Simulating and Visualizing Construction Operations using Robot Simulators and Discrete Event Simulation

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ABSTRACT

Despite benefits offered by the simulation and visualization of construction processes, this class of technologies has yet to be adopted on a large scale in the industry. Reasons include the time and effort required for data collection and preparation of Discrete Event Simulation (DES) models and the requirement to consider additional geometric information about the visualized components (e.g. work site, work product, equipment) in order to correctly and completely visualize the simulated operation. This paper introduces an approach to the simulation and visualization of construction operations that employs robot simulators for the encapsulation of functionality and performance characteristics and that enables the intelligent execution of programmed work tasks with due consideration of the virtual environment in which they are conducted. Our conceptualization of a robust methodology for the introduction of robots into construction sites through the synergistic combination of two proven technologies, viz. DES and robot simulation, is described. The abstraction of geometric and performance characteristics within a reusable robot model frees the operation modeler from concern over details such as activity durations and geometric considerations, greatly decreasing the time and effort required to produce correct and convincing visualizations of operations, which in turn could lead to the widespread adoption of these technologies in the industry.

INTRODUCTION

Several tools and techniques have evolved from research efforts in construction simulation and visualization that help us to see construction happen as it would in the real world in a virtual setting. While the benefits offered by the use of these tools is undisputed and well documented (Zhang et al. 2011; Kamat et al. 2010), there is very little adoption of process visualization in the construction industry. This situation can be attributed partly to the time and effort needed to gather information that is necessary for producing convincing visualizations of real world operations. This information pertains to, among others, spatial and geometric data about the work site and duration data about the various activities in the operation for the underlying simulation model. The very nature of the Discrete Event Simulation (DES) models used to visualize the process being studied requires instructions to be sent from the DES model at discrete points in time (the starting and ending of activities) to update a continuous animation. The operation modeler thus needs to capture and model every aspect of the desired visualization into the DES model which would then inform and manipulate CAD objects to perform the operation in the virtual environment, even though some of that information is not relevant to the goals of the simulation model itself.

The primary reason for this work flow is the lack of any intelligence in the CAD objects which, being used solely for visualization purposes, do not have any sense of their states or environment. Efforts at reducing the modeler's concern over geometric and low level details of the operation, include that of Kamat and Martinez (2005), who enabled the communication of animation instructions at activity level rather than geometric transformation level for articulated equipment and the use of Augmented Reality (AR) in construction visualization (Behzadan and Kamat 2009). Neither of these approaches change the fundamental paradigm of having the DES model communicate all details of the animation to the virtual CAD models. Such a demanding requirement prompts the desire for a new intelligent CAD object that has encapsulated within it its properties and functionalities that allow it to perform as directed with due consideration for its environment which would greatly reduce the amount of information detail to be communicated from the DES model.

In our conceptualization of such an object, we found most promise in the technology of robot simulation, which is partially inspired by our long term research objective of using robots to perform construction operations. Robot simulators are virtual environments that allow for the design and testing of robot models. The robots themselves encapsulate all of the information, intelligence, and functionality which allow it to perform commands as programmed, through the use of sensors and actuators with due consideration of its environment. This feature of the technology would allow for all of the low level information regarding the equipment's performance to be abstracted into their corresponding model in the robot simulator.

Our proposed methodology employs a hybrid approach wherein a modified DES model of the operation is used to direct virtual equipment in the robot simulator, which would perform the requisite tasks according to their programmed and encapsulated functionality, thus freeing up the modeler to focus on operation level modeling. Sensing capabilities on the robot would allow it to react to its virtual environment appropriately, thereby obviating the need for the entry of any spatial and geometric information into the DES model. The encapsulated performance data of the robot would allow it to perform tasks without the need for accompanying duration data, which would exempt the modeler from having to collect that data from real world operations. In addition to already existing implementations of collision detection and inverse kinematics in construction technologies, the use of robot simulators would also enable the consideration of dynamics in construction visualizations, which could greatly improve the realism of visualizations and thereby the credibility of simulations.

We believe that the combination of two established technologies, viz. DES and robot simulators, has the potential to greatly improve the fidelity of construction visualization while drastically reducing the time and effort needed for its creation.

We have provided a brief history of the evolution of construction visualization to provide our research context. An overview of the proposed methodology and a review of capabilities of robotic simulation technologies is then described. A discussion of preliminary conclusions and plans for implementation of the presented conceptualization follows the methodology section.

VISUALIZATION OF CONSTRUCTION OPERATIONS

Field construction can be visualized at the activity/ schedule level and the operation/ process level (Kamat et al. 2010). Activity level visualizations are enabled by linking together the CAD objects of the work product components and the project schedule (Cleveland 1989) and have come to be known as 4D CAD. On the other hand, operation level visualizations are achieved by linking together DES models and CAD objects and comprise realistic depictions of construction operations of any duration and complexity (Kamat and Martinez 2003). Our research is set within the domain of operation level visualization of construction operations. This section describes the evolution of operation visualization techniques in construction and summarizes the limitations in the current state of the art that necessitates the approach that we have adopted in formulating the presented methodology.

Operation Level Construction Visualization. Construction visualization at the operation level was borne out of the need to validate and verify DES models in order to improve their credibility with domain experts who were not necessarily familiar with simulation technologies (Kamat and Martinez 2003). Earlier visualization methods included the use of schematic models and graphical icons which did help the modeler to debug the model (verification) but not to convey the model to a domain expert (validation). 2D visualization of DES models did succeed in both the verification and validation stages of model development, but inherently lacked the ability to produce realistic representation of complex construction operations (Kamat and Martinez 2003). Although some construction processes are amenable to being modeled and visualized by simulation systems applied in the manufacturing industry, they are unable to handle some of the aspects of construction sites that differentiate it from manufacturing, such as the change in terrain (Tucker et al. 1998).

The aforementioned lack of suitable support technologies to enable the visualization of modeled construction operations led to the development of systems such as VITASCOPE (Kamat and Martinez 2003), which was designed to be a visualization system to generate animations of simulated operations using data generated by an external process. Another example of simulation enabled visualization was the integration of 3D Studio Max with a special purpose simulation system of crane operations (Al-Hussein et al. 2006; Manrique et al. 2007). This layer of abstraction was necessitated by the authors' consideration for allowing modelers to continue using their simulation engine/authoring tool of choice and resulted in the need to convert animation commands from the DES model at discrete events to smooth dynamic animations. Also, in order to establish the generality of the animations that could be achieved with due consideration given to the breadth of construction operations, the animation statements were designed to communicate the activity being performed at the geometric transformation level of description, which is the lowest level after elemental motions, in the hierarchy of decomposition of construction operations (Bernhold 1990). This design choice was also necessitated by the fact that the animation commands were to be applied to virtual CAD models that had no inherent knowledge of their capabilities or environment (Kamat and Martinez 2005).

Necessary Consideration of Low Level Operation Details. An undesired consequence of having to generate low level animation instructions (geometric level) is the need to model the operation at a very high level of detail regardless of its necessity for the purposes of the simulation model. This work process also concerns the simulation modeler with extraneous geometric and spatial information required to produce accurate animations. Kamat and Martinez (2005) recognized these issues and developed an add-on to the VITASCOPE system that allowed for the communication of animation information at the work task level rather than the geometric transformations for multiply-articulated equipment.

The developed add-on dubbed KineMach (Kamat and Martinez 2005) exploits the technique of inverse kinematics to decompose a parameterized work task level command into the appropriate set of geometric transformations that need to be applied to the various joints of the construction equipment to achieve the required work task visualization. While this approach does reduce the amount of information communicated by the modeler, it does not relieve him of consideration of unnecessary geometric details as the CAD objects that operate in the virtual environment still lack any awareness about their functionalities and environment and need to be explicitly directed by the DES model. In their presentation of KineMach, Kamat and Martinez revealed the source of their inspiration for inverse kinematics to be the field of robotics. They also drew an analogy between robotics and virtual CAD models in how they both lack any inherent knowledge of the environment that they operate in and thus need to be explicitly directed to do so.

In our proposed methodology, we take this analogy a step further and present virtual CAD objects that can be programmed with the functionality that would allow them to intelligently perform the commands as directed by an external application/agent with due consideration of the prevailing site conditions and environment. This would allow DES modelers to communicate animation instructions to the visualizer at any level of detail so long as the virtual equipment has been pre-programmed with the capability of understanding and executing that command. We also posit that this approach could relieve the modeler from any geometric data considerations as this responsibility could also be shouldered by the intelligent equipment that is performing the task. Similarly, we contend that performance data encoded into the intelligent virtual equipment that allow it to perform activities in its virtual environment could preclude the need for the modeler to collect duration data about activities in the operation, which is one of the most time consuming, challenging, and sometimes even impossible, aspects of DES modeling.

As mentioned earlier we turn to the technology of robot simulators, motivated by our long term objective of introducing robots to construction sites, to aid in the creation of operation level visualizations of construction processes. The following section details the capabilities of robot simulators that render them the most

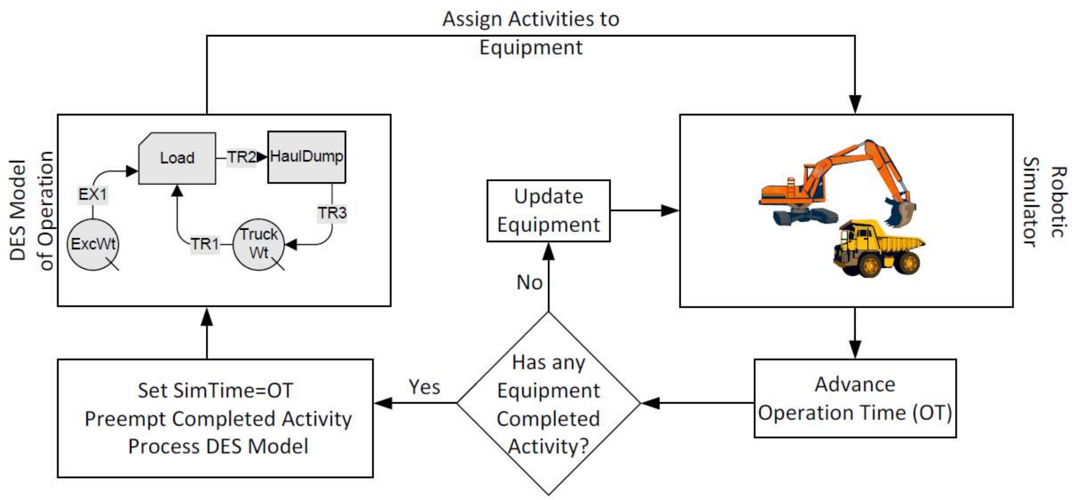

Figure 1. Proposed methodology for operation visualization

promising technology to fulfill the role of a programmable intelligent object in our proposed methodology. It can be seen from Figure 1 that the clock advance phase of the DES model is triggered by the robot simulator rather than the Future Events List (FEL), as in traditional implementations of the Activity Cycle Diagram (ACD), the modeling paradigm that is most appropriate for construction operations (Martinez and Iannou 1999). This aspect of the methodology is explained later in this section. It must be noted that while the proposed methodology is sufficiently generic to model general construction processes, it is particularly geared towards those that employ heavy equipment such as earthmoving and crane operations, etc. The fact that such operations typically involve repetitive processes make them amenable to DES modeling and visualization.

Robot Simulators for Construction Visualization. Robot simulators and simulation systems are software mechanisms that allow for the simulation and testing of robotic models, sensors, actuators, and control algorithms in a virtual environment (Staranowicz and Mariottini 2011). Their emergence stems from the proliferation of modern robotic technologies in which robots closely interact with humans (Staranowicz and Mariottini 2011). There is thus a need for robotics simulators due to their role in the adoption of new technology, potential for low cost training, and their utility in research (Craighead et al. 2007). Among the numerous robot simulation packages that have been surveyed in literature on various criteria such as physical and functional fidelity, ease of development and cost (Craighead et al. 2007; Staranowicz and Mariottini 2011), we identified the Virtual Robot Experimentation Platform (V-REP) (Freese et al. 2010) as having the greatest potential for our purposes. While a complete description of V-REP's capabilities are beyond the scope of this paper, it was selected for its extensible architecture that would allow for the development of custom robots from scratch using primitive geometric shapes, sensors, and actuators, which could be provided with the required functionality through the use of scripts. V-REP provides for the customization of almost every aspect of robot simulation and its plug-in architecture makes it ideal for interfacing with an external simulation engine, as required in our methodology.

As explained above, we intend to utilize the customizable features of V-REP to create "robots" that would serve as intelligent CAD models with the required functionality to operate in the virtual environment, under supervision from a DES model. Figure 2 provides screenshots of the construction equipment in the V-REP application that would be used in our visualization of construction operations. The next section provides a description of the methodology that would enable the synergistic combination of reusable virtual robots as construction equipment and DES model to enable the simulation and visualization of construction operations.

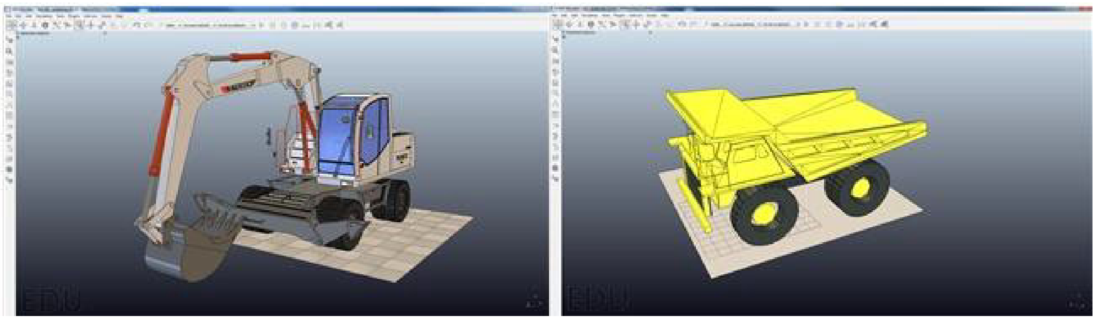

Figure 2. Screenshots of construction equipment in V-REP

Modified ACD Algorithm for DES with Robot Simulator. In our implementation of the proposed methodology, we use a modified algorithm for the DES model wherein the activities in the model do not need to have a duration specified for them. This aspect of the simulation model is controlled by the encapsulated data in the intelligent CAD models of resources that reside in the robot simulators. This design consideration frees up the modeler from having to consider equipment characteristics in the simulation model and focus rather on operation level logistics, much like a project manager on a construction site.

The modified DES algorithm initially assumes that instantiated activities run for an infinite period of time until a signal is received from the corresponding resource in the robot simulator indicating that the activity is done. Upon receipt of this signal, the particular activity instance is preempted to a stop and resources released which will initiate succeeding activities as per the logic of the simulation model. Initiated activities would then communicate the type of activity to be performed to the virtual object in the robot modeler, which will continue to update the Operation Time (OT) that indicates the time elapsed in the animation, and the virtual equipment in the operation. In this manner, the flow of control will alternate between the simulation phase (DES model) of the operation and the visualization phase (robot simulator).

Implementation of Methodology. While the proposed methodology is generic enough to be applied to any simulation engine and robot simulator packages that are designed to be extensible, our implementation of the framework is built specifically for the use of STROBOSCOPE (Martinez 1996) and V-REP (Freese et al. 2010). The interface between these two disparate technologies is implemented as a plug-in that exploits the extensible architecture of the two applications.

Since we have developed this methodology with the goal of abstracting away low level details of equipment performance from the operation modeler, it follows that this responsibility is shouldered by the model creator of the equipment within the robot simulator. It is thus necessary to ensure that there is a protocol or dictionary in place that will allow for the communication of the equipment's capabilities from its creator to the operation modeler. Currently, this will be implemented as a text document that accompanies the robot equipment model detailing the keywords to be used to instruct the equipment to perform its activities along with a description of what that activity entails. This measure would allow for the reuse of equipment models created in the robot simulator across different operation visualizations by different operation modelers. This feature is better explained by its real world analogy wherein equipment is used by different operators across projects without the project manager having to understand its internal workings.

CONCLUSIONS AND FUTURE WORK

By the methodology that we present in this paper, we seek to address some of the issues with creating operation level visualizations of construction operations that have adversely affected its adoption by the industry in spite of the numerous benefits that it offers. Specifically, our method provides a necessary layer of abstraction between the low level details of the operation that concern the performance and functionality of the operation resources and operational level logic of construction processes. This objective was achieved by encapsulating performance data and equipment characteristics within the CAD model of the object using robot simulators.

The customizable and programmable features of robot simulators allow for the creation of intelligent virtual objects to represent construction equipment visually and functionally. This capability obviates the need for the collection of duration data and geometric detail about the work environment and resources solely for the purpose of producing spatially correct visualizations. The encapsulation of the data within the virtual CAD object renders it reusable between different projects and sites as the built-in intelligence would allow for the appropriate behavior of the equipment with due consideration for prevailing site conditions.

This methodology introduces the established field of robot simulation into construction visualization, which opens the door to a host of useful features from the former into the latter. While some features of robot simulators such as inverse kinematics and collision detection have been implemented as add-ons to construction visualization systems, there is no instance of the considerations of dynamics as yet in this domain, which is now straightforward with the use of robot simulators. Lastly, this methodology fulfils our overarching goal of planning for the introduction of robots to construction sites. This framework allows for testing control mechanisms of robotic systems in virtual environments before they can be deployed on construction sites. In terms of work that is on-going in the implementation of the proposed methodology, we are building a fleet of virtual equipment in the robot simulator and developing a dictionary of actions that will allow for its use by operation modelers in DES simulation systems. A case study of an earthmoving operation using this methodology is also under way.

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