Automating Construction Operations using Discrete Event Simulation Models

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ABSTRACT

The level of automation in the construction industry stands in stark contrast to other engineering industries such as automobile manufacturing wherein most of the tasks are done by machines with minimal oversight from human operators. This disparity can be attributed to the distinctive nature of construction vis-à-vis manufacturing: customized projects, uncontrolled outdoor work sites, and necessary collaboration between disparate entities. New approaches to control are required to address these challenges. This paper introduces such a novel method that enables the automation of entire construction operations by using discrete event simulation models to orchestrate and actuate robots on the construction site. It is hypothesized that the adoption of this method would enable hitherto unexperienced levels of operation productivity and quality, cost and time savings, as well as reduction in safety incidents on construction work sites. A preliminary demonstration of the orchestration of small scale electronically operated equipment models in the real world using a DES model is also presented in this paper.

INTRODUCTION

Even though the automation of construction tasks has been an active research domain since the 1970s, few actual technological innovations in construction robotics and automation have made it past the test bed stage and onto the construction site. It has even be argued that at the fundamental level, the construction process has changed little from the pre-industrial era; and this stagnation has hurt the industry in terms of productivity and quality of projects completed. Several papers (Bernhold 1987; Everett 1994; Warszawski and Navon 1998) have recognized the need to automate construction worksites in order to counter the threats of an aging workforce, unsafe conditions, declining/stagnating productivity, and huge cost and time overruns on projects. The fact that the productivity of the industry is in decline stands in stark contrast to non-farm industries, which have seen an annual increase in the labor productivity index (revenue per work hour), according to a comparison done by Teicholz in 2004. All of the above problems elicit the proposition of an overhaul of the construction process as it is being performed today by introducing the automation of construction operations.

A fully automated construction site has been described as a dream of civil engineers (Santos 2002). It remains a dream today in spite of several research attempts to introduce automation into construction. Most of these previous attempts have been inspired by the success of automation in the manufacturing industry and by adapting concepts from manufacturing into the construction context, such as Computer Integrated Manufacturing (CIM) to Computer Integrated Construction (CIC), etc. It is still thus judicious to juxtapose construction and manufacturing to identify some of the key differences that have proven critical in the failure of
automation to catch on in construction. The prime distinctions between the two industries can be summarized thus: Every construction project is unique, unlike the engineered products in manufacturing. Construction happens in an uncontrolled outdoor environment as opposed to a typically enclosed and closely controlled factory setting, which renders the planning for construction projects to be fraught with uncertainty and makes the worksite itself difficult to manage. The fact that construction is usually spread over a great area involving the movement of large quantities of materials requires the oftentimes remote collaboration of multiple disparate resource entities to get work done, which is different from an assembly line setting wherein the raw materials are engineered by a series of local resources (machines) until completion. The above distinctions need to be considered and overcome for the successful automation of construction operations. While it has often been the aim of researchers to robotize construction tasks, we propose that it is the automation of construction operations that will pave the way for the widespread adoption of such robotization on the site.

It can be seen that a methodology that seeks to achieve construction site automation would need to address certain challenges that have rendered previous research attempts toward the same goal unsuitable. We postulate that any such methodology ought to be developed uniquely from scratch for construction, rather than by adopting concepts from other industries and adapting them to construction. Such a methodology would have to factor in the technical and structural challenges that typify the construction work site. There are three primary challenges to be considered in the development of such a methodology: (1) to factor in the uncertainty that is inevitable in construction processes in terms of amounts of materials, availability of resources, duration of activities, etc.; (2) to allow for the collaboration of different resources and equipment that may interact according to a number of context sensitive rules and circumstances; (3) to allow for the ability to represent and perform an unlimited number of scenarios of an operation and indeed an unlimited number and variety of operations, as each construction project and operation is unique.

It is with these issues in mind that we introduce our framework for the automation of construction operations. We propose the use of modified Discrete Event Simulation (DES) models to orchestrate automated construction equipment on worksites to perform construction operations. Our method is inspired by the fact that simulation, and DES in particular, has been established and proven to be the most effective tool for modeling and analyzing construction operations (Martinez and Ioannou 1999). This assertion has been made in the light of its application breadth, modeling paradigm, and flexibility that make it the most suited for the modeling of construction operations (Martinez and Ioannou 1999). The methodology developed in our research effort uses the power and flexibility of DES models in an unprecedented manner to actually perform construction on the construction site. The proposed framework uses STROBOSCOPE (Martinez 1996), an extensible general purpose simulation system specifically designed to model construction operations (Martinez and Ioannou 1994). The attributes of STROBOSCOPE that make it particularly suited to our goal are that it enables the consideration of uncertainty in any aspect (not just time); it combines and allocates resources and control of the activation tasks by subjecting them to complex logical conditions; and it can be used to model any construction operation by virtue of being a general purpose simulation system (Martinez and Ioannou 1994). In addition to the modeling and analysis of construction operations, STROBOSCOPE has been used extensively to validate complex construction simulation models using 3D visualization (Kamat and Martinez 2003) and to create virtual environments where domain experts in construction can interact with and challenge simulations (Rekapalli 2008).
through concurrent simulation animations. We believe that our proposed methodology is a natural, yet radical, extension of the capabilities of construction simulation systems in general and STROBOSCOPE in particular by breaking out from the virtual world into the real world.

To underscore the novelty of our approach, a brief history of automation attempts in the construction industry is provided which is then followed by an overview and description of the methodology developed. A proof-of-concept technical demonstration of the feasibility of the methodology is then described, followed by a delineation of the potential research contributions, limitations of the demonstration and plan for future work.

PRIOR WORK IN CONSTRUCTION AUTOMATION

It has been established that the application of automation technology and information technology is essential to the continued growth and survival of the construction industry. A review of existing literature on the subject reveals how construction automation and robotics is seen to be the answer to numerous problems that the industry is facing. This section traces the history of attempts to automate construction operations, starting with the promise that was seen for construction automation from the late 1970s up to the present day, wherein the focus has shifted from actual robots being used on site to soft robotics that encompasses software integration, simulation and VR, sensory based monitoring and tracking, etc.

Early Promise of Robotics in Construction

The potential for applying robotics and automation to the construction industry was very well established by the 1980s, as evidenced by the following quotes by Albus (1981): “From the standpoint of creating wealth and increasing the standard of living, the introduction of robotics into the construction industry is extremely important.”; and by Whittaker (1985): “Construction is a ripe, virtually untouched and inevitable arena for robotic applications. Representing six to ten percent of the Gross National Product, construction dwarfs manufacturing and other industries that have successfully embraced simpler, deterministic automation.” In a study on the potential for automation and robotics in construction, Bernhold (1987) concluded that even though there are a lot of institutional barriers to their introduction, related to the fragmented and unstructured nature of the industry, there exists the prospect for restructuring the approach to construction during both the design and construction phases to allow for the easier diffusion of automation technologies into construction.

Taking a leaf from the success in manufacturing in implementing the concepts of repetition and standardization that led to automation and mass production, Bernhold points the reader to Halpin and Woodhead’s (1976) organization of construction management into a 6-tier hierarchy consisting of the levels of organization, project, activity, operation, process and work task; the last three levels of which are very related to the cyclic sequence of work tasks, a characteristic that could be exploited while planning for automation in construction. Strategies for identifying the needs and potential of introducing automation and robotics are prescribed both from a top-down and bottom-up approach that relates to the economic importance and operational characteristics of the operation or task being considered, respectively.

Bernhold (1987) recognized the evolutionary nature of construction processes and described two methods to introduce high technology into the field: adaptation of high technology into traditional processes; and redesign of traditional methods. It is noted that merely automating tasks as currently done, while easier to implement in the field, would result in the loss of great opportunities for the industry to rethink traditional processes as they have been performed by
humans to date. This point is directly related to Skibniewski’s (1992) observation while analyzing the initial American approach to construction applications of robotics - that most prototypes of robots were made to simply mimic the actions of humans in unstructured job environments - neglected the need to restructure the jobsite to accommodate new processes.

**Manufacturing to Construction**

One of the foremost tactics put forth to facilitate the automation of construction operations was the introduction of automation concepts that had found widespread acceptance in the manufacturing industry. Sanvido and Medeiros (1990) performed a comparison of the two industries to identify potential areas for the cross-fertilization of concepts and concluded that the similarities between the two industries outweigh the differences and thus define a strategy for implementation of successful integrative manufacturing tools and concepts, such as Computer Integrated Manufacturing (CIM), in construction as Computer Integrated Construction (CIC). Miyatake and Kangari (1993) define CIC as “a strategy, incorporating computers and robotics, for linking existing technology and people in order to optimize business activity.” They noted that there is no standard formula for CIC and that each company must formulate its own system for implementing CIC, but do mention that CIC usually results from an integrated information flow; the widespread application of computers; and high levels of automation. They described a system for the implementation of CIC in a company that is divided into the following three major areas: 1) integrated design/construction planning, 2) site-automation system, and 3) factory automation which was used to implement CIC in a prototype construction system called the SMART system (Shimizu Manufacturing system by Advanced Robotics Technology) in Japan. The SMART system, when applied to an office building project in Japan (Miyatake and Kangari, 1993) is purported to have reduced labor by a total of 30%, which is perhaps the most successful implementation of CIC in a real project, although it has not been repeated. In addition to the high implementation cost of the SMART system, possible explanations for this attempt at CIC not being repeated might be the fact that the systems and technologies developed were only applicable to a narrow class of high rise building projects and the system was not fully automated.

A more recent example of applying a manufacturing concept into construction is the introduction of 3D printing on construction sites, of which one of the foremost examples is the Contour Crafting method proposed by Khoshnevis (2004) that uses additive manufacturing methods to “print” houses. While it greatly reduces the cost and time to build dwellings using in-situ resources without compromising on the flexibility of design like traditional manufactured houses, it is not generic enough to be applied to a class of construction activities other than that of raising the shells of buildings. All these manufacturing-inspired research efforts, which have not yet solved the problem of scant automation in construction, echo the conclusions of Everett (1994) that construction needs to develop its own strategies for automation rather than copy them from manufacturing as they are fundamentally different in the relationships among product design, process design, and fabrication.

**Current State of the Art in Construction Automation**

In spite of the development of several prototype construction robots (Kangari and Yoshida 1990, Skibniewski 1992) and the introduction of CIC etc., the world has yet to witness a huge change in the way the construction industry operates. Warsawzki and Navon (1998) lamented the failure of the diffusion of robotics in the 1990s in spite of early promising research
efforts and cited the following reasons to be its cause: then-current building and construction practices were not amenable to being performed by robots; insufficient development of construction robots to deal with site conditions; the lack of economic justification for construction robots; and the managerial environment in the construction industry. This sentiment was shared by Balaguer (2000) who concluded that the industry still operated by the same philosophy as from the pre-industrial era, the only major advancements being the use of motors to apply force and the replacement of human and animal power with machines to do the same work while manual control, visual feedback, human operators, etc. still played a central role in construction. Even though these observations were made more than a decade ago, we allege that this characterization still applies to the construction industry today. Balaguer also noted that most of the successes of CIC were limited to the implementation of IT practices in construction in the design stages and not in the production and construction stages.

This general trend towards the softer side of robotics and automation is reflected in the findings of Son et al. (2010), who attempted to describe the global trends in research and development of automation and robotics in the construction industry by analyzing International Symposium on Automation and Robotics in Construction (ISARC) papers of the last 2 decades. It was found that the percentage of papers categorized under “Construction Robotics” declined from 71% in 1990 to 33% in 2008, which stands in contrast to all of the other categories, which have all seemed to attract a larger research focus during the same period. Thus, it is evident that there is a need for a fresh look at the automation of construction sites to fulfill the vision of early pioneers and realize the dream of a fully automated construction worksite.

PROPOSED METHODOLOGY

We propose a synergistic combination of DES and autonomous construction robots in our methodology to automate construction operations. DES has been an established technology that has proven to be of significant utility in planning, analyzing, and visualizing scenarios in construction engineering. However, it has not been used for the control of automated construction operations. In light of the three primary challenges noted in the introduction to this paper, we are confident that this methodology will enable the automation of any construction operation that can be represented by a DES model and whose individual activities can be performed by autonomous robots. Our use of the term robots refers to machines equipped with the capability to receive instructions, perform tasks accordingly, and communicate its work status back to the operations controller. A description of the methodology is provided in the following section, followed by a description of a technology demonstration that constitutes a step towards the development and implementation of the proposed methodology.

Concurrent simulation and automation of construction operation

In the proposed methodology, construction operations are automated by enabling a concurrent simulation and automation (or simulation-automation) wherein a DES model orchestrates autonomous robots on the construction site. The concurrency of the model ensures that it advances its state only after the robots communicate back to the model that they have completed the previously assigned task. This allows for the factoring of uncertainties in activity duration and other unforeseen events into the DES model. The autonomous robots are required to have the capability of communicating with a central computer system that acts as the command center.
For example, in order to completely automate an earthmoving operation, we would require a discrete event simulation model of the operation itself, which can be created in a DES modeling environment such as STROBOSCOPE, and robots to perform the excavators’ and dumptrucks’ roles in the operation. An autonomous excavator, such as the Autonomous Loading System (ALS) described by Santos (2002), and an autonomous dumptruck similar to the Caterpillar mining truck (Caterpillar 2014).

A conceptual design of the methodology that enables the simulation-automation of construction operations is provided in Figure 1. It can be seen here that the red arrows indicate commands issued from the model to the robots and the green arrows represent the feedback from the robots to the command center. This communication structure facilitates the robots in the field telling the command center when they are finished with the activity last assigned to them; upon which, the command center will update the state of the simulation model in STROBOSCOPE and relay any resulting commands to the robots.

![Figure 1. Conceptual design of simulation-automation](image)

It is important to note that this framework does not require a priori knowledge of the activity durations, which is a necessity for traditional DES models that are used to analyze operations, but which is however impossible to obtain and implement when using the model to automate the operation. This aspect of the methodology factors in the uncertainty with which the construction environment is usually fraught, rendering the framework applicable to real world construction operations. It is postulated that this approach to performing construction is a radical change from the current state of practice and would pave the way for an unprecedented adoption of automation technologies on the construction worksite as well as increase the use of modeling techniques in the planning and monitoring stages of construction projects.

**Development Step: Trace File Driven Automation**

In order to confirm the technical feasibility of the proposed technology, a demonstration to link a DES model and robots was conducted. This consisted of demonstrating a particular facet of the proposed methodology and was performed as a development step towards the realization of the complete framework. The first development step consisted of enabling construction automation under very controlled conditions (i.e., minimal uncertainty) by using a traditional DES model whose activities have pre-determined durations to automate an operation, a goal we achieved by the use of a trace file generated by a DES model to coordinate the actions
of the robots. The rationale for the development of this step was inspired by the development history of the concurrent simulation and visualization engine VITASCOPE++ (Rekapalli 2008), which was built upon the visualization capabilities of a trace file driven animation engine VITASCOPE (Kamat 2003). The conceptual framework achieved in this development step is shown in Figure 2. STROBOSCOPE can be instrumented to write out trace ASCII commands to a text file during the startup of activities with the following three details: identification of the robot that represents the equipment to which the command is sent, the simulation timestamp when the activity starts, and the duration of the activity. When the simulation is complete, a control center establishes communication with all the robotic equipment involved in the operation, after which the trace file is parsed and commands are sent to the robots to perform specific, pre-programmed activities. The robots performing these activities in a timely manner according the operational logic of the DES model allows for the correct and autonomous performance of the operation.

![Conceptual design trace file driven automation](image)

As noted earlier, this development step assumes that the time taken to actually perform the activity in the real world is congruent with the time duration that is used for its respective activity in the simulation model. While this shortcoming in the framework renders it unsuitable for any real world implementation other than extremely controlled settings, it was nevertheless an important step towards proving the feasibility of using DES models to coordinate and actuate robots temporally in the real world to perform operations.

**Demonstration of Development Step**

In a technical demonstration of this development step of the proposed methodology, an “earth” moving operation was simulated and performed using a scaled down set of robot models of an excavator and dumptruck, which can be seen in Figure 3. The earth itself was represented using lightweight packing peanuts. A layout of the test site is provided in Figure 4.
The robots were pre-programmed, enabled to perform the following actions and also provided with the capability of receiving commands remotely from a desktop computer:

Excavator: Load bucket, Swing loaded bucket towards truck, Dump bucket, Swing empty
Dumptruck: Haul earth to dumpsite, Dump earth, Return to loadsite

The durations of these activities in the model were congruent to the durations that the robots would take to perform the respective activities. This was done by ensuring that the respective actuators on the robots were run for the required amount of time (specified as activity durations in the model). The simulation-operation occurred as planned and represented in the STROBOSCOPE model. The “earth” was loaded into the truck using three passes of the excavator and the truck backed up all the way to the dumpsite where the earth then was dumped, after which the truck traveled back to the loadsite to repeat the cycle. As expected and noted, any disruption to the truck’s travel irrevocably ruins the coordination between the excavator and truck according to the model. However, the aim of this test was merely to demonstrate the ability to generate commands from a DES model that could be communicated to robots in the real world in order to orchestrate their functions.

CONTRIBUTIONS AND FUTURE WORK

This research effort makes a fresh attempt at fulfilling the dream of a fully automated construction site. The proposed methodology uses DES in an unprecedented way to actuate robots in the real world. Such a system allows for the transfer the results of a computer model into the real world without the need for human operatives to interpret the results of the model. The proposed methodology allows different and disparate construction automation technologies to work together to achieve the operational objective. We believe that this will accelerate the adoption of robots on construction sites and is a step forward in the current state-of-the-art by moving from the automation of tasks to the automation of operations.

The fact that the concept employs a general purpose simulation engine to drive operations ensures that this technology is generic enough to be applied to any repetitive construction process. Apart from the obvious benefits of construction automation in terms of a project’s safety, cost, duration and quality, the proposed methodology would also help to diffuse a more analytic approach to the planning of construction projects within the industry by making the modeling of operations using proven scientific tools and methods and analysis an inevitable necessity in the project delivery process.
Future work will first involve the use of a modified DES processing algorithm that will allow for its use as a true control mechanism. This modified DES model will not require durations of the activity instances to be known a-priori, but will rather depend upon the robots to inform the control system when the assigned activity is completed. This important change in the methodology factors in the uncertainty that is inherent in construction and is key to realizing the proposed framework for the use of DES to automate construction operations.

Also, we are developing on-board intelligence for the robots as well as providing the capabilities of two-way communication between the robots and command center to enable the complete implementation of the proposed methodology. We are also in the process of testing the framework with a more robust and sophisticated set of robots with superior automated guidance and navigation capabilities, material handling capabilities, and greater suitability for less structured environments.

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