Modified Discrete Event Simulation Algorithm for Control of Automated Construction Operations

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Abstract -

Few robots are found on the worksite today and the construction process has remained unchanged since pre-industrial times, the only major advancement being the replacement of human and animal power with motors, despite research efforts in construction automation. Contrarily, the planning stages of projects have benefited from advances in simulation and modeling technologies. We propose a mechanism for leveraging information rich models to automate construction operations by using Discrete Event Simulation (DES) models of operations to drive the process in the real world using autonomous robots. This endeavour requires a new method to process DES models as they are currently used for the fundamentally different task of analyzing operations. Technically, this method is necessitated by the fact that activity durations are not known a-priori when the DES model is controlling a real world operation. We put forth a novel algorithm for processing DES that enables construction automation. Our lack of prior knowledge of activity durations are accounted for by assuming that initiated activities continue until pre-empted to a stop by communication from the autonomous robot performing it. The primary contribution of our presented research is enabling the unprecedented use of DES models for construction automation. This approach allows for the automation of any construction operation, given the application breadth of DES. This modeling approach also enables new construction visualization techniques with the use of robot simulators that free up the operation modeler from consideration of low level equipment and geometric details and from the collection of activity duration data.

Keywords -

Automation and Control, Simulation, Robots, Construction Operations

1 Introduction

The level of automation in the construction industry stands in stark contrast to other engineering industries wherein most tasks are performed by machines with minimal oversight from human operatives. Several papers [1, 2, 3] 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. Tiecholz [4], in his comparison of productivities across industries, concluded that the construction industry labor productivity index is in decline, as opposed to an annual increase of the same in other non-farm industries. All of the above problems elicit the proposition of an overhaul of the construction process as it is being performed today by introducing the notion of automating construction operations as opposed to construction tasks.

A fully automated construction site 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 thereby adapting concepts from manufacturing into the construction context, such as Computer Integrated Manufacturing (CIM) to Computer Integrated Construction (CIC), etc. However, a judicious juxtaposition of construction and manufacturing reveals the following key differences that have proven critical in the failure of automation to catch on in construction: Every construction project is unique, unlike the engineered products in manufacturing. Construction generally happens in an uncontrolled outdoor environment as opposed to a controlled factory setting, which renders the planning for construction projects to be fraught with uncertainty and makes the worksite itself difficult to control. The fact that construction is usually spread over a great area involving the movement of large quantities of materials, equipment, and labor resources 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 in turn by a series of local resources (machines) until completion.

It is with these issues in mind that we developed a framework for construction automation that uses the power and flexibility of Discrete Event Simulation (DES) models to orchestrate autonomous construction equipment on worksites to perform construction operations, as shown in Figure 1. Our method is inspired by the fact that DES has been established to be the most effective tool for modeling and analyzing construction operations [5]. It can be seen in the figure that the solid arrows indicate commands issued from the model to the robots and the dashed arrows represent the feedback from the robots to the DES-based command center. This framework facilitates the communication between robots and the DES model, which allows for the timely advancement of the operation based on the model's operational logic dependent on the communication received from the robots.

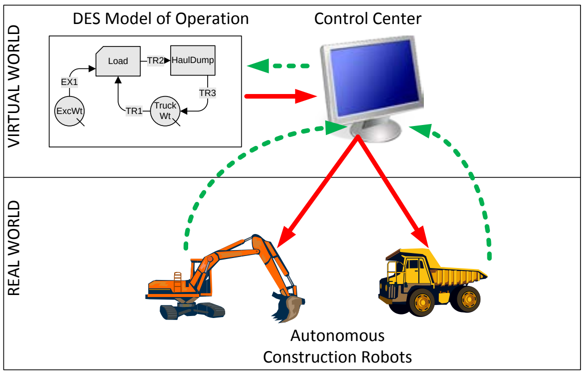

Figure 1. Conceptual design of DES orchestrated worksite automation

However, DES models have hitherto been used only for the analysis and design of operations and never as a control system for construction operations. Thus, a new mode of processing DES models is required in order for them to be able to control an operation in the real world. The technical reason required for this modification is the fact that DES models for analysis require the duration of activities to be input into the system a-priori, i.e. before the activity occurs in the simulation. However, it is impossible to know the duration of any construction activity in the real world until after it has happened due to the prevalent uncertainty in worksites. In this paper, we present a novel methodology that allows for the use of DES models as control mechanisms to enable the automation of complete construction operations. The key challenge addressed by the presented framework is obviating the need for a-priori duration data. We anticipate our methodology to be a prime enabler for our overarching goal of realizing automated construction sites (or major operations therein) using the framework illustrated in Figure 1 that marries the power and flexibility of DES modeling with the burgeoning sophistication of autonomous equipment. We also believe that the envisioned DES processing algorithm will enable novel methods for the simulation and visualization of construction operations by alleviating the modeler from concern over low level equipment and geometric details of the worksite, thereby allowing for faster model development and focus on operation level design.

An overview of construction automation attempts is provided in this paper to highlight its challenging nature. The use of DES in the construction context is also discussed to underscore the novelty of our approach, which is then described along with its applications. The final section of this paper contains a delineation of expected research contributions and plan for future work.

2 Background

This section details the research efforts that have aimed to introduce automation into the construction work site. A review of the use and state of the art of DES models in analyzing construction operations is also provided to set the context within which our methodology is presented.

2.1 Automation in Construction

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. Two dominant themes that have characterized prior research efforts are discussed here to provide an overview of the state of automation efforts in construction: 1) The idea that concepts that were successful in implementing automation in the manufacturing sector could be translated into the construction industry; 2) The notable shift of research focus from robotics and automation to "soft robotics" that encompasses software integration, simulation and VR, sensory based monitoring and tracking, etc.

2.1.1 Manufacturing to Construction

In a study on the potential for automation and robotics in construction, Bernhold [1] concluded that even though there are a lot of institutional barriers related to the fragmented and unstructured nature of the construction 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. Bernhold referred his readers to Halpin and Woodhead's [6] 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 amenable to the concepts of repetition and standardization that led to automation and mass production in manufacturing.

Sanvido and Medeiros [7] 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 defined 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 [8] defined 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 they did mention that CIC usually results from an integrated information flow, the widespread application of computers, and high levels of automation. They described a prototype construction system called the SMART system (Shimizu Manufacturing system by Advanced Robotics Technology) in Japan that implemented CIC by focusing on three major areas: 1) integrated design/construction planning, 2) site-automation system, and 3) factory automation; which when applied to an office building project in Japan in 1994 was purported to have reduced labor by a total of 30%, although it has not been repeated since. Possible explanations for this attempt at CIC not being repeated are its high implementation cost, the fact that the technologies developed were only applicable to a narrow class of high rise building projects, and that 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 [9] 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 automation in construction, echo the conclusions of Everett and Slocum [2] 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.

2.1.2 Current State of the Art and Trends in Construction Automation

In spite of the development of several prototype construction robots [3] [10] 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 [3] 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: current building and construction practices not being amenable to performance by robots; insufficient development of construction robots to deal with site conditions; the lack of economic justification of robots; and the managerial environment in the construction industry. This sentiment was shared by Balaguer [11] who concluded that the industry still operates 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 play a vital role in construction. 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. [12] 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 seemed to attract a larger research focus during the same period.

It is with due regard to the trends described above that we present our methodology. Specifically, we ensure that our proposed framework is developed for construction with due consideration for the uncertainty, diversity, and complexity of its operations. By using DES, our method exploits the sophistication achieved in modeling and simulation tools as a result of the focus of recent research. The next section describes the application of DES in construction and the current DES processing algorithm, which would serve to provide the background for our framework.

2.2 Discrete Event Simulation in Construction

Personnel involved in the design of construction operations are expected to make decisions about the complex processes which may involve several decision alternatives, each of which is associated with its own expected outcome, which can be estimated using either real world experimentation, mathematical modeling, or simulation, which involves imitating the system under study. Martinez [13] noted that of the three techniques mentioned above, simulation is the most convenient, as it is both realistic (as opposed to mathematical modeling) and inexpensive, fast and flexible (versus real world experimentation). Discrete Event Simulation (DES), a type of simulation wherein the state of the system changes at discrete points of time marked by events per the DES model, is very effective at modeling construction processes [13].

2.2.1 DES for Analysis of Construction Operations

Applications for the simulation of systems follow two main simulation strategies: process interaction (PI) and activity scanning (AS). Event scanning (ES), a third approach is often used in conjunction with either PI or AS. Martinez and Ioannou [5], in their comparison of the two dominant strategies, establish that AS models, built from the perspective of activities in the operation, are more suited to modeling construction operations than PI models which are created from the perspective of the resources that flow through the system. The authors note that PI modeling is more suited to systems wherein resources that flow through the system have many differentiating attributes as opposed to stationary entities that serve them; a situation characteristic of manufacturing and industrial systems. On the other hand, construction operations involve heavy interaction between machines that can have many attributes and be in several states, which justifies the focus on activities rather than on differentiating resources as either flowing or stationary.

Three-Phase AS is a hybrid strategy that optimizes the performance of AS by combining it with ES. Three-Phase AS is represented at the conceptual level by a network of activities and queues that make up the operation called Activity Cycle Diagrams (ACDs). Figure 2 shows the method for processing Three-Phase AS models.

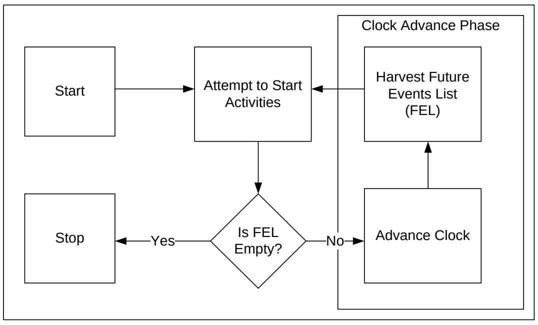

Figure 2: Traditional Discrete Event Simulation Loop for Construction Simulation [13]

In Figure 2, the Future Events List (FEL) refers to a list of activity instances that have already been started, that are arranged in ascending order of their end times. In the Clock Advance Phase, the clock is advanced to the time of the activity that is ending the soonest, before that activity can be harvested (or ended) in the FEL. Thus it can be seen that the durations of activities must be known before the activity ends, which is an impossibility in real world operations.

2.2.2 DES Enabled Operation Visualization

Construction visualization at the operations level displays DES-generated animations of the resources on a work site as they build a product or perform a support service [14] and was borne of the need to verify and validate DES models. While initial implementations including VITASCOPE [15] completely separated the generating process (eg. DES model) from the visualizer, a later advancement in the art of visualizing construction so as to enable user interactivity with the underlying DES model, known as DES-Based-Virtual Reality (VR) [16], is of particular interest to our research goals. This interest is due to the fact that the interactivity could only be achieved if the simulation ran concurrently with the visualization, and allowed for unplanned changes in the underlying DES model due to user interaction.

While a complete description of DES-based-VR is beyond the scope of this paper, Figure 3 depicts the conceptual time advance algorithm that allowed for the synergistic combination of DES and animation to enable user interactivity.

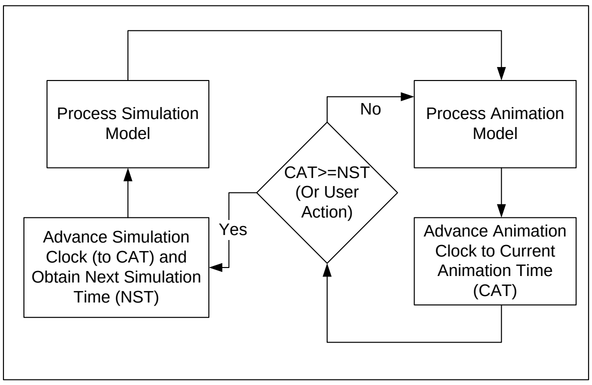

Figure 3: Conceptual Time Advance Algorithm for DES-Based-VR [16]

In Figure 3, it can be seen that while the duration of activities is still required to be known a-priori in order for the regular processing of the simulation model, there is an element of uncertainty in the user interactions that are unforeseeable. Rekapalli [16], in his implementation of the incorporation of user interaction affected the model by preempting the relevant activity to a stop. As will be seen in Section 3, we borrow of the concepts that are used in enabling concurrent simulation visualization in enabling the DES model to be used as a control mechanism of real world construction operations and in enabling a novel paradigm of construction visualization using robot simulators.

3 Proposed Methodology

This section provides a conceptual overview and plan of implementation for the modified DES processing algorithm to be used as a control mechanism for the automation of construction operations. The proposed methodology is explained by revisiting the traditional method for processing Three-Phase AS models. In addition to the goal of construction automation, we also describe the plan for implementation to enable a new mode of construction simulation and visualization.

The primary assumption made in the development of our methodology is the availability of entities that are capable of communicating with the DES model. These “entities”, that could be robots in the real world or virtual objects, are assumed to be able to receive commands from the DES models to start doing a specific pre-programmed activity and to be able to communicate their status back to the DES model when the activity assigned is completed.

3.1 Conceptual Overview

In order to use DES models as control mechanisms to orchestrate autonomous robots to automate construction operations, it is necessary to account for the lack of a-priori information regarding the activity durations, which is a primary input for DES models. For a conventional DES, each activity’s duration is required to be known to ascertain end times of each activity instance, which determines its place in the Future Events List (FEL), subsequently driving the advancement of the simulation model as shown in Figure 2. In order to compensate for the lack of a-priori knowledge of activity durations in our control scheme, we propose the modified DES processing algorithm which is presented in Figure 4.

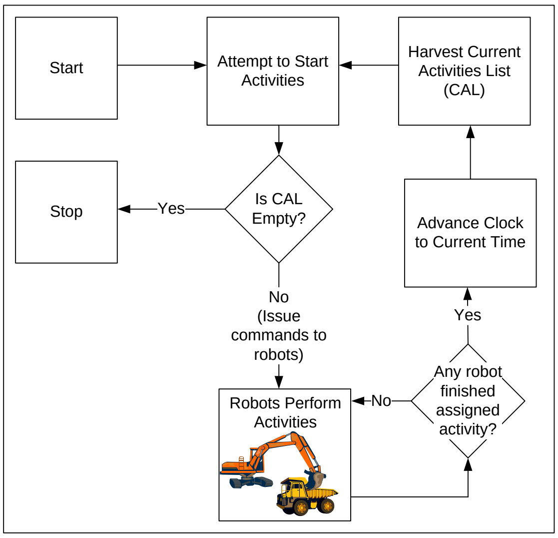

Figure 4: Modified Discrete Event Simulation Loop for Construction Automation

As can be observed from Figure 4, a Current Activities List (CAL) replaces the FEL from the traditional implementation shown in Figure 2. The CAL contains an unordered list of all activities that have been started and are being performed by robots on the construction site. The activity items in the CAL contain only their starting time and not their end time. The clock advance will thus happen only when any of the robots on the work site complete their assigned activity, upon which the clock is advanced to the current time, and the corresponding activity from the CAL is harvested and forced to a stop in the DES model. Subsequent activities may be triggered by the end of one activity as per the model logic, which in turn may trigger robots on the worksite to perform more activities, until the CAL is empty.

We believe that this approach exploits the power and flexibility of existing DES modeling tools for the control of multiple robots on the work site to perform complex operations. The algorithm modification described above to account for the fact that no a-priori information is available about activity durations allows for the incorporation of duration uncertainty in our approach.

3.2 Methodology Implementation

We present the following two strategies for implementing the modified DES algorithm to enable construction automation and visualization respectively. Both of the implementations described use STROBOSCOPE [14], an extensible general purpose simulation system specifically designed to model construction operations. The attributes of STROBOSCOPE that make it particularly suited to our goal are: its consideration of uncertainty in any aspect (not just time); its combination and allocation of resources and control of the activation tasks by subjecting them to complex logical conditions; and its usefulness to model any construction operation by virtue of being a general purpose simulation system [14]. The extensibility of the capabilities of STROBOSCOPE through the use of add-ons makes it particularly amenable to our efforts at implementing the presented methodologies.

3.2.1 Construction Automation

In our methodology, construction operations are automated in the real world by enabling a concurrent simulation and automation (or *simulation-automation*) wherein a DES model orchestrates autonomous robots on the construction site as per the framework described in Figures 1 and 2. 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, thus incorporating the uncertainties in activity durations when performed by robots. Other events that could disrupt the regular operation can be dealt with by accounting for the same in the DES model, as long as the robots in the field can effectively communicate the occurrence of such irregularities to the model.

3.2.2 Construction Visualization

As stated above, construction visualization was borne of the need to verify and validate DES models. Animating simulated construction operations suffers from the following limitations that places additional burden on the operation modeler: Animation instructions from the DES model need to be communicated at a very high level of detail that may not be relevant to the purpose of the model from a decision making perspective; operation modelers need to concern themselves with geometric detail, mostly irrelevant in DES analysis, to create spatially correct and convincing visualizations [17]. The collection of duration data to input to DES models is also a very time consuming and sometimes impossible process, for activities that have not yet been performed in the real world that need to be simulated. The paradigm for simulating and visualizing operations described in this section is necessitated by the fact that conventional visualization techniques for verifying and validating DES models are not applicable to the modified DES processing algorithm, and this paradigm has the potential to overcome the limitations of conventional visualization systems described above.

We propose to replace the use of traditional virtual CAD models in 3d operations visualization with models in robot simulators [18, 19], a measure that allows for the encapsulation of all of the low level information regarding the equipment's performance within its virtual model. Our methodology for visualization and simulation uses a hybrid approach wherein the modified DES control model of the operation is used to direct virtual equipment in the robot simulator (as per Figure 1). The virtual equipment would perform the tasks required in the operation according to their programed and encapsulated functionality, thus freeing up the modeler from animation modeling to focus on operation level modeling. Sensing capabilities on the virtual 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. While this 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 [13] and the Virtual Robot Experimental Platform (V-REP) [18]. The methodology provides a more accessible means to create construction visualizations, and at the same time, constitutes a means to develop and test the modified algorithm for DES-based control of construction operations as we propose.

4 Contributions and Future Work

The algorithm described herein for the processing of DES models to enable their use as control mechanisms enables a fresh attempt at the automation of construction operations. We contend that our methodology allows for the unprecedented use of the power and flexibility of information rich DES models to automate *any* construction operation. The primary challenge that was tackled here in enabling the transition of a DES model from analysis and planning to control mechanism was obviating the need for a-priori information regarding the performance of activities, namely durations. Instead, the resulting concurrency of the DES model and the real world operation are enabled by the use of communications from autonomous robots to advance the state of the DES model instead.

We believe that this approach to automation pays due consideration to the dominant trends that have characterized research efforts in automating construction: 1) by developing a methodology that considers the challenges of unpredictability, specificity of projects, and complex processes, that are characteristic and inherent to the construction industry; and 2) by leveraging the sophistication of modeling techniques that benefitted from research focus in the construction context. The presented approach is generic enough to be applied to a wide class of processes that can be suitably modeled using DES. The automation of entire operations also eludes the problem of islands of automation that has been characteristic of past efforts of task automation.

We also contend that the use of the modified DES algorithm in conjunction with robot simulators for the validation and verification purposes of the control mechanism presents a new approach to the simulation and visualization of construction processes that has numerous benefits over traditional methods which require the durations of activities as input. Instead, the use of encapsulated performance data of equipment (easier to acquire from manufacturers) in their corresponding models in the robot simulator relieves the operation modeler from 1) the intensive time and effort and sometimes impossible task of collecting duration data for activities and 2) concern over geometric data that is otherwise irrelevant to the purposes of the DES model from the decision making perspective, but essential to creating convincing and spatially correct visualizations of the operation. The encapsulation of data and functionality within the robot simulator model also permits the operation modeler to communicate animation instructions to the visualizer at the activity level instead of the elemental motion level.

While we have developed the implementation strategy for both the automation and simulation-visualization of construction operations using the modified DES models, we are currently in the process of developing a protocol to describe the capabilities of the robot/ robot model to the operation modeler. This would enable the separation of operational level and low level equipment details and thus alleviate the responsibility on the concern of the operation modeler over aspects that are irrelevant to the simulation. We have completed the development of an add-on to STROBOSCOPE that implements the modification to the DES processing algorithm as described in this paper. We are working on developing robot models, both in the real world and in V-REP, to test the overall methodology for the automation and visualization respectively of typical construction operations. A future step in the development of the presented methodology is to utilize the feature of STROBOSCOPE, which allows for access into the state of the model and its resources at any point, to access highly contextual real time information about the operation being performed. This advancement would enable automated and real time monitoring and control of the already automated operation.

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