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TOWARDS REAL-TIME SIMULATION OF CONSTRUCTION ACTIVITIES CONSIDERING SPATIO-TEMPORAL RESOLUTION REQUIREMENTS FOR IMPROVING SAFETY AND PRODUCTIVITY

Amin Hammad

Concordia University
Concordia Institute for Information Systems Engineering
1515 St-Catherine W., EV07-634
Montreal, H3G 2W1, CANADA

Cheng Zhang

Concordia University
Department of Building, Civil, and Environmental Engineering
1515 St-Catherine W., EV09-215
Montreal, H3G 2W1, CANADA

ABSTRACT

Traditional simulation models use statistical data to estimate task durations. However, to make the simulation results more realistic and reflecting the changes during the task execution, real-time simulation has been suggested by several researchers. On the other hand, little consideration is given to spatio-temporal constraints in simulation models. Several spatial modeling methods, such as maps, grids and 3D models, have been used in construction simulation. However, different resolutions of spatio-temporal representations should be used based on the specific requirements when considering spatio-temporal conflicts. The present paper aims to propose the basic concept of real-time simulation of construction activities considering spatio-temporal resolution requirements for improving safety and productivity. The objectives of the paper are: (1) to review real-time simulation methods of construction activities considering spatio-temporal conflicts; (2) to investigate the spatio-temporal requirements in the real-time simulation environment; and (3) to investigate the integration of simulation models at different spatio-temporal resolutions.

1 INTRODUCTION

Simulation has been used in construction since the seventies to help in understanding the construction environment and solving the problems of scheduling construction tasks. Traditional simulation models use statistical data to estimate task durations. However, to make the simulation results more realistic and reflecting the changes during the task execution, real-time simulation has been suggested by several researchers (Lu, Dai, and Chen 2007; Moallemi et al. 2010). In real-time simulation, the input of the simulation should be adjusted according to the real situation on site. For example, traffic delays may affect the transportation duration for a construction cycle.

On the other hand, little consideration of spatio-temporal constraints is integrated in the simulation. Cell-based Discrete-EVents systems Specification (cell-DEVS) has been used to represent the geometry of the construction site using grids (Zhang et al. 2007). However, the simulation results highly depend on the resolution of the grids. Geographic Information Systems (GIS) maps also have been used in simulation to represent the route of transporting construction materials (Lu, Dai, and Chen 2007). However, this simulation did not consider the details of the situation on site. 3D representations can be too complex to be used for the whole project including the transportation routes; therefore, most previous research has used 3D visualization only for checking potential collisions that may happen between construction equipment (e.g., Kamat and Martinez 2001).

Furthermore, based on our previous research, different resolutions of spatio-temporal representations should be used based on different requirements when considering spatio-temporal conflicts. For example, a cell-based representation can be suitable for estimating the productivity of the material transportation tasks (Zhang et al. 2007); whereas, detailed spatio-temporal representation is needed for improving safety of construction equipment where accurate collision detection should be done in near real time to avoid collisions (Zhang, AlBahnassi, and Hammad 2010).

The present paper aims to propose the basic concept of real-time simulation of construction activities considering spatio-temporal resolution requirements for improving safety and productivity. The objectives of the paper are: (1) to review real-time simulation methods of construction activities considering spatio-temporal conflicts; (2) to investigate the spatio-temporal requirements in the real-time simulation environment; and (3) to investigate the integration of simulation models at different spatio-temporal resolutions.

2 LITERATURE REVIEW

2.1 Space Representation in Discrete-event Simulation

In the seventies, Zeigler (1976) defined a theory for Discrete-EVents systems Specification (DEVS). It is a formal method to build models using a hierarchical and modular approach. This approach allows the developer to build a Model Base permitting easy reuse of models that have been validated. A real system modeled with this paradigm can be described as several sub-models coupled into a hierarchy. Each model can be behavioral (atomic) or structural (coupled), consisting of a time base, inputs, states, outputs and functions to compute the next states and outputs. The basic idea is that each model uses input/output ports in the interface to communicate with other models. Also, Zeigler (1976) defined a cell space model, which consists of an infinite set of geometrically defined cells, each cell containing the same computational apparatus as all other cells and connected to other cells in a uniform way.

Simulation has been used in construction for process planning and resource allocation. Several simulation software systems for construction were developed to model and analyze the process and help decision-making. MicroCYCLONE (Halpin 1977), Simphony (Hajjar and AbouRizk 1999), and Stroboscope (Martinez 1998) are the most popular software used in the construction area. They have been proved to be effective and efficient in simulating various construction projects. AbouRizk et al. (1999) modeled and analyzed the tunneling process using the Special Purpose Tunnel Template developed with Simphony. Zayed and Halpin (2001) applied simulation to concrete batching operations to analyze alternative solutions and resource management using MicroCYCLONE. Martinez, Trani, and Ioannou (2001) applied the simulation of air-side airport operations. The above mentioned simulation tools can provide the logical relationships between the different resources; however, they are not suited to define the spatial relationships between resources on a specific construction site. This could result in spatial constraints being ignored in the simulation, and the simulation result may not reflect the real situation of the construction site. Therefore, construction simulation models should be built in a way that the space can be represented explicitly, which makes the model more representative of the real construction environment, resulting in a more realistic simulation.

Cell-based analysis has been applied in construction site analysis although it was not clearly defined. Elbeltagi, Hegazy, and Eldosouky (2004) have represented each facility as a number of small grid units that can take irregular shapes. A similar representation of the construction site was applied to decompose and aggregate work zones based on triangular meshes that can represent activity workflow, project spatial hierarchy, and activity state information of a component at any given time (Akbas and Fischer, 2002). However, cell-based spatio-temporal analysis has not been studied fully because the space representation was not considered in the simulation.

Zhang et al. (2007) have proposed a cell-DEVS modeling approach to represent space resources in construction simulation, which enables conflict analysis and visualization of the work site and the occupation of spaces. Based on the cell representation of the spatial model, the information of the construction environment can be understood more easily and the optimal resource combination can be found not only based on resource constraints, but also the availability of workspaces, which is one of the main reasons that cause delays (Guo 2002). Spatio-temporal conflicts can be avoided by applying rules to control the movement of equipment and other objects. However, the creation of the rules that control the behavior of the cells is complex, especially when the number of rules increases.

2.2 3D Simulation for Construction Equipment Motion Planning

Simulation can be also used to position and plan the motion of construction equipment. For example, Zhou and Zhang (2007) have proposed a 3D simulation of an automatic pouring system of a concrete boom pump. The trajectories of the boom are analyzed using inverse kinematics to select a feasible path of the boom. However, no collision detection was applied between the boom sections and the obstacles in the environment. Training simulation for equipment operations has been used as a cost-effective tool (Ritchie 2005). Simlog (2010) provides training for different equipment with various scenarios, such as pouring concrete using a bucket lifted by a tower crane. Simulating the construction environment and processes has the advantage of ensuring the reliability of a construction plan by checking for potential collisions or other problems. However, this simulation deals only with the static environment without considering the dynamic features on site, thus reducing the practical value of the simulation in supporting real-time decision-making. Capturing and using near real-time data can provide new opportunities for quality control and safety assurance.

To improve the safety of mobile crane operations and to provide more awareness on site, Zhang, Hammad, and Rodriguez (2011) have proposed a 3D motion planning approach to efficiently generate safe and smooth paths for crane motions, mainly for the boom movement, while taking into account the engineering constraints and the path quality.

2.3 Monitoring of Construction Site

2.3.1 Location Tracking and Monitoring

A construction site has two types of obstacles: static and dynamic. Static obstacles are those obstacles that do not move, and about which information can be known in advance. Therefore, they can be considered during the planning phase. Examples of these obstacles include buildings, electrical poles, etc. Dynamic obstacles are objects that move on site, such as trucks, workers, and construction equipment. These dynamic obstacles should be detected and updated while the initial plan is being executed. Such obstacles may necessitate re-planning because of potential collisions. By the utilization of a wide array of sensors, equipment operators can have better situation awareness and can make more informed decisions. Researchers have been trying different technologies to create accurate 3D models of construction sites and to track and control equipment automatically.

The most popular tracking technology used on construction sites is the Global Positioning System (GPS), which is widely used in construction, mining, and infrastructure projects. For example, in earthmoving projects, GPS and total station technology are used to accurately position the blade of the excavator in real time, significantly reducing material overages and dramatically improving contractors' productivity and profitability (Trimble 2010). Navon (2005) has developed a tracking and control system using GPS and on-board instrumentation (OBI) to monitor, in real-time, the activity of major construction equipment, such as tower cranes, concrete pumps, etc. Alshibani and Moselhi (2007) have used GPS for tracking earthmoving equipment to forecast performance. Riaz, Edwards, and Thorpe (2006) have tracked vehicles and workers using GPS and sensors to reduce accident rates. However, GPS requires direct line of sight from the satellites to the receiver, and accurate GPS receivers are expensive to install on every moving object on site. Therefore, other tracking technologies have been applied in several research projects, such as infrared, optical, ultrasound, and Radio Frequency Identification (RFID) technologies. Chae and Yoshida (2008) have discussed collecting data on site using RFID active tags to prevent collision accidents. BodyGuard - Vehicle Proximity Alert and Collision Avoidance System (Orbit Communications 2008) is an RFID-based system that offers continuous detection and notification of proximity between moving objects and other moving or fixed objects by setting up protection zones around a vehicle, equipment, and buildings to offer continuous protection for valuable resources. However, RFID can give only approximate locations.

The Real-time Automated Project Information and Decision Systems (RAPIDS) lab at Georgia Institute of Technology is testing 3D laser scanners, 3D range cameras, total stations, GPS, RFID, and other types of sensors and technologies for automated collection and processing of data for applications in construction projects (Teizer and Castro-Lacouture 2007). However, most of this research is still at the initial testing stage.

Recently, real-time location systems (RTLSs) have been applied in various areas, such as logistics and manufacturing. RTLSs can track and identify the location of objects in real time using tags attached to objects and sensors fixed at known locations. The sensors detect signals emitted by the tags and calculate the locations of these tags. According to Muthukrishnan and Hazas (2009), ultra-wideband (UWB) technology delivers a robust localization with an accuracy of up to 15 cm in good conditions.

2.3.2 Monitoring Other On-Site Information

Weather information can be collected in real time from an external weather database using the Internet as well as from on-site weather sensors to warn on impending wind-related hazards (Lee and Bernold, 2008). The traffic information may also affects the time of transporting concrete from plants far from the construction site, thus the schedule of the project (Lu, Dai, and Chen 2007).

2.4 Real-time Simulation

Song, Ramos, and Arnold (2008) have described a framework of real-time simulation for modeling heavy construction operations. Real-time data and process knowledge are coupled to enable a self-adaptive modeling process that validates and refines a process simulation model. Compared with traditional simulation, real-time simulation has the potential to improve the accuracy of performance forecasting while reducing modeling burdens on the end users. Lu, Dai, and Chen (2007) have developed a real-time decision support system by integrating a vehicle tracking system, a DEVS algorithm, and an evolutionary optimization algorithm.

Moallemi et al. (2011) have introduced a method to integrate cell-DEVS models with DEVS-based robotic agents and an advanced immersive environment for emergency management. The emergency is handled by an autonomous robot controlled by a real-time DEVS model. The model controlling the robot interacts with a simulation for emergencies, receiving real-time data about its location on a cell space. The simulation results of both the cell-DEVS emergency model and the DEVS-based robotic first responder are visualized dynamically in real time. The real-time visualization allows for supervisory control of the emergency and first responders activities.

In the research of Zhang, Hammad, and Rodriguez (2011) discussed in Subsection 2.2, location data are collected from tags attached to cranes and other dynamic objects, and are processed by an agent system to identify the poses of dynamic objects, which are used to generate new motion plans to guide the cranes' movements and thus to avoid potential collisions. However, due to the limitation of the tracking technology, only part of the construction site is monitored and simulated.

3 PROPOSED APPROACH

Our proposed approach has the following steps: (1) Building a DEVS/cell-DEVS model for the project to help understand the construction situation at the project level; (2) Identifying the tasks and workspaces that need to be simulated using 3D modeling, and creating a detailed 3D model for those workspaces; (3) Monitoring and updating the models using suitable tracking technologies in real time; (4) Re-planning when changes occur, such as delays due to traffic congestion or potential collisions; and (5) Integrating the two simulation models.

As shown in Figure 1, two levels of simulation models are considered according to different spatio-temporal requirements. Moving objects are tracked by using different technologies, for example, using GPS for transportation equipment (level-1 modeling), while using UWB for other equipment that will stay in the predefined workspaces (level-2 modeling). The location data are processed into information that can be used in the 2D and 3D simulation models in parallel according to the spatio-temporal resolution requirements.

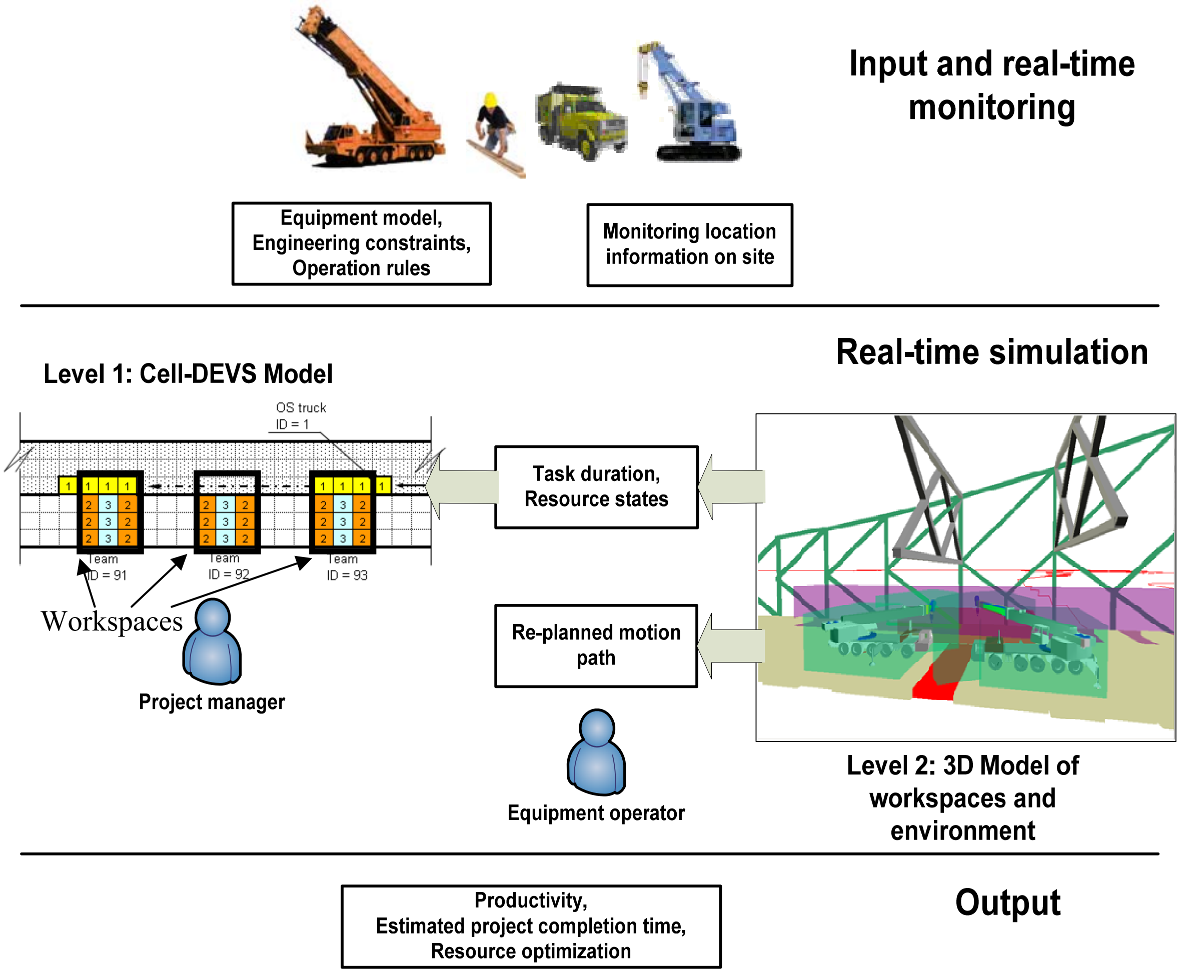

Figure 1: Concept of the proposed two-level real-time simulation

A 2D cell representation is used in the first-level simulation model to represent space occupation, where equipment is represented by one or multiple cells depending on the shape and the size of the equipment. For example, trucks are represented by occupying four specific cells in the cell-DEVS model of the site (Figure 1). Simple collision avoidance can be achieved by checking the occupancy of each cell and avoiding multiple occupancy of a single cell. Simulation is run during the planning stage to estimate the duration of the project, the expected productivity, the best combination of the resources, etc. During construction, real-time information of the construction tasks can be captured using tracking technologies and updated in the simulation model. For example, GPS can be used to update the real-time locations of the trucks in the cell-DEVS simulation model. Re-planning should be done to check the effects of the changes on site due to the resource availability and task durations. Productivity can be re-evaluated based on the updated information and resource optimization can be carried out by adjusting resource combinations in real time.

The second level considers a 3D model of the workspace, where more details are needed for real-time control and safety purpose. Collision-free motion plans can be generated during the planning stage for specific construction equipment, such as cranes. During the execution stage, the motion of cranes and other equipment are monitored and updated in the 3D simulation environment. Cranes do not move when lifting an object. The boom of a hydraulic crane will raise, rotate, or extend within the capacity range; therefore, monitoring and simulating the motion of the boom is necessary to improve safety on site by avoiding collisions in real time. If a potential collision is detected, motion re-planning is triggered and a revised motion plan is generated in real time to guide the movement of the equipment. Advanced planning and re-planning algorithms are applied to create collision-free path for equipment (Zhang, Hammad, and Rodriguez 2011). The result of the execution of the equipment tasks will be input to the 2D simulation model, for example, the duration of each task and the resource states, such as the idle state of a crane or the availability of a truck. Based on these updated information and the real location of the equipment, the cell-based simulation will continue running to estimate the completion time for the project or to find a better combination of the resources.

3.1 Creating a Cell-DEVS Simulation Model

Figure 2 shows the steps of creating the cell-based simulation. It consists of three phases: model creation, planning and re-planning. Model creation includes analyzing the spatial resolution requirement, building the cell-DEVS model and identifying the workspaces that need real-time updating. Planning focuses on deciding site layout patterns and resource optimization by running the simulation model. More details about the cell-DEVS modeling can be found in Hammad, Pang, and Zhang (2011).

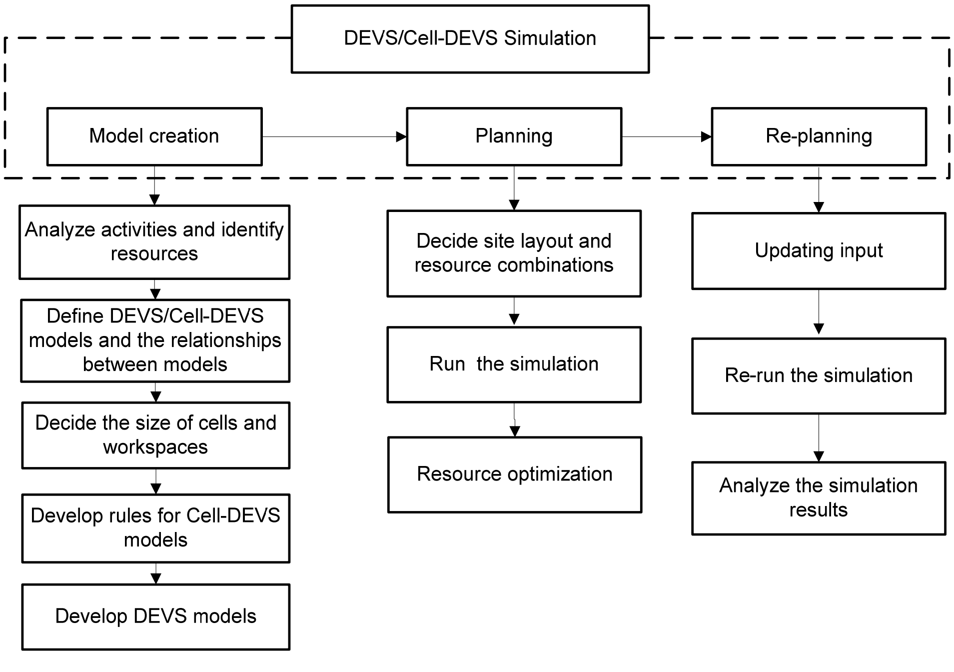

Figure 2: Steps of cell-DEVS simulation (adapted from Hammad, Pang, and Zhang 2011)

The present paper focuses on the re-planning process, which includes updating the input of the system and re-running the simulation according to the location and duration information to check the impact of these changes on the simulation result. Two types of changes are considered in updating the cell-DEVS model: time and space. Two sources are used to update the task durations and space occupation: one is from monitoring the locations of vehicles using GPS, RFID, blue-tooth technology, etc.; the other is from the output of the 3D simulation model, where detailed task execution is monitored. From these two sources, the space occupation of the cells in the cell-DEVS model is updated in real time, and the actual tasks' durations are used to update the duration distribution model to estimate the task durations for look ahead scheduling.

3.2 Creating 3D Models for Motion Planning

3D models of the workspaces including the structures and the construction equipment are created based on the 3D structure models and database of the equipment. After identifying the areas of the construction site that should be analyzed in 3D, tasks realized within these areas are simulated in detail and monitored in real time. During the planning stage, collision-free motion plans are generated for the construction equipment taking into account engineering constraints and operation rules (Zhang, Hammad, and Rodriguez 2011). During the actual construction work, an UWB RTLS is used to capture on-site data. Multiple UWB tags with identification numbers (IDs) are attached to the different components of cranes and other equipment and workers, at predefined locations, to monitor their positions and orientations. The updated environment information is used to check the motion plans for any potential collision. In the case an obstacle is detected, the equipment involved is stopped to ensure safety and a new motion plan is generated in near real time according to the updated environment. Near real-time re-planning is defined as finding a new collision-free path based on the sensed data in a short period of time (a few seconds) after detecting the potential collision. The short delay is caused by the relatively low update rates of some tags and the calculation time. Figure 3 shows the simplified flowchart of the near real-time re-planning algorithm. More details can be found in Zhang, Hammad, and Rodriguez (2011).

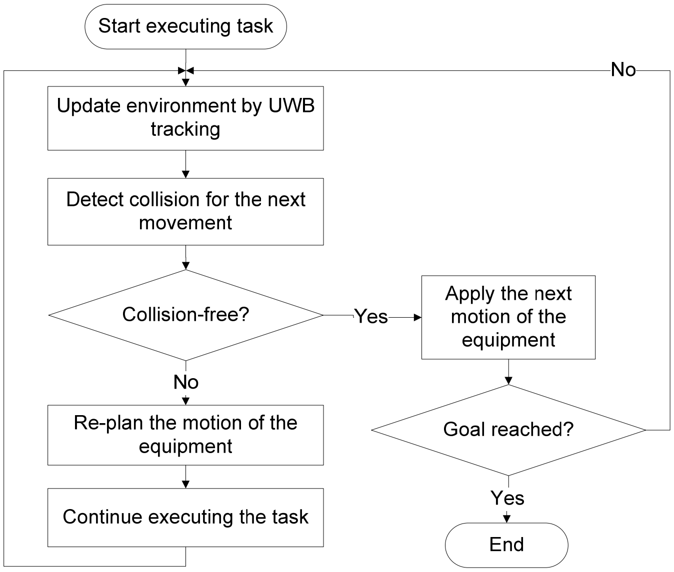

Figure 3: Simplified flowchart of near real-time crane motion re-planning algorithm

3.3 Integration of the Two Levels of the Simulation

As shown in Figure 1, workspaces are defined in the cell-DEVS model to indicate the areas where detailed 3D simulation for the tasks need to be applied. A specific event will trigger the 3D simulation, for example, when a truck reaches the unloading area where two cranes will lift the new panel from the trailer. The lifting task is simulated in the 3D simulation model while spatial constraints are taken into account to improve safety on site. After the truck finishes the unloading, a signal is sent to the cell-DEVS model to indicate the resource releasing. After the two cranes finish the lifting task, another signal is sent to the cell-DEVS model to indicate that the two cranes are available. In this way, the space and the time in the cell-DEVS model can be updated and the cell-based simulation will continue running to check any changes that may happen according to the real situation on site. Short-term and long-term prediction of the productivity can be achieved depending on the users' demand.

4 CASE STUDIES

The following two case studies are demonstrated as typical examples of cell-DEVS simulation and 3D simulation for crane motion planning, respectively.

4.1 Bridge Rehabilitation Simulation using Cell-DEVS

A cell-based simulation model is developed using a bridge re-decking project (Zhang et al. 2007). The old sections were transported to a dumping area near the bridge. The new panels were transported from a plant located at the south end of the bridge. Semi-trailer trucks were used to transport the old sections and new panels. Most of the time, two teams worked in parallel on different parts of the bridge. Each team used two telescopic cranes located at both sides of the section to be replaced. Resources required in this project include: teams (two cranes and crews), saws (including operators), trucks (including the drivers) for carrying old sections, trucks (including the drivers) for carrying new panels, a small crane for loading new panels in the plant, a forklift for dumping the old sections in the dump area, empty deck space of the removed section, truck working space, etc. The developed model consists of several cycles; three of the main cycles are described as follows: (1) Old Section (OS) cycle: The existing deck is cut by a saw into sections. Empty trucks are waiting for the team to load old sections. After loading, the truck transports the old section to the dump area. After dumping, the truck goes back to the bridge for loading the next old section; (2) New Panel (NP) cycle: New panels are transported from the plant to the bridge. The same team for removing an old section also installs a new panel. After installation, the truck goes to the plant to load a new panel; and (3) Team cycle: Teams are located at different locations on the bridge for removing old sections and installing new panels. They move to the next location on the bridge after they finish installing each panel.

A sensitivity analysis is carried out the find a good combination of the resources (the combination for teams, saws, and trucks for carrying OS and NP), which is adjusted according to the real-time information. The generated number of combinations is 1296 (6×6×6×6) to change the number of teams from one to six with one team increment; saws from one to six with one saw increment; OS trucks from one to six with one truck increment; and NP trucks from one to six with one truck increment.

The results of each combination are documented to select the optimal one based on further analysis. The combinations that have higher productivity and lower cost are selected because they dominate the other combinations that have similar or lower productivity and higher cost. By updating the cell-DEVS model using real-time data, the simulation will result in different resource combinations.

4.2 3D Simulation for Crane Motion Planning

A 3D simulation environment is created by using Softimage (Autodesk 2010). The 3D environment is created in a scene, including static and dynamic objects. Ubisense software is used as the platform of the near real-time location system (Ubisense 2011). A plug-in of Ubisense is developed to transfer data into Softimage. This allows Softimage to read near real-time location data from the UWB system and to show the traces of the tags that are attached to the physical cranes for updating the location of the virtual cranes in the virtual scene.

Two radio-controlled (RC), scaled (1:18) hydraulic crane models were used in the tests (Hobby Engine 2010). Each crane has six motors that allow the movement of the body of the crane (drive forward/backward, turn right/left), of the boom (swing right/left, turn up/down, extend/retract), and of the hook (move up/down). A crane can be manually controlled using a remote control with different buttons and joysticks that allow the movement of one DoF at a time. All the scaled cranes within the range of the remote controller (at about 10 m) receive and execute the same commands because the remote controller does not specify a specific target crane for a specific command. To control multiple cranes in the same area by a computer, one remote controller was interfaced with a microcontroller (Phidgets 2010) connected to the computer with a USB cable. An encoding scheme was implemented allowing for sending commands from the computer equivalent to pushing buttons on the remote control. Furthermore, the receiver circuits of the scaled cranes were modified to react only to commands sent to that specific crane. As a result, it became possible to send a series of commands from the computer to control each crane separately using software developed in C++ based on the API library of the microcontroller.

Figure 4(a) shows a picture of the two scaled crane models, with UWB tags attached to the tip of the boom of Crane-2 and with a simple frame structure representing static obstacles. Figure 4(b) shows the virtual models representing the cranes and the frame structure. It is assumed that Crane-2 has a higher priority than Crane-1 based on the safety, task, cost, or time factors related to the tasks that are executed. The location data of the UWB tags attached to Crane-2 were used to update its pose in the virtual model, which was used in the motion re-planning of Crane-1. The scaled model Crane-2 was controlled by using the remote controller to swing the boom in a way that blocks the movement of Crane-1. In the virtual scene, the movements of the boom of Crane-2 followed the physical scaled crane and a potential collision was detected by the agent of Crane-1. Then, motion re-planning was triggered and Crane-1 followed the new path to avoid potential collision with Crane-2. The test successfully demonstrated the applicability of the proposed methods for real-time simulation in a 3D environment.

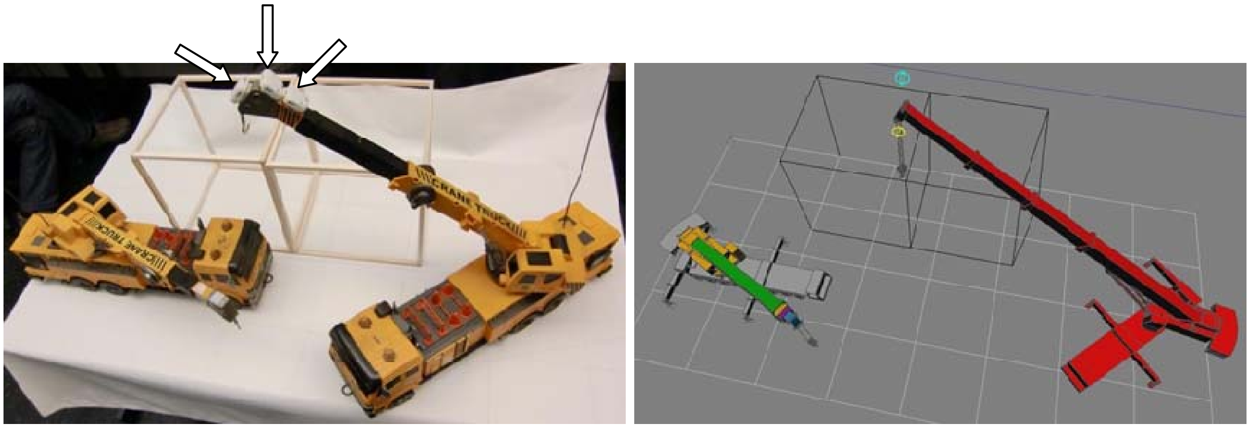

Figure 4: Real world and the simulation environment

5 CONCLUSIONS AND FUTURE WORK

Traditional simulation models use statistical data to estimate task durations. However, to make the simulation results more realistic and reflecting the changes during the task execution, real-time simulation has been suggested by several researchers. On the other hand, little consideration is given to spatio-temporal constraints in simulation models. Several spatial modeling methods, such as maps, grids and 3D models, have been used in construction simulation. However, different resolutions of spatio-temporal representations should be used based on the specific requirements when considering spatio-temporal conflicts. The present paper proposed the initial concept of real-time simulation of construction activities considering spatio-temporal resolution requirements for improving safety and productivity. The benefit of this approach is that safety and efficiency on site can be improved by re-planning for equipment and adjusting resource combinations in real-time. Future work should further consider the details of the integration of the two levels of the simulation models.

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AUTHOR BIOGRAPHIES

AMIN HAMMAD is an Associate Professor at the Concordia Institute for Information Systems Engineering. His research focuses on sustainable infrastructure lifecycle management systems and investigates several methods and techniques including spatio-temporal information modeling and analysis, simulation, visualization, optimization, wireless communications, sensing, auto-identification, and real-time location tracking. His email is hammad@ciise.concordia.ca.

CHENG ZHANG is a Post Doctoral Follow at Concordia Institute for Information Systems Engineering. She received her Ph.D. from the Department of Building, Civil, and Environmental Engineering at Concordia University. Her research interests are in automation in construction, improving safety on construction site, and real-time location systems. Her email address is lilyzc2003@hotmail.com.