Context-Realistic Virtual Reality-based Training Simulators for Asphalt Operations

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Abstract -
Asphalt operations are equipment-intensive, highly-coordinated, and context-sensitive. To ensure high-quality asphalt, operators need to be mindful of, among others, the degree of compaction required/achieved, temperature of the asphalt mixture, its cooling rate, other equipment, and the supply logistics. However, the current training program for the operators of asphalt equipment is inadequate because (1) the training heavily depends on the use of actual equipment for the training and because of the cost/safety risks involved in using actual equipment, novice trainees do not get enough opportunity to develop the required skills; and (2) given the sensitivity of the asphalt operations to the environment, the type of the asphalt mixture, logistics, etc., it is very difficult to allow trainees become sensitized to all the influential parameters in a limited time provided for the practical training.

In recent years, Virtual Reality (VR) based training simulators are employed to help train operators in a safe environment. However, scenarios used in the construction simulators are mostly hypothetical. The context of operation in these scenarios is static and devoid of dynamism common in a construction site. This is a major oversight, particularly in highly-collaborative asphalt operations. Therefore, it seems crucial to better represent the actual work context in the training simulators. Given the myriad of parameters involved in the asphalt operations, designing a training scenario based on pure modeling is very challenging.

This research proposes an approach for developing a training simulator based on the data collected from actual asphalt operations. The collected data will be analyzed and translated into a training simulator that can better capture the interaction between various operators of asphalt operations. A prototype is developed and a case study is conducted to demonstrate the feasibility of the proposed approach. It is shown that actual data can be used to effectively generate realistic training scenarios.

Keywords -
Virtual Reality; Context-realistic; Operator Training; Asphalt operations

1 Introduction

Hot mixed asphalt (HMA) is the dominant material of choice for road construction all over the world. However, the quality of HMA is very sensitive to the construction operations [1]. For HMA to be of desirable quality, the compaction must be executed over a limited period when the asphalt is within a certain temperature window, which depends on the type of the mix. Compaction below and above this temperature window results in suboptimal quality [2,3]. Therefore, operators of asphalt operation equipment (i.e., paver and compactor) need to be aligned with one another. Additionally, operators need to be able to process a wide range of information (e.g., the temperature of the asphalt, the number of desired and achieved compaction, the speed of pavers, the movement of compactors, etc.) to be able to deliver a high-quality operation. This requires a high degree of coordination and operational skills.

Operators of asphalt construction equipment go through rigorous training before they are certified to work on the site. However, there are several limitations that compromise the effectiveness of the current training programs. First and foremost, since the practical training with the equipment is expensive, trainees may not have the chance to sufficiently train with actual equipment for work in different types of operations. Second, given the sensitivity of the HMA quality to multitude of environmental (e.g., weather), design (e.g., type of mix), and operational (e.g., the size of the team) parameters, the current training programs cannot sensitize the trainees to all the influential parameters in a limited time provided for the practical training.

Virtual Reality (VR) based training simulators have been used in other industries (e.g., aviation) to address the very same problems. The construction industry has also started to use VR for training in recent years [4,5]. These simulators can considerably reduce the cost and

risks involved in on-equipment training[6]. However, to the best of the authors' knowledge, a comprehensive training simulator for asphalt operation is missing. Besides, the available construction simulators (dominantly focusing on excavators and cranes) mainly focus on the dexterity and equipment handling skills of the operators. Accordingly, a lion share of the developers' attention is placed on the graphical fidelity and realistic kinematics of the equipment. While very important, this steers the focus away from capturing the realistic context of the training. In other words, the current simulators place the trainee in a mostly isolated and static site where the trainee can move freely and unhindered. For a highly collaborative work such as asphalt operations, this is a major oversight because operators need to perform the tasks in view of many peripheral parameters about the operation of other equipment, the behavior of the asphalt layer, and weather condition. For instance, when considering the trajectories of other compactors in the team, what could have been an optimal path for a single compactor may become very unsafe or inefficient in tandem compaction. Additionally, since the focus is too much on kinematics, many other aspects of physics in the simulators are left out. Current simulators use theoretical principles to develop the physics of the scene. Even though these theoretical principles are very effective, they are normally simplified and can hardly account for the complex interaction between the behavior of the of the asphalt layer, the type of the mix, weather condition, and the compaction regime. Capturing this complex interaction through physics-based modeling is very difficult.

Recent advancements in sensing technologies and Internet of Things (IoT) allow for the collection of a wide range of data about various aspects of actual construction sites. The authors have previously indicated the potentials of using various types of sensors to track and monitor asphalt operations [7]. The collected data from actual site capture various aspects of the context of asphalt operations that are not represented in the current hypothetical training scenes. This includes the context-specific cooling rate of the asphalt as well as the movement and motions of all the equipment in the asphalt operation team. It is argued that these data can be used to reconstruct the actual asphalt operations in a VR environment. Because the virtualized scene incorporates several elements of the operational context, the training scene created in this fashion is expected to be more realistic in terms of fidelity to the context. Trainees can use these simulators to become more sensitized to the collaborative nature of asphalt operations and to delicacies involved around compaction at the right temperature.

The authors have previously proposed a generic framework for data-driven context-realistic training simulator for construction operations [8]. However, the previous work of the authors is generic and not focused on a specific operation. Besides, the previous work of the authors assumed that most of the feedback about the performance of trainees is provided at the end of the session. This is a limitation because novice trainees and early-stage learners can benefit from mid-training guidance to build up competency about the development of compaction strategy.

Therefore, the primary objective of this research is to present an approach for developing an asphalt-specific training simulator using the previously presented framework for context-realistic training simulators. In this research work, the focus is placed on asphalt operation and the generic framework is retrofitted to adapt to the requirements of training simulators for asphalt operations. In particular, the paper extends the previous work of the authors to incorporate mid-training guidance targeted at novice and early-stage learners.

The layout of the paper is as follows: first, the proposed approach is presented. Next, the implemented prototype and case study is introduced. Finally, the conclusions and future work of the research is presented.

2 Proposed Approach

Figure 1 shows the overview of the proposed approach for the generation of context-realistic training simulators for asphalt operations, focusing on mid-training guidance. As stated in Section 1, this framework is retrofitted from the generic framework presented in the previous work of the authors [8] to customize the training simulators for the purpose of asphalt operations.

A training simulator focusing on the asphalt operation should be able to sensitize trainees to the importance of compacting asphalt at the right temperature. Given the complexity involved in simulating the behavior of asphalt on the construction site, the application of context-realistic simulators seems to be appropriate and helpful. The proposed approach has four main steps, namely, data collection, context generation, scene reconstruction, and context-based feedback.

2.1 Data Collection

During the data collection step, all the relevant data for the representation of the context of asphalt operation need to be collected. The context of asphalt operation is defined as the combination of environment, mobile equipment, and behavior of the asphalt.

In recent years, many municipalities and provincial government of large cities provide either the 3D models of their jurisdictions or the essential data needed for the reconstruction of 3D models. For instance, CityGML models of many major cities are now publicly available [9,10]. These models can be used to represent the

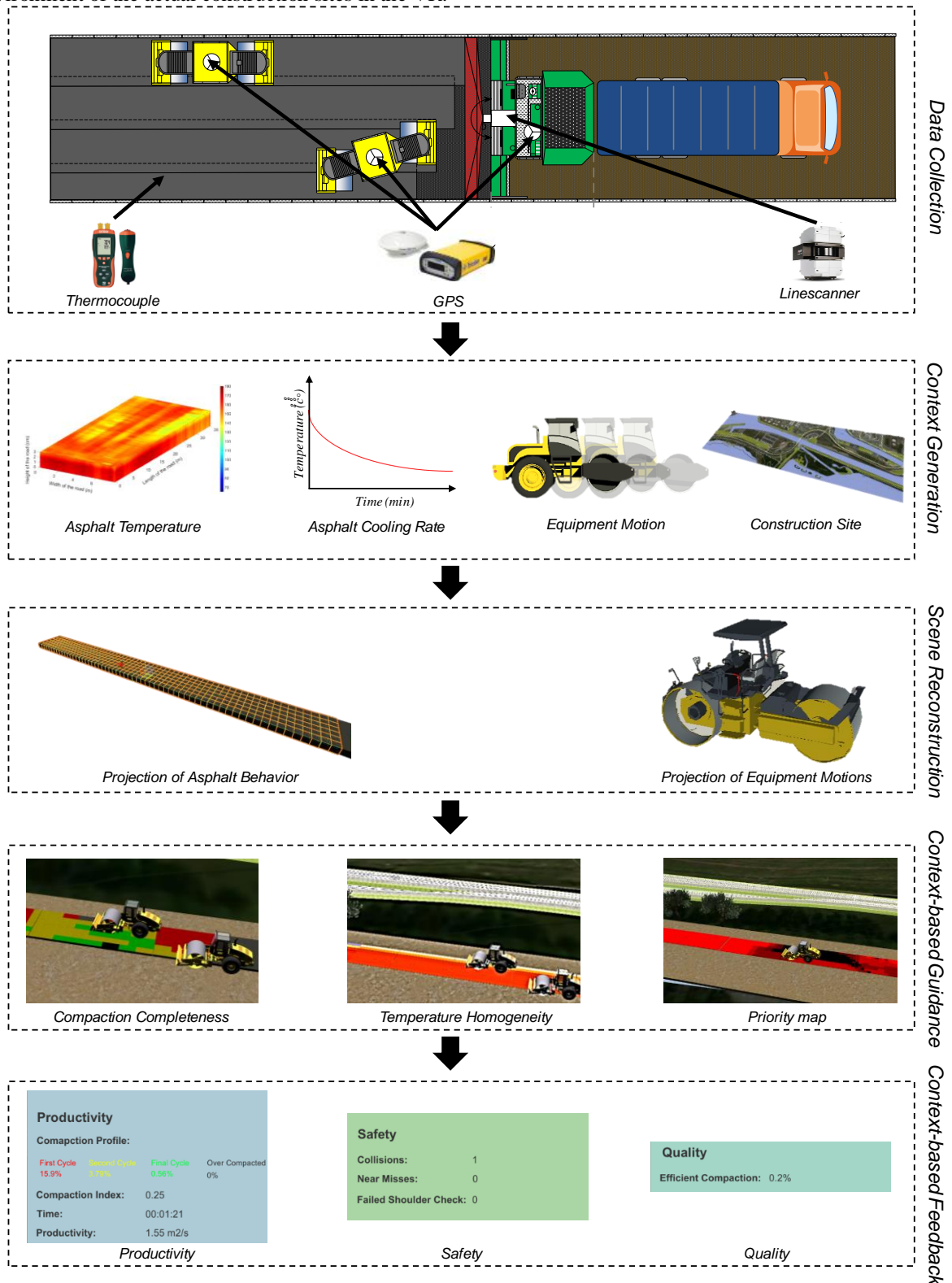environment of the actual construction sites in the VR.

Figure 1. Overview of the proposed approach for context-realistic asphalt operation training simulators

For tracking mobile equipment, Global Positioning System (GPS) can be used. Since the kinematics of pavers and rollers are rather simple, 2D tracking is enough for representing mobile equipment in the VR scene. GPS rovers can be installed on each equipment. The data collected from GPS rovers can later be projected to the local coordinate of the VR scene. As for the asphalt behavior, the proposed simulator only focuses on the temperature of asphalt and the cooling rate. These two pieces of information indicate the temperature of the asphalt layer (at surface and core) and the rate at which it cools down. These data are critical for effective compaction and they are sensitive to various parameters such as weather condition, layer thickness, logistics, and type of asphalt mix, which makes them context-sensitive.

The previous work of the authors provides a comprehensive account of how this data can be collected from asphalt operations [1,7]. However, for the completeness, a brief description will be provided here.

The surface temperature of the laid asphalt mixture is collected using linescanner mounted at the rear of the paver, as shown in Figure 1. The width of the asphalt layer is split into several points and the temperature of each point is measured. By synchronizing GPS and linescanner data, the surface temperature data is geo-referenced. To be able to determine the cooling rate of asphalt, a set of thermocouples in combination with infrared camera are used to continuously measure the core and surface temperature of the asphalt layer at a fixed location. It should be noted that the cooling rate of the asphalt is not a constant value but rather a non-linear function, as shown in Figure 1.

2.2 Context Generation

Using the continuous stream of core and surface temperatures at the fixed location (i.e., the output of the thermocouples) and the initial surface temperature of different parts of the asphalt mat (i.e., the output of linescanner), we can interpolate the core temperature of the asphalt at any other points on the mat. With all the measured and calculated data, the 3D temperature contour of the asphalt mat and the cooling curve of the asphalt at the core and surface can be determined. These two types of data can be fed into the simulator to realistically represent the thermal behavior of asphalt in the context. Since this behavior is extracted from actual construction sites, the asphalt behavior captures the complex causal relationships that impact the thermal behavior of asphalt (e.g., weather condition, layer thickness, type of asphalt mix, etc.) without requiring to model these relationships mathematically.

Another element of context in asphalt operation training simulator is the 3D model of the site. As stated before, the data required for 3D modeling of the site can

be extracted from public data (e.g., CityGML). Depending on the Level of Detail (LoD) of the available data, the 3D model may need some adjustment such as draping and minor geometric adjustment. Also, additional pieces of information such as new buildings and underground utilities can be extracted from relevant asset information models such as Building Information Models (BIM). Asset information models can be incorporated into CityGML model using available tools for BIM and GIS integration (e.g., Infraworks [11]).

The final element of context in the simulators is motions of different pieces of equipment. For this element, GPS data need to be corrected. Authors have previously presented an approach for enhancing the quality of the location data [12].

2.3 Scene Reconstruction

In the next phase of the proposed approach, the context data and the 3D model of the site need to be integrated. Game engines can be used for this purpose. The first step in this phase is to import the 3D model of the site into the game engine. In many cases, when the 3D model is imported into the game engine, the native coordinate system is distorted. If this happens, the 3D model needs to be re-scaled and re-positioned. This process is explained in the previous work of the authors [12].

The next step in this phase is data synchronization. Depending on the used sensors, different types of data have different resolution and frequency. To improve the consistency of the scene, it is best to unify the update rate of different types of data and align the timeframe across all the data. This can be done through averaging the data and interpolation.

Upon the completion of data synchronization, temperature, cooling rate, and mobility data should be integrated into the scene. Figure 2 presents an overview of how these types of data are integrated into the VR scene. As shown in Figure 2A, the first step is to translate the latitude and longitude data coming from GPS to the local coordinate of VR scene, using the method explained in the previous work of the authors [8]. Since pieces of equipment used in the asphalt paving operations have rather simple kinematics (i.e., 1 controllable degree of freedom for transitional movements), the project time-stamped coordinate data can be linked to a single point hinged to the 3D model of the equipment at the same location where GPS rover was installed on the actual equipment.

To incorporate the temperature ($T_{x,y}$) and cooling rate (dT/dt) data into the scene, first, the geo-location of each data point needs to be projected to the local coordinate of the VR scene, similar to the previous step. Then, the 3D model of the asphalt layer needs to be discretized into a grid, as shown in Figure 2b. Since the data collected by

linescanner, i.e., red dots in Figure 2b, (1) are not necessarily projectable into a uniform grid and (2) have a very high update rate that may render the VR scene very slow if they are supposed to be used as is, the grid size in the VR scene is determined by human modeler. Then, by intersecting the coordinates of the temperature data $(IT_{x,y})$ with the user-defined grid and applying interpolation the initial temperature of each cell of the asphalt layer in VR scene $(IT_{i,j})$ is determined. In the VR scene, each cell becomes visible only when it collides with the paver for the first time (i.e., when it is placed on the mat on actual site). From that moment, the temperature cools down according to the measured cooling rate.

(a) GPS data integration

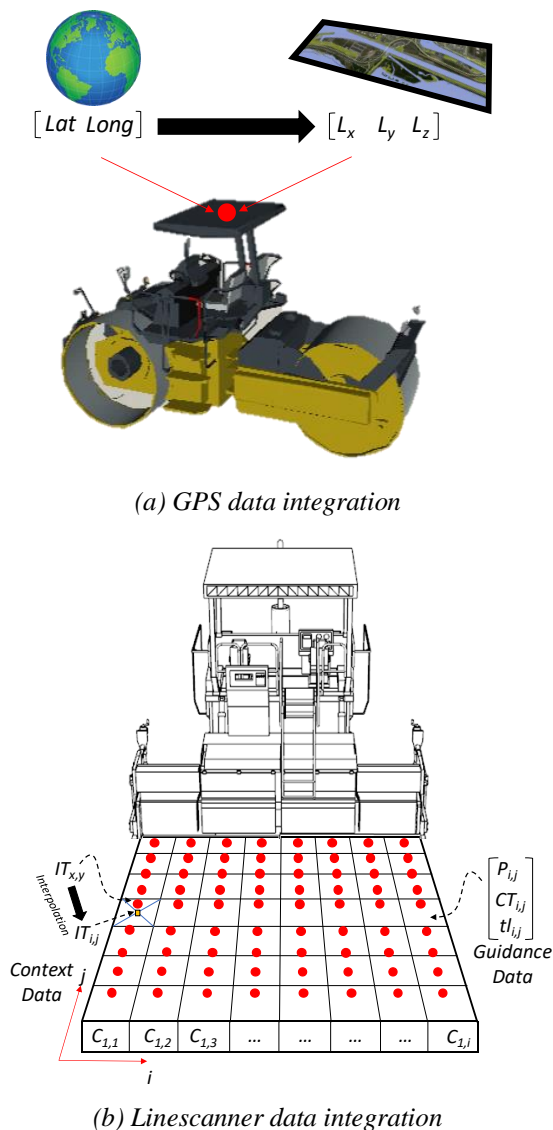
(b) Linescanner data integration

Figure 2. Overview of the proposed approach for context-realistic asphalt operation training simulators

2.4 Context-based Guidance

Upon the integration of data in the VR scene, the next step is to develop a guidance mechanism inside the scene. The guidance is supposed to help trainees (particularly novice learners) develop better compaction strategies by observing the behavior of the asphalt and the impact of decisions made on the site. To this end, three types of guidance are provided to the trainees: (1) compaction completeness, (2) temperature homogeneity, (3) proximity, and (4) compaction priority map. These three types of guidance are provided on-demand, meaning that the trainee can choose which of the three types of guidance he/she wants to see on the main screen and which one of the guidance types he/she wants to see in small side windows. More experienced trainees can choose not to use any of the guidance types at all.

Compaction completeness measures the number of times each cell in the grid is subject to compaction $(P_{i,j})$, as shown in Figure 2b. This index is calculated by counting the number of times the drum of the trainee-operated roller collides (i.e., come to contact) with each cell. This type of guidance is displayed through the use of a color coding scheme. This means that based on the required number of compaction, which is a function of the type of the asphalt and the thickness of the layer, different colors in the spectrum of dark red to dark green indicates the number of compaction achieved at each cell. Also, the cells that are over-compacted can be indicated by changing the color to black. The user uses this guidance to (1) evaluate his completed work and (2) devise a plan for compacting the reminder of work.

Temperature homogeneity guidance displays the current temperature of each cell. As shown in Figure 3, this is done by considering (1) the initial temperature of the cell and (2) the simulation time (t) passed from the moment each cell is placed on the mat.

The cooling curve of the asphalt, which is generated at the end of the data gathering phase, is used to determine the current temperature of each cell at each frame of the VR scene $(CT_{i,j})$. Similar to the compaction completeness index, the temperature of the cell can be visualized using a color coding scheme. Trainees can use this form of guidance to determine whether or not a cell is still within a compactable temperature zone and how much time there is before a cell becomes too cold for compaction.

Proximity guidance indicates the distance of the trainee-operated equipment to other pieces of equipment. Additionally, when the trainee-operated equipment become hazardously close to any other equipment/workers in the scene, a warning is generated. The trainee can use this guidance to become sensitized to situation awareness required for safe execution of the job.
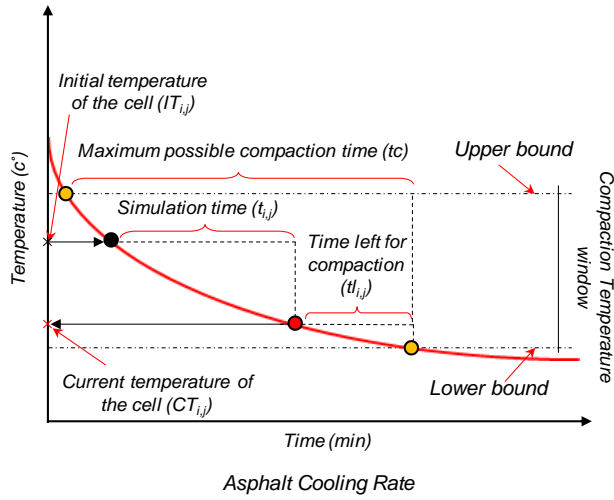
Figure 3. Calculation of the current temperature of each cell based on the initial temperature and the cooling rate

The last type of guidance that can be provided to the trainee is the compaction priority map. While the previous two guidance types merely indicate the state of asphalt layer in terms of compaction and temperature, the priority map tries to combine the two state data into guidance about how compaction of different parts of the asphalt needs to be prioritized. In order to generate the priority map, two parameters are considered. The first parameter is the time left for the compaction of a cell. As shown in Figure 3, this is determined by calculating the time left to the lower bound of compaction temperature window ($tl_{i,j}$) for each cell at every frame of the VR scene. The second parameter is the number of compaction achieved so far for each cell ($P_{i,j}$). These two parameters are translated to a priority index using Equations 1 to 3.

$$R_{i,j} = CP_{i,j} \times TP_{i,j} \quad (1)$$

$$CP_{i,j} = \begin{cases} \dfrac{PD - P_{i,j}}{PD} & PD \geq P_{i,j} \\ 0 & PD < P_{i,j} \end{cases} \quad (2)$$

$$TP_{i,j} = \begin{cases} 0 & tl_{i,j} > t_c \\ \dfrac{t_c - tl_{i,j}}{t_c} & 0 < tl_{i,j} \leq t_c \\ 0 & tl_{i,j} = 0 \end{cases} \quad (3)$$

Where:

$R_{i,j}$ = Priority of cell i and j
$CP_{i,j}$ = Compaction priority of cell i and j
$TP_{i,j}$ = Temperature priority of cell i and j
PD = Desired number of compaction
$P_{i,j}$ = Compaction achieved at cell i and j
tc = Maximum possible compaction time
$tl_{i,j}$ = Time left for compaction of cell i and j

The priority value ($R_{i,j}$) is displayed using a color coding scheme in the spectrum of light to dark red, corresponding to high and low priorities. Trainees can use this form of guidance to plan the compaction path.

2.5 Context-based Feedback

The next phase in the proposed approach is to provide relevant feedback to trainees, i.e., after the training session is completed. Feedback helps trainees better pinpoint areas of attention in their practices. Additionally, feedbacks and the metrics used to assess the performances of the trainees can help track the progress of the trainees throughout the training program. Based on the scope, feedbacks can be categorized in 3 classes: (1) productivity-related, (2) safety-related, and (3) quality-related. Productivity-related feedback measure the overall compaction time, proportion of under, adequately, and over compacted cells, average compaction, and productivity. Safety-related feedback indicates the number of collision with other objects/equipment, the near misses, and failed shoulder checks (i.e., if VR goggle is used). Finally, quality-related feedback measures the ratio of cells that have been properly compacted within the compaction temperature window to the overall asphalt area.

3 Implementation and Case Study

To demonstrate the feasibility of the proposed approach case study is conducted. The case study is built upon the previous case study presented by the authors [8]. For completeness, the description of the case study is repeated in this paper.

The data collected from a surface rehabilitation of a part of a highway (A15) near Rotterdam is used. The collected data included the GPS of the paver and two compactors and the temperature/cooling of the asphalt. The principles explained in the earlier work of the authors are used for data collection [1].

The 3D model of the site is generated using Infraworks and Unity 3D, as explained the previous work of the authors [12]. The data collected from linescanner and GPS rovers are integrated with the asphalt cells and the 3D model of equipment, respectively.

The scene is designed so that one trainee can operate one of the rollers in the scene. Depending on the purpose of the training, the trainee can decide to be the leader or follower in the compaction process. The details of the two possible scenarios and how they are implemented in the scene can be found in the previous work of the authors.

As stated in Section 1, the main focus of the paper is to generate mid-training guidance to the trainees. Therefore, the principles explained in Section 2.4 is implemented in the VR scene. Figure 4 shows different types of mid-training guidance that trainees will receive.

As shown in this figure, the discretization of asphalt into cells can help provide easy guidance to the trainees. Also, the dangerous proximity of the trainee-operated equipment to other equipment is warned using the highlights in the real-time proximity indicator.
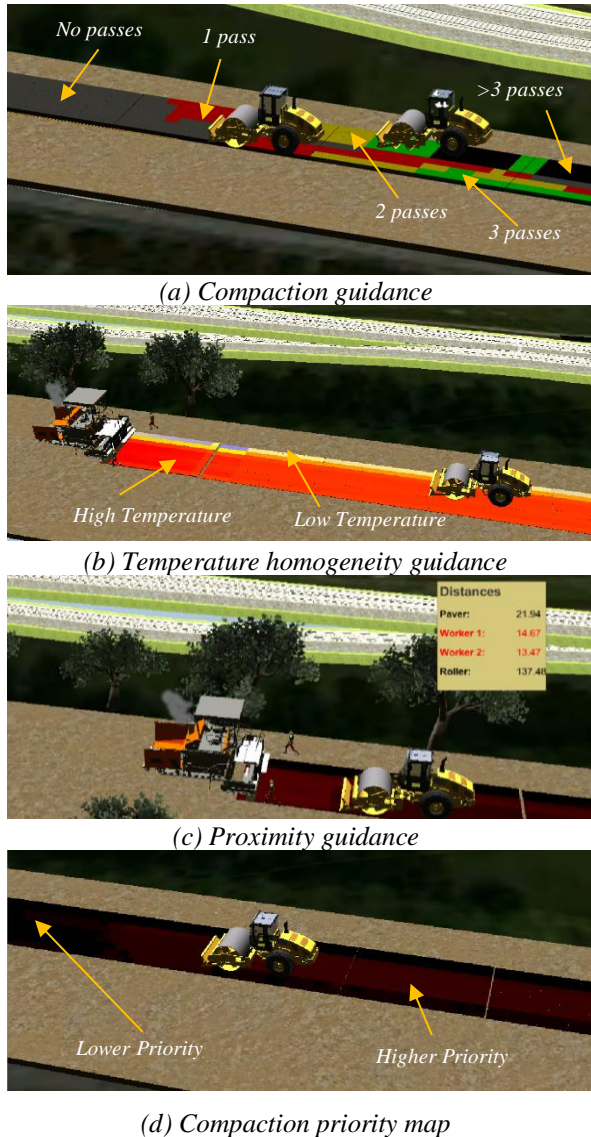

(a) Compaction guidance

(b) Temperature homogeneity guidance

(c) Proximity guidance

(d) Compaction priority map

Figure 4. Overview of different types of mid-training guidance that can be provided to the trainees in the context-realistic training simulators

4   Conclusions and Future Work

In this paper, an approach for the generation of context-realistic training simulators for paving operation was presented. A generic framework developed by the authors was tailored to the specific characteristics of paving operations. Additionally, special focus was placed on the incorporation of mid-training guidance for early

stage learners. A case study was conducted to demonstrate the feasibility of the proposed approach based on actual data collected from a paving operation.

The result of the case study indicated that the actual data collected from paving operations can be easily used to generate context-realistic training simulators. It is shown that a variety of real-time calculations can be applied to provide early-stage learners with various types of guidance. These mid-training guidance can be used by trainees to hone the skills required for developing compaction strategies faster.

While the results are promising, the positive impact of mid-training guidance on the development of compaction skills needs to be validated in a case study with a group of actual trainees. This would be the future focus of this research.

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