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SIMPAVE: Evaluation of Virtual Environments for Pavement Construction Simulations

By

George Turkiyyah
Department of Civil and Environmental Engineering
University of Washington
Seattle, WA 98195

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Transportation Northwest (TransNow)
University of Washington
135 More Hall, Box 352700
Seattle, Washington 98195-2700

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ABSTRACT

In the last couple of years, we have been developing virtual simulations for modeling the construction of asphalt pavements. The simulations are graphically rich, interactive, three-dimensional, with realistic physics, and allow multiple people working on a set of networked machines to collaborate on performing the compaction of hot-mix asphalt. These simulations may be used in training, examining what-if scenarios, studying bottlenecks and difficulties in the construction process, etc. The demonstrations we have shown at conferences have received a lot of success and we propose to build the next generation of such systems. The next generation will not only improve the graphical realism of the environment but will add additional behavioral models for various agents acting in the environment. This will allow to handle a broader set of scenarios including safety issues associated with construction, logistical issues associated with construction/rehabilitation in congested areas, lower visibility associated with night work, etc.

A major equipment manufacturer (Roadtec) has indicated interest in helping us to further develop the simulations using detailed 3D equipment models from their designs, including pavers, trucks that move hot-mix from geographically distant plants to the construction site, as well as their models and experience with asphalt construction planning and monitoring.

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In this report we describe our experience with the development, use, evaluation, and assessment of a first-generation interactive simulation system for hotmix placement. The goal was to gauge the strengths and weaknesses of the key features of the system including its basic game-like metaphor, its interactivity, extensibility, and network multiuser capabilities, with a view towards proposing architectural improvements and modifications for next-generation simulators.

1. Introduction

As knowledge, technology, and the operating environment of hotmix construction changes, today's engineers (as well as technicians, supervisors, inspectors, construction workers, and others) must increasingly rely on training as a means to stay current and acquire new knowledge and skills. Computer-assisted tools have the potential of enhancing the effectiveness of novice training. Computer training environments have already shown their efficacy in a number of areas. Interactive manuals are used by aircraft technicians to learn about servicing and maintaining airplanes, flight simulators are used by pilots in-training to become familiar with basic procedures, surgical simulators are used to train medical students or paramedics to perform basic suturing procedures, etc. The computational capabilities of desktop machines as well as the video, 3D graphics rendering capabilities of modern graphics cards, now enable the realistic visualization and interaction with computer models of equipment, tools, and machines to produce compelling environments for training purposes.

The applications of this technology to the processes involved in building and maintaining asphalt pavements is still in its infancy. This is despite the fact that 95 percent of the highway system is surfaced with asphalt concrete and represent a significant infrastructure investment. During 2006, for example, over 550 million tons of hot mix were placed in the U.S. Given typical costs of producing and placing this material, this amounts to over $20 billion per year. Even small mistakes due to incomplete training of design or construction personnel can have enormous economic consequences. Given the effect of physical construction practices on the quality and life of pavement systems, graphical simulations of construction processes related to pavements are particularly important for novices.

This project is part of a larger effort to develop next generation training tools for the pavement industry. The tools are envisioned to be interactive, media rich, available on demand for just-in-time and self-training activities, targeted to students as well as young practitioners, and encompassing design, material specifications, as well as construction activities. A modest step towards this larger goal was to evaluate an interactive real-time hotmix paving simulator we had developed, in order to assess its strengths and weaknesses to help in the design of an improved simulator.

2. Problem Statement and Objectives

The roller simulator was developed as a proof of concept system to allow us to explore the potential of interactive game-like tools for providing a new way of presenting training materials and illustrating the process, constraints, and complexities of pavement construction. Using a game-like metaphor, simulations that are interactive and graphically rich provide a compelling mechanism to engage the user in the training process. Beyond the physical aspects of construction, the introduction of network-enabled multi-user simulations increases the value and realism of the training by incorporating the group dynamics of the construction process such as the cooperation and coordination of construction personnel. In this report we briefly examine the design decisions we made in the course of development and use this evaluation to justify the architectural modifications we feel are necessary for improved simulations in the overall educational context.

3. The Gaming Metaphor

The roller simulator belongs to a class of interactive, multi-person, realtime, 3D simulations ("game-like" simulations). The natural question to ask and assess first is whether this format of conveying information is more effective than other alternatives. The other main computer-based training alternative is electronic courseware where textbooks, brochures, manuals are formatted for online/onscreen presentation, sometimes augmented and enhanced with animations, and divided into units, perhaps with questions at the end of each unit to make sure readers did go through the material. This format, while very useful, does not immerse the trainee/user in the subject matter and its environment.

Games on the other hand are totally engaging. The game narrative provides a task or a set of tasks that must be performed by the trainee/user. In the course of reaching the objective, he or she has to be aware of the limitations and capabilities of various equipment, impact of various environmental conditions on the task at hand, etc. Without actively considering these factors the objective may not be reached. In our discussions and presentations, the uniform feedback we obtained was that the experiential nature and active engagement of the game-like interaction allow the information about timings and constraints of construction tasks to be conveyed vividly.

However, games are far more complex and expensive to develop than noninteractive, non real time training media. In the current state of the art, games have to be handcrafted, user interaction has to be programmed at fairly low levels, and the environment, models and textures used have to be built specifically for the expected interactions. In addition, the behavior of the individual equipment has to be adaptive to guarantee the smooth real-time graphical display on the available hardware, and multi-user interaction on a network has to be coordinated and synchronized (in the presence of random latencies). All these elements contribute to making the development of general-purpose 3D real-time interactive simulators demanding. The situation is likely to be change as higher-level development environments and tools become available. These environments make it easier to generate composite behavior by plugging-in individual pre-existing components without significant reprogramming.

3. Evaluation of the Simulator Architecture

Fig 1 shows a schematic of the architecture of the roller simulator. At the beginning of a run, a scenario file is loaded. The scenario contains a description of the environment and task to be accomplished and is used by the core engine to instantiate various geometric models to set up the static environment (the background world of the simulation), the active objects of the simulations (parameterized equipment models, road geometry to be paved, etc.), and set environmental parameters (wind sped, temperature, etc.). Network connections are also established with other computers that are running the simulation. Each computer is responsible for controlling one aspect of the task (moving one of the rollers or a paver). When the simulation starts every local user moves and steers his/her roller and the display is updated to reflect the aggregate effects of all actions on the network (positions and orientation of all equipment, all compacted regions, etc.). Feedback to users is in the form of updated colors reflecting temperatures of the hotmix and amount of compaction, and a "heads up" display that provides a temperature readout and other pertinent information in a corner of the application window which is updated every minute of simulated time.

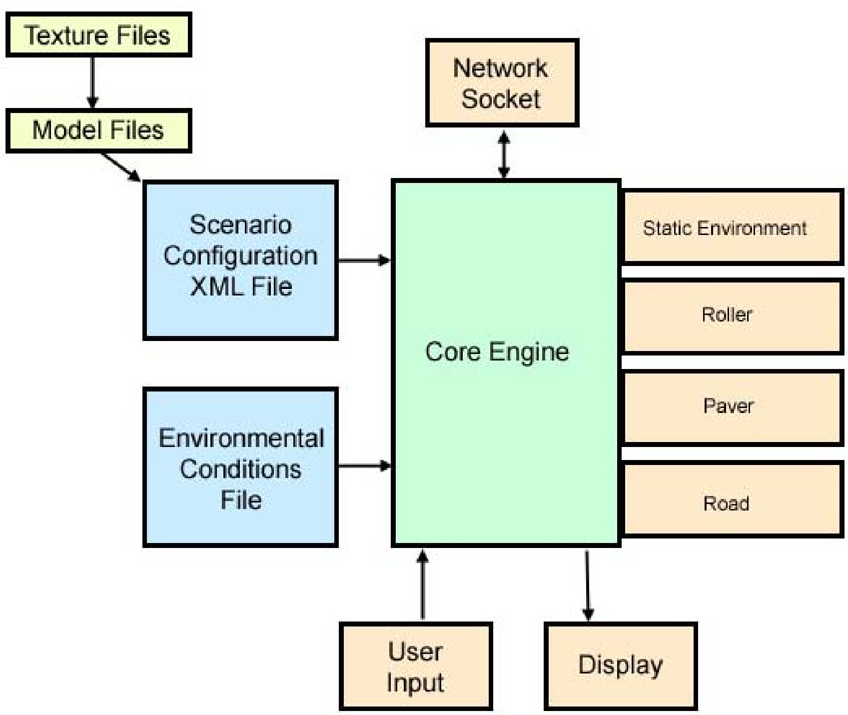

Figure 1. Simulator Architecture

We performed a number of tests and evaluations and obtained feedback from a number of users on three aspects of the system: the interactivity and the look and feel of the simulation, the ease of defining new construction scenarios, and the multiuser networked capabilities.

System Interactivity

The main distinguishing characteristic of the system is its ability to place the user in a dynamic setting where he or she is interacting with a changing environment, reacting to these changes and to the actions of other users involved in the virtual construction task. This is in constrast to the usual computer based training where the user simply watches illustrations and animations on the screen. Users of the system uniformly were enthusiastic about this feature of the system. The "game-like" feel of the system has an undeniable and readily apparent appeal when users sit in front of the computer and start a simulation. The graphics were designed at medium resolution (a few thousand triangles per object in the scene) to allow rapid display even on modest computers. The response of the system was smooth on a variety of hardware the system was tested on.

To allow for broad usage, we relied on input from the mouse and keyboard. While this worked well for testing and demonstration purposes, we performed some limited tests with more specialized interfaces, namely a wheel. This allowed a more natural and well-received interface for controlling the action of the roller but required a bulkier setup that may not always be available or convenient. In the future we believe that the new generation of controllers used in commercial games may be the best hardware interface to these simulators. They are inexpensive, standard, and feature-full and they work both on game consoles as well as PCs.

Declarative Data Inputs for defining new scenarios

In order to be useful for training purposes the simulator provides the ability to set up different paving scenarios to be accomplished, without requiring programming. Users or administrators of the simulation can define the layout of the road to be paved, the number of participants in the construction operation, the environmental parameters that affect the cooling of the hotmix, and the more general environment in which the simulation takes place. Allowing users to create and modify their own paving scenarios ensures that trainers and planners can use the simulation for customized training, applicable to their specific objectives.

This was accomplished through an XML-based configuration file that gets loaded at startup without having to write new code or recompile the existing software. The usefulness and practicality of this feature was evaluated informally with students to test the efficacy of generating such data files. The extensible markup language (XML) has become a standard format for storing and exchanging a wide variety of data on the web and elsewhere. After learning the syntactic structure of the format, most students were readily able to define and add their own scenarios to build the static environment (background buildings, rural/urban settings, etc.), define new paving conditions, and equipment for a simulation (width of rollers, default speed of paver, etc.). We believe this feature should be enhanced in any future developments as it allows users to essentially extend the system by adding customized scenarios that most significantly fit the need of a particular training task.

Multiuser Network Capabilities

A key element of the virtual construction site is the ability for multiple users to interact within the same simulation simultaneously. Users can play the role of a roller operator, with multiple rollers allowed in a single simulation. Users also can control the paving machine, dictating the timing of the hotmix laydown, with the goal of coordinating with the rollers to ensure that the asphalt can be compacted within the cooling time window. Users can also participate in the simulation as observers that can monitor the activities of the other participants and direct and advise them if needed. This multi-user interaction is achieved by making the simulation software network-enabled. Participants run the software on separate computers communicating over a network.

At any given time the virtual world of the simulation is fully specified by a set of parameters that define the current simulation state. They include the position and states of the paver, rollers, and the conditions of all objects in the virtual site. Users perceive and react to the simulation through their individual networked computers, and their displays render the virtual environment based on updates of the current state. Authoritative modifications of the shared state are done by a central server. The main difficulty in developing robust networked simulations is to maintain synchronicity and consistency between the various computers on the network, even when these computers have varying capabilities. Inconsistency occurs because of the delay between the time of issuance of an action and the rendering of the actions on the various computers that are part of the simulation. It also occurs because the state of the simulation that a user is operating on is necessarily outdated to some degree because the real current simulation state has changed in the time it takes the updated data to reach their destination.

We put the system through a number of tests with four networked computers simultaneously modifying the virtual site. Our goal was to insure that the delays encountered are not very significant and do not detract from the ability to coordinate actions between multiple rollers and pavers. The tests showed that even with machines of varying graphics and CPU capabilities the difference in the state that the various computers were operating on was almost unnoticeable. Rollers, pavers, etc. moved in synchronicity on the various machines. Network observers of the simulation were able to communicate with the other computers in sync. without latency that affected control and decision making. Slower machines occasionally did exhibit some jerkiness on per-frame basis. But this can be remedied either by using coarser models of the environment and equipment on these computers.

4. Autonomous Environments

In the roller simulation virtual world, all active equipment must be controlled by one of the users on the network. The paver speed, the rollers, etc. are actively controlled by user interaction. Moving, steering, changing speeds, turning, stopping, etc. are performed by users in response to changing environments, and in reaction to the location of other equipment and progress made towards accomplishing the task. This was an active design decision at the time, and allowed users to be fully engaged in the hotmix laydown, cooling and related details. It turned out however that, users were focused on the low level control decisions of the construction task and were not always sufficiently aware of the “bigger picture”.

The main conclusion we reached is that the main narrative of the game could be shifted from the specific task of compacting hotmix to a more management-oriented task: to provide the user with the high-level control over resources. Instead of controlling equipment and moving them around, the user only allocates a number of rollers to a given task and watches them go. This will make the system higher level but may have some useful applications. This change in narrative serves a different class of users, namely students in pavement courses.

In terms of the game design, this requires that the virtual world, in which these decisions are made, be populated by objects (trucks, pavers, rollers, etc.) that can behave and react autonomously to dynamically changing conditions in the site environment. For instance, rollers may have the objective of paving a lane and would autonomously plan and generate the individual movements to cover the regions with the appropriate number of passes. Similarly, the trucks hauling the hotmix from a plant would automatically navigate a dynamically chosen route to the paver. Such additions require a different interaction model and algorithms to control the behavior of equipment under randomly changing conditions. This autonomous part of the environment has been the main feature of the new design of the system.

As an example of how the overall storyline of the game may develop, the user may be given the task to pave a predetermined section of highway and spend the minimum amount of money while obtaining an adequately compacted pavement. The choices a user has to make then involve the plant production rate, the number and type of trucks to use (end dump vs bottom dump; with or without tarp), the number and types of rollers (static, vibratory, or pneumatic) and their size, as well as paver speed. These decisions may be of course be adjusted dynamically as paving conditions change (wind, temperature, traffic, etc.) with the goal of matching production and laydown/compaction rates. However adjustments in equipment use may incur a mobilization/demobilization cost.

Feedback is obtained in terms of money spent as the simulation progresses. The cost is an aggregate measure of the cost associated with the individual resources used by the user: material costs are given per ton, trucking to the site is derived from the hourly cost of operating the truck and varies with time of day, compaction roller cost is also in terms of hourly nominal rates. Feedback is also obtained on the quality of the compacted pavement and is derived from the number of roller passes and the hotmix temperature when the passes took place. The goal of the game is to achieve a fully compacted pavement at minimal cost. Such narratives are relatively easy to develop and will represent the next feature in the development of interactive simulators.

5. Conclusion

We described our experience in evaluating a roller compaction simulator. Our findings were that users enjoyed the game-like metaphor and were drawn to the virtual site because of its interactive 3D graphics and the ability to effect the progress of the construction task. The multiuser network aspect of the simulator worked smoothly and allowed synchronized operations. Discrepancies between states of the site among different machines were no more than a fraction of a second at any point. One of the findings during evaluation was that, while the system is great for technicians or equipment operators, its use in classroom situations will benefit from a “management-oriented” perspective, where users are responsible for allocating resources to task, instead of directly executing the necessary setup and construction tasks. Much of the infrastructure for this new perspective is in place, and we have as a result designed a new system that accomplishes this goal. The design of the system is described in a separate document.