk involved in using actual equipment for the training hinder more substantial inclusion of communication and collaboration factors in the training program.

In recent years, Virtual Reality (VR) is used to build training simulators that would allow the trainees to train with the equipment in the virtual world (CMLabs 2016, Tenstar Simulations 2016). While these simulators help reduce the cost and risks involved in the training of the operators, there are some limitations in the way these simulators are currently developed. Firstly, similar to conventional training programs, the training simulators focus primarily on the equipment handling and motor skills. This practice can potentially undermine the value of the training because although the trainees are given ample opportunities to learn much about the handling of the equipment, very little opportunity is provided to learn about skills needed to avoid the hazardous situations that may arise from insufficient or improper coordination/communication with other crew members in the fleet. Secondly, the process of building these scenarios can be laborious and time-consuming, which can eventually result in the availability of a limited number of scenarios from which the trainees can choose.

In order to address these issues, the authors have previously presented a comprehensive framework for the generation of realistic sensor-driven training scenarios by integrating the sensory data from the site with a Multi-agent System (MAS) to address the interaction between the real and virtual world (Hammad et al. 2016). The emergence of Global Positioning System (GPS)-based machine guidance systems (Caterpillar 2015, Topcon 2015) has significantly paved the way to use the valuable sensor data from the equipment and capture the dynamism of construction sites. In these simulators, the data from actual equipment are used to generate a scene where the trainee is supposed to operate the equipment in face of the movements of many other pieces of surrounding equipment. For this purpose, sensor data need to be integrated with the MAS to capture the behaviour of many equipment and workers. Nonetheless, the first step towards the generation of such a scene is to reconstruct the actual construction site in the VR environment. Accordingly, the present paper is dedicated to outlining a practical method that can be used to apply the off-the-shelf tools to recreate the realistic geographical features of the surroundings of a construction site and replay the sensor data captured from an actual project in the VR environment. To this end, Section 2 presents the literature review. Section 3 elaborates on the overview of the proposed framework and Section 4 presents a case study. Finally, the conclusions and discussion are presented.

2 LITERATURE REVIEW

In many high-risk professions, acquisition of a minimum level of expertise in the job is essential before one is ready to go on the field. This applies to, among many others, pilots, firefighters, soldiers, construction and mining workers, and operators of industrial equipment, etc. Given the high risks and costs involved in training of novice operators/workers in the actual workplace, training simulators are used to allow trainees gain the required skills in a virtual replica of their workplace (Goldman and Knerr 1997, Chung and Huda 1999, Oliveira et al. 2007, Dennis and Harris 2009, Cha et al. 2012). According to Canadian Apprenticeship Forum (2013), simulation technology offers the following advantages to the training programs: (1) Simulators are sometimes less expensive than actual equipment and consume less energy; (2) Simulators are safer, which is especially important for novice trainees; (3) Simulators detect and correct errors before they become habits; (4) Dexterity skills (i.e., motor skills) are acquired at least as efficiently using simulator technology and may be acquired more quickly; and (5) The level of complexity can be altered using a simulator so that tasks become progressively more challenging.

The construction industry, also, has adopted VR-based simulators for various types of training programs. Simulators are used in such areas as safety training (Lin et al. 2011, Guo et al. 2013, Hilfert et al. 2016), construction management and planning (Sherif and Mekkawi 2009, Ku et al. 2011, Li et al. 2015), and equipment training (Freund et al. 2002, Wang et al. 2004, Ni et al. 2013, Fang and Teizer 2014, Vasenev et al. 2016). With the earthmoving operations being among the riskiest and costliest operations in the industry, many training simulators are developed in recent years to enhance the quality of education for the excavator operators. The advancements in excavation simulator have resulted in robust commercial tools, e.g., Vortex (CMLabs 2016) and Tenstar (2016), that are currently used by many training schools. However, the major focuses of the developer and researchers have so far been mainly on the ergonomics of the simulator and accuracy of the simulation physics. Furthermore, almost in all cases, the presented simulators are based on hypothetical scenarios. As stated before, this approach makes the scenario preparation processes laborious, time-consuming and costly. Additionally, this would eventually lead to the availability of only a limited number of scenarios the trainees can choose from. In recent years, some researchers proposed the application of sensor data from actual construction sites to generate training scenarios. For instance, Fang and Teizer (2014) presented a framework for using actual site data for the development of training VR environment. Nevertheless, this framework does not account for conflicts between the trainee-controlled equipment and the interacting surrounding equipment. As a result, many inconsistencies can happen during the training when the behaviour of the trainees is different from the actual operators on the site. Vasenev et al. (2016) developed a VR environment for the visualization of roller operations using actual data from the site that can be further used to analyze alternative routes for the roller. However, this methodology does not address the training aspect of the simulators. The authors have previously presented a method to integrate sensory data with a MAS to address the issue of realistic interaction between the operator and VR environment (Hammad et al. 2016).

The first step towards the framework previously proposed by the author is the generation of the 3D model of the construction site based on the available Geographic Information System (GIS) and surveying data. Research in the domain of geo-informatics has long been focused on the accurate 3D modeling of the built environment. Built environment consists of multiple layers and objects. These include the natural surface of the earth or the terrain, buildings, road network, vegetation, rivers and conduits, bridges, underground utilities, etc. Given that the visualization of these objects can contribute to improving the design and management of the built environment, the experts and specialists continuously try to improve the accuracy and realism of the built environment by (1) developing more realisable and accurate measurement technologies, and (2) enhancing visualization of the surveyed data. Efforts in the earlier direction led to advancements in laser technology, aerial photogrammetry, image processing, and sensor technologies. Because of technologies such as Laser Detection and Ranging (LiDAR), it is now possible to perform high-accuracy spatial measurements of the built environment. On the other hand, the integration of Building Information Modeling (BIM), Infrastructure Information Modeling (IIM), and Digital Terrain Models (DTM) allows for the precise 3D modeling of various features of the built environment.

Until recently, 3D modeling techniques for the built environment features have been very fragmented. Different disciplines would use their own methods/platforms to generate 3D models of their features of interest. However, in the past decade, more and more municipalities and provincial governments have been striving to provide accurate 3D models of their jurisdictions. The core idea behind these efforts was to combine various sources of data into a single geospatial model that would enable a wide range of macro and micro analysis of the built environment.

GIS has been used for many years to store, manage, analyze, and visualize georeferenced data. However, GIS was primarily used as a 2D spatial analysis platform and focused more on the geolocation and spatial relationship between the objects. As such, it is inherently devoid of valuable details that are crucial to architects and designers of the built environment. On the other hand, BIM and IIM are more concerned with the design details of isolated objects (e.g., buildings). The integration of semantically-rich 3D models (e.g., BIM) with GIS has been the subject of many research efforts in previous years (Isikdag and Zlatanova 2009, de Laat and Van Berlo 2011, Mignard and Nicolle 2014).

CityGML emerged as a result of efforts to consolidate the GIS world with semantically-rich 3D modeling methods. Many cities are trying to use CityGML to provide high-quality geo-referenced semantic models of their jurisdictions (City of Montreal 2017, City of Rotterdam 2017). Software packages such as Infraworks (2017) are the result of such efforts. Integrated models can be used for a wide spectrum of purposes ranging from promotions to urban development planning and even to disaster management and homeland security (Kolbe 2009). For instance, Randt et al. (2011) applied CityGML to develop a training simulator for emergency drivers (i.e., police patrol and ambulance).

However, to the best of the authors' knowledge, such as integrative approach has seldom been employed in the context of construction simulators. This is basically due to the fact that the manufactures of the simulators are more concerned with the accurate representation of simulation physics (e.g., soil-blade interaction, soil-rubber interaction, particle motions, dynamic force simulations, etc.). For instance, Dopico et al. (2010) focused primarily on the modeling of the excavation forces at the tip of the excavator bucket to accurately replicate the bucket filling motions. Ni et al. (2013) focused on the dynamic terrain modeling to simulate the changes in the terrain caused by the excavation process. Other examples of studies on soil modeling can be found in the works of Freund et al. (2012) and Holz et al. (2015). Others have focused on human-computer interaction and ergonomics of the VR simulators (Segura et al. 2007). Additionally, a considerable number of construction sites (specially road building projects) are outside the focus of municipalities; and thus the amount of available data is considerably less than projects inside the urban area. Therefore, in many instances, the available CityGML models are not sufficient to model construction sites.

A realistic VR scene that is based on the integration of real-time location data needs to incorporate both GIS and BIM (or IIM) models. This is important because GIS would allow replaying the equipment motions collected by the GPS and BIM would enable modelling of important features such as underground pipes and accurate road networks. In this study, various combinations of data sources will be investigated to find the most promising tools that allow accurate representation of construction site.

3 PROPOSED METHOD

As stated in Section 1, the current paper focuses on the generation of realistic VR scenes for heavy equipment training simulators. As a result, this paper is dedicated to the first three phases of the overarching framework the authors presented for the next generation of VR-based construction equipment training simulators (Hammad et al. 2016). However, for completeness, the entire framework is elaborated in the following section.

3.1 Overview of the Proposed Method

Figure 1 illustrates the overall framework for the proposed VR-based construction equipment training. At the high level of abstraction, the framework consists of five main phases, namely (1) Data Collection, (2) Data Preparation, (3) Training Scenario Generation, (4) User Interaction, and (5) Feedback on Safety and Productivity Performance.

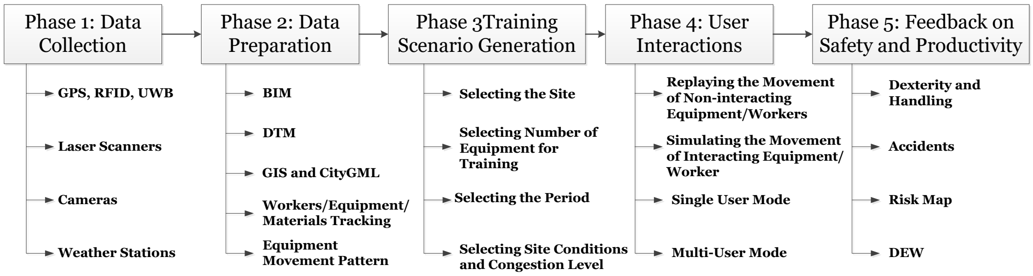


Figure 1: The overview of the framework for the proposed method simulators (Hammad et al. 2016)

In the first phase of the framework, various types of sensors are used to capture the state of the construction site. Various tracking technologies (e.g., GPS, Ultra Wideband, Radio Frequency Identification, etc.) are used to track the location and movement of equipment and other resources (e.g., workers and materials) on the construction site (Vahdatikhaki et al. 2015).

In the second phase, the raw data collected from the site are integrated with GIS and BIM data to generate the VR scene. This scene would include various urban objects in the surrounding of the site, DTM, the re-playable motions of the equipment/workers, and pattern of equipment behaviour (Vahdatikhaki et al. 2014).

In the third phase, the training specialist will decide about the equipment that is going to be operated by the trainee. This decision is based on the consideration of (1) which construction sites best suites the need of the trainee (according to the geographic specifications of where the trainees are going to work and the nature of the work they are going to perform), (2) what and how many pieces of equipment need to be operated by the trainees, (3) which periods of the construction operation had more equipment activities that can be used as educational material, and finally (4) what portion of data is going to be used in the VR scene to generate a scenario suitable for the expertise level of the trainee (i.e., some equipment can be intentionally left out to make the scene easier for novice trainees).

In phase four, the user will interact with the surrounding equipment to complete his training tasks. The multi-user compatible setting of the proposed method allows trainees not only to develop their dexterity and equipment handling skills but also their communication skills. The most striking point to consider in this phase is that the representation of the surrounding equipment must be done for both non-interacting and interacting equipment. Non-interacting pieces of equipment are those pieces of equipment whose behavior on the site does not depend on the decisions and action made by the trainee-operated equipment. These pieces of equipment can be represented by simply replaying the tracking data. Interacting pieces of equipment, on the other hand, are those whose actions and operations depend on the performance of the trainee. To avoid breaches in the logical processing of the scene, these pieces of equipment should be represented by the agents in a MAS.

In the last phase, the trainees are evaluated based on the equipment control and productivity (i.e., dexterity and smooth motions) and safety performance. The control and productivity performance is measured considering (1) the average cycle time of the operation, (2) the waiting time and length in the queue, (3) the length and the smoothness of the paths generated by the trainee, (4) the ability to control multiple Degrees of Freedom (DoFs) simultaneously, and (5) the ability to coordinate with other trainees or agents.

3.2 Data-Driven Scenario Generation

Figure 2 shows the flowchart of the proposed method for the generation of data-driven VR scene. A realistic VR scene for the training simulator should include the terrain model and geometrical features of the site (e.g., the road, surrounding buildings, etc.). The terrain model can be generated from heightmaps or national digital elevation data such as those provided by NASA’s Shuttle Radar Topography Mission (SRTM 2017). The data about the geometric objects on the site can be obtained from the combination of surveying data (e.g., using ground laser scanning) and national cadasters and GIS data. For more precise modeling, depending on the region and availability, various Building Information Modelling (BIM) products can be used to more realistically represent the peripheral data of the site. Additionally, the relevant data about underground utilities can be utilized to generate the 3D model of the underground infrastructure (Olde Scholtenhuis et al., 2016). The underground utility information can be of a particular interest for training the operators of the excavator. On top of these principal sources of data, weather information can be collected from the relevant meteorological agencies that retain and archive accurate account of the weather conditions for various locations.

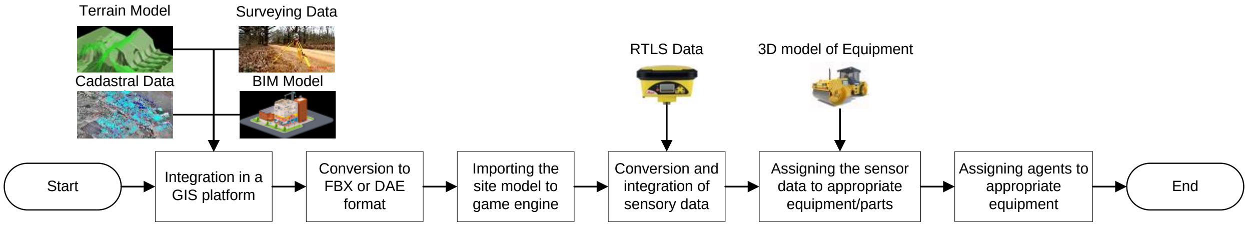


Figure 2: The process of generating data-driven VR training scenario

Once all the relevant data are gathered, they need to be integrated into a single geo-referenced model. In cases where CityGML files are available, many of the data sources are already integrated, but in cases where various sources of data are collected from different sources, they need to be integrated using a common coordinate system. Once the data are collected in a central platform, they need to be converted to a model compatible with the Game Engine where the training scenario is being developed. This can be usually achieved by using FBX or COLLADA (DAE) formats. Once ready, the site model is imported to the game engine and sensor data are imported into the scene. It is important to ensure that the data are in the same coordinate system as the 3D model. Later the sensor data are assigned to the relevant 3D models of the equipment they represent. Depending on the equipment DoFs and the level of granularity of the data, sensor data can be attributed to the entire equipment as a single rigid body, or to specific parts of the equipment. Similarly, for pieces of equipment that are represented by the MAS, the appropriate model behaviour needs to be assigned to the equipment. Upon completion of these steps, the scene is presented to the trainee to start interacting with the chosen equipment.

The generated scene should meet several requirements to be ready for use in the VR scene. These requirements include: (1) *Accuracy:* data should be accurate enough so that integration of RTLS data and site model can result in realistic representation of the operation, (2) *Resolution:* the model should include enough detail to make the scene evocative of the actual construction site, (3) *Visual Realism:* in line with the resolution of the data, the available data should have proper texturing to be visually appealing, (4) *Deformability of terrain:* the terrain in the final model should be deformable so that the interaction of equipment with the soil can be modeled, (5) *Ease of use:* the model should be easy to use and manipulate, (6) *Reliability*: the provided model should be continually updated to represent most recent state of the construction site, and (7) *Extensibility:* the model should be extensible so that details (e.g., BIM objects) can be added as needed along the process.

4 IMPLEMENTATION AND CASE STUDY

This section presents an implementation and a case study for the generation of the realistic VR scenes using off-the-shelf tools. The scope of the case study is to reconstruct the construction sites (i.e., terrain model, road model, building model, etc.) and integrate GPS data to replay the actual movements of the equipment tracked on the site in the VR environment. In the prototype system, Infraworks 360 (2016) was used to generate the 3D model of the site and the readily available 3D equipment models were obtained from Google 3D Warehouse (2016). Finally, Unity 3D (2016) was used as the main platform for the creation of the realistic training scene.

The case study was based on the highway rehabilitation project performed in the Rotterdam area in the Netherlands. The project was on a 250 m stretch of Europaweg highway between kilometers 28.500 and 28.750 km. Figure 3 shows the location of the project as extracted from Google Map and Figure 4(a) shows the bird's eye view of the site. The project involved a paver and two rollers that were used to compact the freshly laid asphalt. The pieces of equipment were tracked using Differential GPS rovers (Trimble 2017). The training in the scene requires the trainee to operate one roller while another roller and the paver are propelled by the GPS data.

Figure 3: The project location in Rotterdam area, the Netherlands

For the creation of the 3D model, two different approaches were followed. In the first approach, the relevant digital topographic data of the project area were obtained from the Dutch public services for maps (PDOK 2017). This data include the terrain model, the building parcels and their height information, the water area, and the road network. The digital topographic data, that are available in Geography Markup Language (GML) format, are then imported in Infraworks 360 and visualized by defining multiple layers for the terrain, the water area, buildings, and the roads. The GML data are used to (1) extrude the footprint of buildings based on the available data and (2) define rules for the textures of the buildings and roads. Figure 4(b) presents an example of the site created using the GML data. In the second approach, the built-in feature of Infraworks 360 is used to reconstruct the 3D model of the site. Infraworks 360 integrates terrain data from various local databases with building and road network data from OpenStreetMaps to generate the 3D model. It then drapes the terrain model with imageries obtained from Microsoft Bing (Infraworks 360). Figure 4(c) represents an example of the site created using this approach.

As presented in Table 1, each model has its own limitations and shortcomings. In essence, the GML-based model is slightly more accurate in terms of the terrain modeling and location accuracy (Bhattacharya 2012). The problem with the models created using Infraworks 360 is that the terrain model has some irregularities and some manual adjustments are necessary to represent the road network. Both methods provide the level of detail 2 according to CityGML standard (Kolbe 2009). On the other hand, Infraworks 360 does a better job in providing more realistic texturing and draping of the scene. The GML-based model requires manual adjustment of road networks (especially intersections), the addition of vegetation and realistic texturing. While both methods originally generates DTM that can be used in Unity to model soil deformation, the conversion to FBX causes the DTM to be transferred into a mesh. In order to enable terrain deformation, some manual adjustment is required in both methods to convert the mesh back to the terrain. Infraworks 360 is much more user-friendly given that the process is fully automated, while the GML-based method requires manual integration and texturing. The GML-based method is updated far less frequently compared to Infraworks 360 (Bhattacharya 2012). Both methods can accommodate the inclusion of BIM objects in the model. Overall, based on the visual analysis of the two models and the extent to which the model can be made ready for simulators with minimal user intervention, the model created using the built-in feature of Infraworks 360 seems to have a slight edge. In this paper, this model is used for further modeling of the simulation scene. Once the model is finalized in Infraworks, it is exported as FBX file and then imported in Unity 3D.

The imported 3D models of the equipment are modified and adjusted in Unity 3D to simulate the actual controllable DoFs of the equipment that can be controlled by the trainee. The adjustment is done through the creation of the rotation joints and creating appropriate parent-child relationships between various parts of the equipment.

Table 1: Compassion of the two approach based on the model requirements

Requirements	**GML-based Model**	**Infraworks 360**
Accuracy	±2 meter	heterogeneous but overall slightly lower than GML-based data (Bhattacharya 2012)
Resolution	LOD2 (e.g., buildings as generalized objects)	LOD2 (e.g., buildings as generalized objects)
Visual Realism	The terrain and the objects are not fully textured	The terrain and objects are textured
Terrain Deformability	Not available in native format	Not available in native format
Ease of Use	Requires manual integration, texturing and draping	Automated process
Reliability	Updated every 2 years (Bhattacharya 2012)	Varied but generally more updated
Extensibility	When imported to Infraworks, BIM models can be integrated	BIM models can be easily integrated

With regard to incorporation of GPS data into the VR scene, the scripting capability of Unity 3D is used to program the connection between Excel and Unity. The scene should be able to read the GPS data from an Excel sheet and transform the location of equipment based on the GPS data. It should be highlighted that in the process of importing the Infraworks model to Unity, the geo-referencing of the data is lost. Therefore, the site model has a local coordinate system defined by the user.

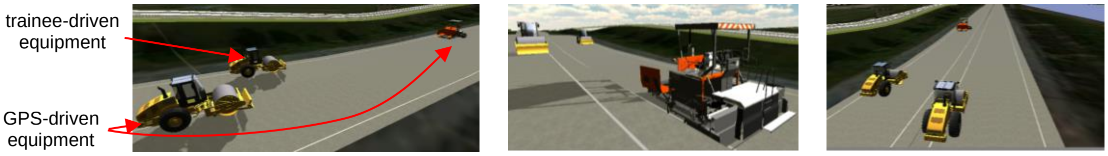

(a) (b) (c)

Figure 4: (a) The bird's eye view of the site in Google Earth, and 3D reconstruction of the site using (b) GML data, and (c) Infraworks 360 built-in feature

Two approaches exist to transform the global local system to the local coordinate system: 1) Reorient the site model by applying the correct translation and rotation to site model so that the model is placed in the global coordinate, and (2) find the transformation matrix that translates the two coordinate systems and use the matrix to translate the GPS data to the local coordinate system of the VR scene. The authors followed the second method because of the faster processing. In this method, first the native lat/long GPS data are projected to standard UTM coordinate system. Next, the global coordinates of two points on the 3D model are found and then using Equation 1 values of θ (i.e., rotation), x_t , y_t (i.e., translation), and K (i.e., scaling factor) are found. It is noteworthy that the Z value in the model is not translated due to lower accuracy. Instead, the 3D models are adjusted to follow the terrain for their height value.

$$\begin{bmatrix} \cos\theta & -\sin\theta & x_t \\ \sin\theta & \cos\theta & y_t \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Kx \\ Ky \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} \qquad \text{Equation (1)}$$

Figure 5 depicts a screenshot of the generated training scenario based on the actual site model and GPS data stored in a Microsoft Excel sheet. The trainee is able to navigate the roller on the site using the keyboard.



(a) (b) (c)

Figure 5. Snapshots of scene generated by integrating GPS data and 3D site model in Unity

Given that the high accuracy GPS rovers were used in this project, the movement of the other equipment are smooth and consistent throughout the operation. The scene would help the trainees focus on the steering of the equipment while trying to avoid collisions with other equipment. Additionally, the movement of the roller should be coordinated in such a way that the rollers are working in tandem.

5 CONCLUSIONS AND FUTURE WORK

In this paper, the process for the generation of realistic VR training scenes based on the integration of GPS data and the 3D model of the actual construction site was presented. An implementation and a case study were developed as a proof of concept. In the light of the findings of this case study, it can be concluded that the proposed method has a potential for improving the realism and effectiveness of equipment training simulators by providing the context of the actual projects. The proposed method enables easy development of multi-user training simulators where the trainees need to coordinate with other equipment to be able to perform the job safely and efficiently. On the other hand, in the current version of the prototype, some manual adjustments are still required to improve the realism of the 3D model. Additionally, the MAS structure is not yet fully incorporated in the model. Accordingly, this research will be further improved in the following lines: (1) investigating the application of LiDAR data from the site to improve the accuracy and realism of the generated scene, and (2) Incorporating the MAS-driven equipment into the model to better demonstrate the full scope of the paper.

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