Dynamic Simulation of Construction Activities Using Real Time Field Data Collection

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Abstract. Simulation has been evolved to facilitate the process of designing, analyzing, planning and controlling of engineering processes and to aid decision-makers in setting long term project goals. Computer simulation tools thus provide an opportunity for engineers to create models that represent activities, resources, and the environment under which a project is taking place. However, such models would be more useful if they include latest project updates and changes to help engineers in short term decision-making and control, and to assist in taking immediate corrective actions. This paper presents a novel concept in construction simulation and the latest results of an ongoing research that uses dynamic data driven application simulation (DDDAS) and real time filed data collection to create live animations and self-adaptive simulations of ongoing construction projects.

1 Introduction

Operations level planning is a critical component of managing and controlling different aspects of an ongoing construction project. A comprehensive operations level plan can help project decision-makers and site personnel foresee potential problems such as spatial conflicts and resource underutilization before the actual operation takes place. This in turn will minimize the time that would have otherwise been spent on reworks, resolving conflicts, and performing change orders, and will ultimately translate into significant savings in project time and cost. Computer applications have thus evolved to facilitate the process of planning, modelling, simulating, and visualizing operations during the past several years (Halpin 1977, Paulson et al. 1987, Liu and Ioannou 1992, Oloufa 1993, Martinez and Ioannou 1994, Shi 1999, Kamat and Martinez 2003, Behzadan and Kamat 2009). In order to create reliable simulation models, one needs to carefully examine every detail of an operation and identify major events and processes that will be represented in the simulation. Once such events and processes are identified, attributes such as resource consumption levels and activity durations should be determined. For a small operation, this can be done in a relatively short time using existing numerical tools and statistical data from similar projects. However, as the size of the operation increases and with the introduction of more resources and activities, creating a simulation model that realistically represents the actual operation turns into a tedious if not an impossible task. In addition, unforeseen site conditions, equipment breakdowns, work delays, and the evolving nature of a construction project will also introduce uncertainties that may be hard to model. As a result, it is very likely that strict rules, simplifying assumptions, and rigid design parameters of traditional simulation models do not precisely reflect an actual dynamic construction operation. In this paper, a comprehensive review of recent research efforts in the area of construction simulation is presented in Section 2. In Section 3, a relatively new simulation paradigm known as Dynamic Data Driven Application Simulation (DDDAS) is introduced. Section 4 describes how this paradigm is currently used by the authors in order to dynamically simulate ongoing construction activities using real time field data. Subsequently, the validation procedure and proof-of-concept details are discussed in Section 5. Finally, a conclusion along with the directions for future work is presented in Section 6.

2 Literature Review

Application of simulation in construction has been always a popular topic in construction automation research. However, only a limited number of previous projects investigated the planning and control of engineering systems through real time simulation and interaction with the system components. In this Section, the history and previous work conducted in the field of construction simulation will be reviewed with a special focus on real time simulation.

2.1 Simulation in Construction

The introduction of CYCLONE (Halpin 1973) marked the beginning of a new era in modern construction simulation research which aimed to simplify the modelling of processes that are cyclic in nature. Subsequently, the development of INSIGHT (Paulson et al. 1987) enabled videotaping of field operations, and extracting and analyzing taped data to obtain estimated values for the productivity of the system and its components. Further studies explored the applicability of object-oriented and modular programming in developing simulation systems. Examples of such efforts include MODSIM (Oloufa 1993) and STROBOSCOPE, an extensible programmable system capable of modelling complex construction operations (Martinez and Ioannou 1994). Later, an activity-based construction modelling and simulation method called ABC was developed by Shi (1999). Using simulation-based animation, Kamat and Martinez (2004) presented VITASCOPE as a general-purpose, user-extensible 3D animation system for visualizing simulated processes in smooth, continuous, 3D virtual worlds. Behzadan and Kamat (2009) designed and implemented ARVISCOPE, an AR-based mobile visualization system that allowed dynamic visualization of simulated operations in outdoor augmented reality (AR) using an external scripting language. Among several potential methods of modelling construction operations, discrete-event simulation (DES) has gained significant credibility since almost every construction operation can be effectively broken down and modeled as a system of discrete activities each consuming resources (personnel, material, and equipment) to be completed (Martinez and Ioannou 1999). DES models provide an effective means to establish logical relationships between activities within a project which compete over and make use of available and often scarce resources. A DES system called COOPS was introduced by Liu and Ioannou (1992) which used object-oriented design for simulation. Martinez and Ioannou (1999) examined the characteristics of DES based on three characteristics: application breadth (general or special purpose), modelling paradigm (process interaction versus activity scanning), and flexibility (i.e. programmability). Also, a new simplified DES approach or SDESA was developed by Lu (2003) for planning construction operations which can be used as a general-purpose construction planning tool to track the performance of individual resources and handle cyclic or looped processes.

2.1 Real Time Simulation of Construction Projects

Traditional construction simulation involves process observation, duration and resource data collection, process modelling, process simulation to estimate productivity, and performing sensitivity analysis to suggest alternatives to improve productivity (Wang and Halpin 2004).

In a complex and evolving construction jobsite, however, data collection becomes time and labor intensive and as a result, automating the process of data collection has gained significant interest. For example, Navon and Shpatnitsky (2005) described a model that automatically collects data referring to the operation of earthmoving equipment in road construction and converts them into real time control information for project scheduling and control. Despite previous work in real time data collection and processing, very limited amount of research has been done in effectively incorporating this data into an existing simulation model for short-term planning and control of the same operation. Chung et al. (2006) suggested using Bayesian techniques to update the distributions of input parameters for tunnel simulation by manually collecting project data from a tunneling project on a bi-weekly basis and using the data to improve simulation input models. Also, Song et al. (2008) described a framework of real time simulation for short-term scheduling for heavy construction operations and developed a prototype system for asphalt hauling and paving projects.

3 Dynamic Data-Driven Application Simulation (DDDAS)

The application of the DDDAS paradigm in construction operations under evolving site conditions is investigated in the presented research. A DDDAS model dynamically measures site data in form of a new information layer and integrates the collected data with the corresponding simulation model to constantly adapt the model to the dynamics of the construction system and update it based on the latest collected operational data (NSF 2006). DDDAS enables a more accurate prediction of how a dynamic construction system behaves based on the current status of its constituents (i.e. resources). The DDDAS technique designed and implemented in this research is aimed to capture real time data from resources on a jobsite, incorporate the collected data to update the corresponding simulation model, create an exact interactive 3D visualization of ongoing operations using the collected data, and finally provide project decision-makers with a reliable means to help in short-term operations planning and control. Figure 1 is a schematic diagram showing the basic components of a DDDAS system applied to the presented research.

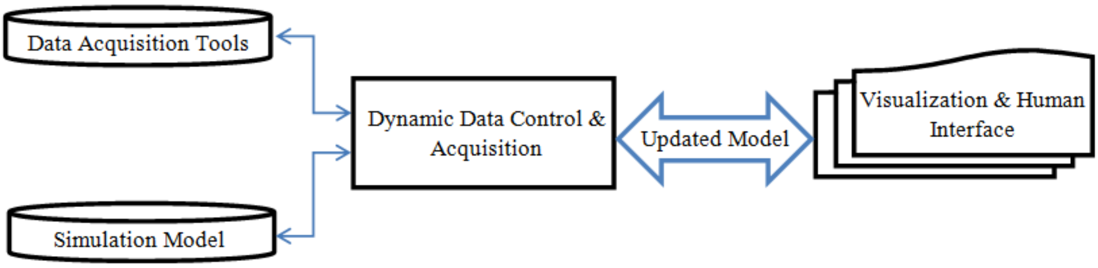


Figure 1: Basic Components of DDDAS

Major challenges to be addressed during the course of this project will include robust data collection and rapid processing, wisely updating the simulation model in order to prevent unnecessary usage of computing and networking resources, and developing methods to allow dynamic data updates during the simulation execution (Celik et al. 2010). The application of DDDAS has been previously explored in areas such as emergency management, contaminant tracking, enhanced chemical progress design, and control and advance vehicle driving assisting systems (NSF 2000, Douglas et al. 2006, Douglas et al. 2004, Darema 2005). However, to the authors' best knowledge, the potential of this simulation paradigm in improving the performance and reliability of construction simulation models has not been yet investigated which highlights the importance and high potential of research in this area.

4 Dynamic Simulation of Construction Activities

The simulation framework developed by the authors follows the system architecture shown in Figure 2. As shown in this Figure, the framework is built around the concept of DDDAS and thus, contains major components (or modules) that were previously illustrated in Figure 1. The following Subsections provide details of these framework components

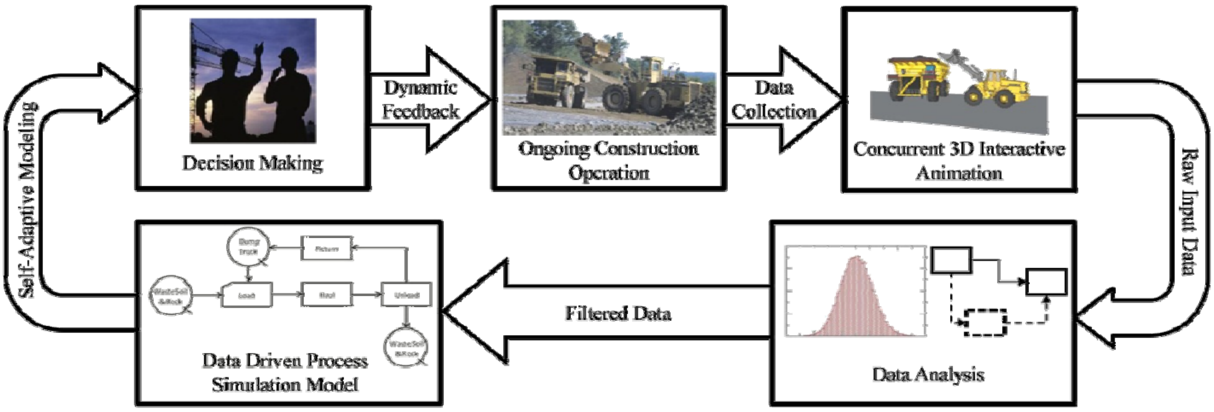


Figure 2: System Architecture of the Presented DDDAS Framework

4.1 Real Time Data Collection of Ongoing Construction Operations

As discussed earlier, dynamic simulation modelling requires real time field data collection. As a result, data acquisition is the most challenging and computing intensive part of a DDDAS simulation given the fact that it is impossible to manually collect such real time data for large projects. Real time data is used not only for updating and fine-tuning the model with the latest changes occurring in the real system, but it also serves as the basis for model validation and verification. Since the model needs to be continually updated, an uninterrupted flow of input data is needed to reflect the latest changes in the status of activities and resources. Therefore, developing and implementing a reliable an automated data collection infrastructure including sensing and communication technologies is necessary. Global Positioning System (GPS) has been previously used to track the real time position of construction equipment in large-scale operations such as earthmoving and road construction (Navon et al. 2005), and concrete and asphalt hauling and paving operation (Lu et al. 2007, Song et al. 2008). In addition to the positional data, several pieces of construction equipment including cranes, excavators, and loaders have articulated bodies and thus, collecting the orientation data for certain body parts is also essential. Such data can be acquired using 3D orientation trackers that capture three angles of rotation (i.e. yaw, pitch, and roll). In the presented research, both positional and orientation data are captured and transmitted to the system in order to simulate and animate the latest body configuration of construction equipment.

4.2 Concurrent 3D Dynamic Animation

As soon as appropriate field data is collected and transmitted to the system, concurrent 3D dynamic animation of the ongoing activities can be created. The 3D animation shows the exact movements of construction equipment and is constantly updated based on the latest data received form remote data acquisition devices. The significance of creating a live 3D visualization in addition to a DDDAS model is that it facilitates the communication of results while providing a convenient means to validate and verify the simulation model. In this research, Open Scene Graph (OSG) is used inside the .NET environment to create dynamic animations of ongoing equipment activities and to link each and every object motion inside the animation to the collected field data that represent the actual motion of that object. OSG is a set of open-source libraries that provide scene management and graphics rendering optimization functionality to applications. OSG provides an object-oriented representation of a scene which releases the user form implementing and optimizing low level graphical programming (Behzadan 2008).

4.3 Data Analysis

One of the most important components of any real time simulation system is the capability of adapting a pre-defined simulation model to the changes in the project processes (Song et al. 2008). Therefore, the simulation model should be able to detect changes in the actual process to adapt itself to the new situations on the field. This can be achieved by continually collecting time-stamped data. The major challenge in collecting a large volume of information is that data not necessarily relevant to the simulation model may also be inevitably collected and transferred. Therefore, collected data must first be filtered so only relevant and useful data is passed onto the simulation model. The process of filtering the collected data is done inside the data analysis module which acts as a middleware between the interactive animation and the simulation model. This relationship guarantees that only relevant data is transferred to the simulation model and that the simulation model is not only the receiving end of the process but also can request certain field data to be collected if needed. The filtering process includes statistical analysis algorithms to categorize the activities based on the trend of the collected data and to remove the outliers and eliminate the non-relevant data.

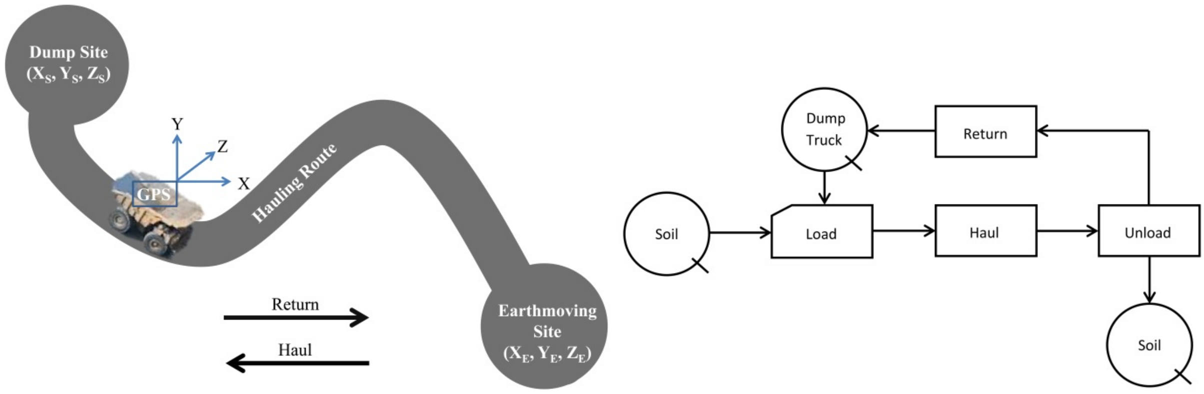
4.4 Data-Driven Simulation

Construction operations can be broken down and modelled as a system of discrete activities. Therefore, DES is the most appropriate approach among several modelling paradigms in the field of modelling construction operations. Since, collected data of an ongoing operation is time-stamped it can be linked to activity durations which can then be used inside the corresponding simulation model. For example, in an earthmoving operation a simplified layout of which is depicted in Figure 4-a, if the start and end points of a hauling route is known, GPS data (longitude, latitude and altitude) transmitted from a dump truck can be compared to the route coordinates to determine whether the dump truck is moving on the hauling route. Moreover, the duration of an instance of the hauling activity can be calculated by comparing the time stamps corresponding to when a dump truck is positioned on the start point of the hauling route and when the same dump truck reaches the end point of the route. An example of how a series of time stamps relate to different activities is shown in Table 1.

Table 1: Identifying Individual Activities within an Earthmoving Operation

Longitude or Latitude	L_{H1}	.	.	.	L_{H2}	L_{U1}	.	.	.	L_{U2}	L_{R1}	.	.	.	L_{R2}	L_{L1}	.	.	.	L_{L2}
Time Stamp	t_1	.	.	.	t_2	t_3	.	.	.	t_4	t_5	.	.	.	t_6	t_7	.	.	.	t_8
Activity	Haul					Unload					Return					Load				
Duration	$T_H=t_2-t_1$					$T_U=t_4-t_3$					$T_R=t_6-t_5$					$T_L=t_8-t_7$				

As shown in Table 1, for every activity, the duration is calculated in each simulation run. Mathematical models will then be applied to a well-populated pool of these calculated durations to determine a distribution function that best represents the duration of that activity. This distribution function is then used to describe the duration of that activity in the simulation model. A DES model of the earthmoving operation is illustrated in Figure 4-b.



(a) (b)

Figure 4: (a) Simplified Layout of an Earthmoving Operation; (b) DES Model of a Typical Earthmoving Operation

4.5 Decision-Making and Dynamic Feedback

Although the framework is designed to be self-adaptive, it is not meant to completely replace an engineer's judgment. A human decision-maker is ultimately responsible for making any modification to the model. Through this intervention, system changes and parameters defined by the self-adaptive framework could be confirmed or declined, if necessary. When necessary changes are approved, the system will be updated to reflect these changes in reality. Therefore, the real system will be refined and fine-tuned based on the output of the simulation model, as well as the insight and judgment of experts and end users.

5. Proof-of-Concept Validation

The authors are currently working on real time motion data collection from laboratory scale equipment in order to create precise 3D animations of ongoing construction activities. Figure 5 illustrates a 3D orientation tracker mounted on an excavator model.

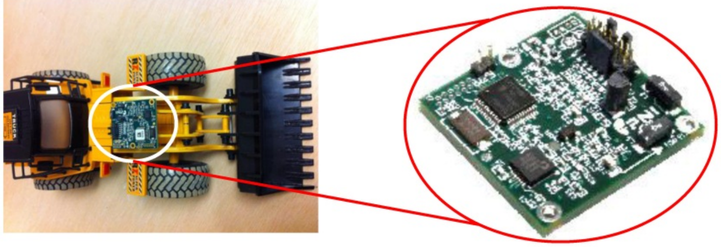


Figure 5: A 3D Orientation Tracker Mounted on an Excavator Model

The collected data was used to create animations of the model construction equipment. As shown in Figure 6, a wireless IP-accessible camera was also used to capture and transmit real time video streams of the same pieces of construction equipment. The video stream and the 3D animation are displayed side-by-side to facilitate the verification and validation processes as well as system control. Since these experiments were conducted in an indoor laboratory environment, GPS positional data were not integrated with the animation and it was assumed that equipment positions were known to the system. The authors will be conducting larger scale experiments in outdoor environments to incorporate both positional and orientation data.

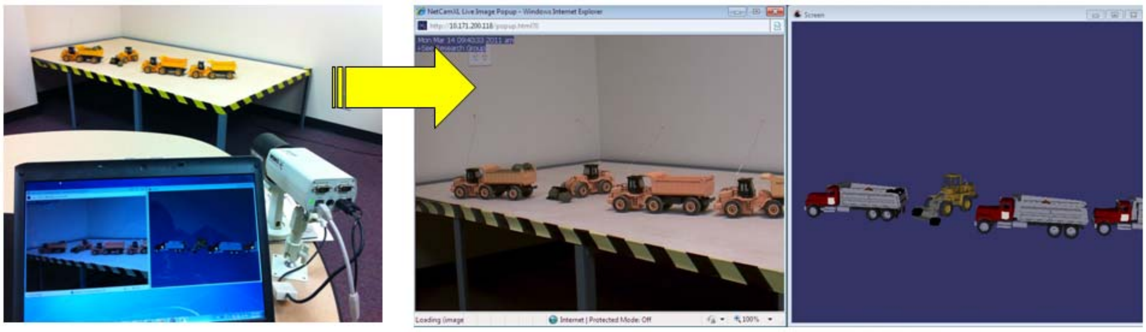


Figure 6: System Setup for Laboratory Proof-of-Concept Experiments

6. Conclusions and Future Work

Currently, most construction simulation systems use static or historical data for the purpose of early project planning and long-term scheduling. This research presented an innovative method in which data from concurrent construction processes is collected and used to build and update a simulation model in real time. Using the OSG data structure, a 3D dynamic animation was also created. Also, the relatively new simulation paradigm of DDDAS was integrated with the traditional DES to create a single decision-making framework for short-term scheduling and system control. The future work of this research will include more in-depth investigation of data collection devices, data fusion, analysis, and filtering techniques to construct self-adaptive simulation models that are responsive to the latest dynamics of a construction jobsite. Successful results of this research will have a major impact on areas such as remote construction, autonomous (self-controlled) construction vehicles, and intelligent construction and manufacturing systems.

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