Global Positioning System Data to Model and Visualize Workspace Density in Construction Safety Planning

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ABSTRACT

Safety as well as productivity performance in construction is often poor due to congested site conditions. We lack a formalized approach in effective activity-level construction planning to avoid workspace congestion. The objective of this study is to investigate and prototype a new Building Information Modeling (BIM) enabled approach for activity-level construction planning that can pro-actively improve construction safety. The presented method establishes automated workspace visualization in a building information model, using workspace modeling as an integral part of construction safety planning. Algorithms were developed for extracting activity-specific workspace parameters from workforce location tracking data. Global Positioning System (GPS) data loggers were attached to the workers' hardhats during the stripping activities of formwork of columns. Workspaces were then visualized on a BIM platform. The developed method can support project stakeholders, such as engineers, planners, construction managers, and site workers with the identification and visualization of required and congested workspaces, hence improving the foundation on how decisions are made related to construction site safety and health, as well as its potential impact on a productive, unobstructed work environment.

Keywords - Building information modeling, Construction safety and health, Data fusion and mining, Decision making and support, Global positioning system, Progress monitoring, Workspace modeling and visualization.

1 Introduction

Traditional safety planning mainly relies on manual observation, which is labor-intensive, time-consuming, and potentially inefficient. The link between planning for safety and work-task execution is often weak. For example, many contractors use two-dimensional drawings or field observations to determine hazard-prevention techniques [1-2]. The resulting safety plans are often error-prone due to subjective judgments of the decision maker and unavailability of information [3].

Currently, historical workspace information for an activity and the corresponding contextual information depicting the condition under which the activity is accomplished are not stored. Hence, space planning for work activities in construction planning is often overlooked. This leads to workspace congestion which may largely impede worker safety and productivity on a construction project. The reasons indicate that we lack a well-structured approach to collect, formalize, and reuse historical activity-specific workspace information. This paper describes a general approach towards gathering work activity specific workspace information by obtaining the required workspace parameters and visualizing the observed workspace in a building information model. Experiments are conducted to test the developed BIM-based application prototype for workspace modeling and visualization. Results show how the developed approach can easily provide decision makers with valuable workspace information required for activity-level construction planning.

2 Background

2.1 Information Technologies Assisted Safety Planning

Information technologies (IT) such as Building Information Modeling (BIM) [4] and Virtual Design and Construction technology (VDC) have become well-known tools in the Architecture, Engineering, and Construction industry. Benjaoran and Bhokha [5] and Zhang et al. [2-3] explored the integration of construction and safety engineering and management based on 4D CAD model (3D and time) and rule-based algorithms. Although these existing studies are trying to improve safety planning using IT, none of them can support activity-level hazard identification and visualization.

2.2 Construction Workspace Representation

Representation and analysis of workspaces for construction activities in 4D environments during the planning, scheduling, and eventually even at the design phase are encouraged since it minimizes workspace congestion and conflicts which frequently occur at construction sites. If workspaces are designed poorly, they keep also the workforce away from working more productively [6].

Thabet and Beliveau [7] and Riley and Sanvido [8] presented an early scheduling model that incorporates work space constraints in the scheduling of repetitive work in multistory buildings. Akbaş [9] described an approach for modeling and simulation of construction processes based on geometric models and techniques to improve construction operations and more effective use of geometry for construction practice and research. Akinci et al. [10-11] developed space templates linked to construction method templates to enable users to define the space requirements of different construction methods. A prototype system, called 4D WorkPlanner Space Generator, was developed that uses the spatial requirement knowledge captured generically in the space templates. It then generates the project-specific instances of spaces automatically and represents them quantitatively in x, y, z and time dimensions. Haque and Rahman [12] linked a 3D BIM model with schedule and construction space requirements, and simulated the 4D model to detect whether there is any space conflict during the activities. However, all of these studies relied on the users to define both space parameters and sequences for the generation of work activity plans or the simulation of the work processes. In addition, no method so far generated accurate space requirement models based on the as-built status of a construction site.

Many existing studies focused on critical space analysis and space planning using simulated workspace requirements as an input in their systems. However, neither one of these approaches provides reliable spatial information since their workspace input parameters are either estimated based on the authors' experience or requiring user input to define further parameters. Riley and Sanvido [13] concluded through observation and testing that various material handling activities have repeating and predictable space needs. These stay common from one project to the next. The challenge now is to find more modern methods to represent or to suggest acceptable values for the requirements of workspaces that allow successful (safe and productive) completion of work activities.

2.3 Location Tracking in Construction Space

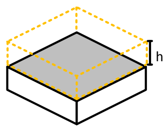
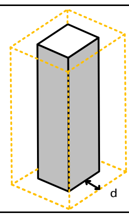
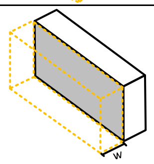
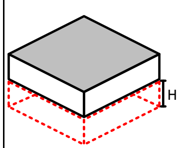
Safety risks on construction sites are often closely related to the proximity of construction materials, equipment, and humans located nearby hazards. Many of these are well-known, for example, the risk of falling from a leading edge of a concrete slab floor to a lower level, or using excessive time to complete an activity because the workspace is obstructed by the placement of other material or presence of other work crews in the same work space. Since the focus of this paper is on safety planning, some of the identified risks have been defined and quantified in Hallowell & Gambatese [14] and Rozenfeld et al. [15]. To further advance the state-of-the-art in safety engineering and management, some researchers recommend using positioning devices to locate construction resources and deliver pro-active safety information in real-time to mitigate a worker from entering a hazardous area [16-19]. Various researchers, incl. Teizer et al. [20], Cheng et al. [21], Zhang et al. [22], and Maalek and Sadeghpour [23] studied the performance of an Ultra Wideband (UWB) tracking system under conditions that can commonly occur on construction sites. Latter article proved that the accuracy of commercially-available real-time location tracking technology can be used for the display of resource location in information models. They further indicated that "the accuracy of the system could be used in the definition of the size of buffer zones in construction site safety applications". Many other technologies exist today that might offer a solution to the problem of pro-active-real-time hazard detection and warning based on pre-defined and geo-referenced hazard zones [20]. One of the technology that enables location tracking are small GPS data loggers [24] and UWB [25-26]. Although each technology has shortcomings, some can gather valuable activity-based location data from workers and equipment movements. Once data such data is gathered efficiently, it can be processed. The resulting information has potential to support workspace modeling and visualization.

We define a construction site as a very dynamic environment in which workspaces related to construction activities are available (space) or continuously change (time). The locations and volumes of these spaces change in three dimensions and across time, according to project-specific design data. Unless major automation or lean approaches are applied, congestion among the various work activities can often not be eliminated, which leads to additional safety hazards that already exist due to poor site or work environment planning [27]. Currently, we lack a formalized approach to enable effective activity-level construction safety planning.

3 Research Objectives and Scope

This study aims to develop a general approach that collects, formalizes, and reuses historical activity-specific workspace information for the automated activity-based workspace visualization and workspace congestion identification in BIM. To limit the scope, this study focuses on concrete column construction activities due to their high frequency and severity of potential incidents and injuries. According to a report of the US Bureau of Labor Statistics [28], contractors pouring concrete of foundations and structures have been identified as one of the specialty trades that are highly exposed to safety risks, for example, falling from height. The GPS devices used are commercially available Wintec G-Ray 2 data loggers. A detailed error analysis of this or similar devices can be found in Pradhananga and Teizer [24].

Table 1: Workspace representation

Reference position	Diagram	Example	Reference object	Space parameter
Above		Space for a worker to pour a concrete slab	Slab	Height of workspace (h)
Around		Space for a worker to strip formwork from a column	Column	Depth of workspace (d)
In front of		Space for a worker for setting pins in the formwork elements	Wall	Width of workspace (w)
Below		Protective space preventing falling object hazards below a crane load	Space for material handling path	Distance to the ground or floor (H)

4 Workspace Modeling and Visualization

Multi-interfaces, defined as the interference between different construction activities, are identified as one of the major causes for construction accidents and higher incident rates. They are very characteristic for many of the large-scale construction projects that exist around the globe. Recent lean process control systems, for example Sacks et al. [29], try to design and test a BIM-based workflow information system to help construction personnel implement lean pull flow strategies. A reason that they exist is that it is often very difficult to coordinate the work of multiple subcontractors in the working interface when only a traditional master plan and schedule is used [30-31].

In this study, workspace is generated corresponding to the reference objects (see Table 1). Reference surfaces are illustrated in grey color, required workspace for the workers is shown by dashed yellow lines. The protective space is shown by dashed red lines. The experiment conducted in this study focuses on the workspace parameters that workers need for the activity: stripping formwork off concrete columns.

5 Implementation and Results

It is assumed that gathering worker location data can provide the value of the approximate workspace that was utilized to complete a work task. The data then generates the work space parameters for a type of work activity. An occupancy grid model, designed after Teizer et al. [16], was used for calculating the frequency of the visits of a worker to a pre-defined virtual cube that represents part of the work space. Creating an occupancy grid map followed according to Cheng et al. [21,26]. Then algorithms were developed for generating and retrieving workspace parameters based on the work area. These parameters were used to later convert distance parameters and references to a building object. Finally, the parameters generated the size of the required workspace for one activity in BIM. This will allow for planning future work activity using the same construction activity and method.

5.1 Data Collection

An experiment was conducted on a construction site for a small-sized laboratory building (see Figure 1). The activities recorded were related to stripping of the formwork of 9 concrete columns on the second floor of the building. Two GPS tags were tagged to each of the hardhats of two volunteering workers who were involved in the activity. A shooting boom forklift lifted and removed the formwork once the workers disassembled smaller pieces of the formwork. A video camera was set up at a nearby structure to record the progress of the experiment. The video data helped in analyzing the collected GPS data. In addition, laser scans of the complete structure acquired the accurate geometric information of the experimental environment. It was also used to reference GPS data and location of the structure.

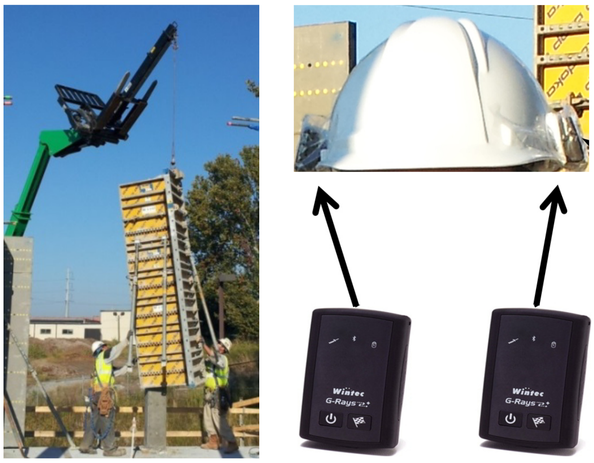


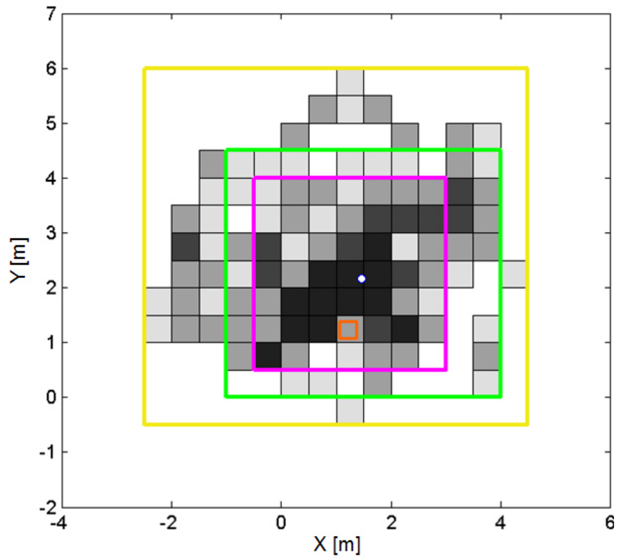
Figure 1. Activity monitoring “striping formwork off concrete columns” with GPS data loggers on workers’ hardhats

5.2 Data Processing

Collected GPS data was first transformed from the world coordinate system to the local coordinate system of the building model. Since the distance between the column in the middle of the floor and the closest column near the slab edge was about 5 m, the value 5 m was used as a threshold to remove GPS data outliers. The data was then filtered using a Robust Kalman Filter [32]. Kalman filtering, as it has historically been used for filtering and smoothing positioning or signal data, helped remove outlier data and error reads [24].

5.3 Workspace Parameter Computation

An occupancy grid model was then applied to visualize different activity levels of the workers. Based on the site dimensions and accuracy of the GPS device, the construction space was divided into virtual cubes of identical dimensions: 0.5 × 0.5 m^2. Figure 2 shows a grid-based map in plan-view for stripping formwork from one of the columns. We explain further the distribution of the required workspace and different activity level. The average point (illustrated by using a white dot in Figure 2), the areas that were occupied by the workers 50%, 75%, and 100% of the time (time it took them to strip the formwork) are marked with red, green, and blue bounding boxes, respectively. The position of the column is shown as a small blue rectangular box. Based on the results from all of the 9 columns (see Table 2), the average workspace parameters for stripping concrete columns are 2.0 m for 50% of all of the time workers spent in the work zone, 2.4 m for 75%, and 3.2 m for 100%, respectively.



No. of Cube Visits	Greyscale
1	
2	
3 to 5	
6 to 8	
Pink	50% time spent
Green	75% time spent
Yellow	100% time spent
Orange	Column

Figure 2. Occupancy grid model.

Table 2: Average distances between column edge and bounding boxes (in meters)

Time \ Column	1	2	3	4	5	6	7	8	9	Mean
50%	2.15	2.33	2.47	1.85	1.97	1.99	1.47	1.72	1.59	1.95
75%	2.47	2.21	2.85	2.23	2.60	2.85	2.10	2.22	2.09	2.40
100%	3.47	2.35	3.60	3.23	3.60	3.73	3.10	3.10	3.00	3.24

The results indicate that planners should keep an area of about 3.5 m to each of a column’s side free of obstruction. Such space would enable workers on this site to work effectively. This information can be used by foreman and supervisors for pre-planning the tasks of the next work day. Although the length of the experiment and size of the construction site did not allow such simulation, the availability of such information may yield optimization of near real-time planning of work spaces, including material handling (e.g., efficient delivery routes and positioning) and crew and equipment management (e.g., crews overlapping). As Cheng et al. [33-34] have shown, information to safety, health, and productivity performance can be visualized.

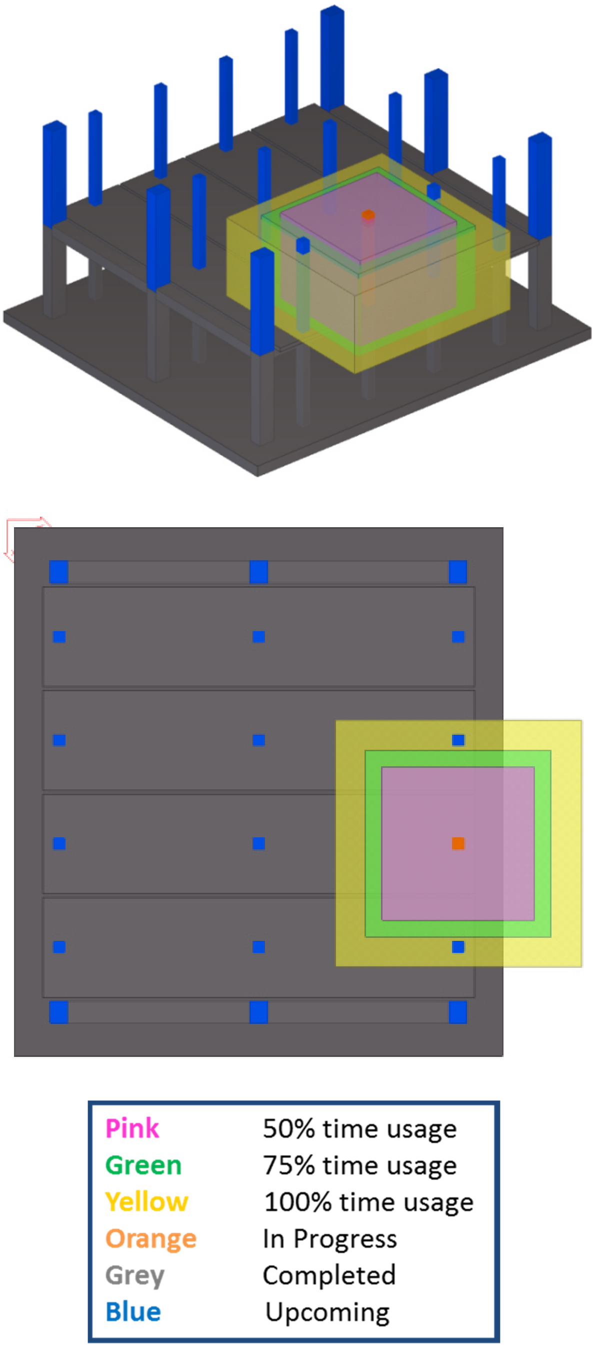


Figure 3. Workspace visualization in BIM for stripping formwork from a concrete column.

5.4 BIM-based Workspace Visualization

The prototype was implemented in Tekla Structures using Tekla's API. Figure 3 shows the feasibility of generating and visualizing the activity-based workspace in BIM. Along with a 4D simulation of construction in progress, workspaces at selected time intervals can be visualized and referenced to building elements in BIM. For example, building elements that are soon under construction are shown in blue in Figure 3. As also shown in Figure 3, the workspace used for stripping the formwork from one concrete column (in orange color) is illustrated using pink (50%), green (75%), and yellow (100%) cubes. The percentage indicates the spatial-temporal relationship of occupied workspace and time required for both of the construction workers that completed the work task.

The space occupied by the equipment has not been modelled since it largely depends on the procurement of the type of the lifting equipment. We assumed in this study that the required work space is modeled by the area the workers occupied and the height of the building object (i.e., column). This work space can then be modeled. As shown in Figure 3, two neighboring columns limit the space that is available to the work crew. Although they are in the outer range of the required workspace, they potentially become an obstacle in executing the work task of stripping the formwork off the column. The space that requires to be obstruction-free can be easily communicated to the other work crews. Ensuring that the work space is free of other materials or equipment has potential to yield safe and productive activity completion. Future studies are necessary to measure the overall safety and productivity performance and bringing into context of the existing overall lean management strategies [29, 35].

6 Conclusion and Discussion

The goal of this study was to gather and visualize data to the size of the workspace that is required by a construction crew to complete an activity. The application was stripping the formwork off a concrete column on a small sized construction site. Global positioning system (GPS) data loggers were used to collect the positioning data of the crew. Algorithms to determine the occupancy grid and visualization in BIM led to modeling the workspace geometry and its parameters. The preliminary results show the feasibility of obtaining workspace parameters from location tracking data and the potential of visualizing and detecting workspace conflicts in BIM. In order to further validate the proposed approach, more data need to be collected to verify the generated workspace parameters. Future research will focus on 1) using highly accurate GPS technology for location tracking, 2) collecting location tracking data from various work activities, 3) developing a framework for detecting workspace conflict between various sets of work activity and identifying their corresponding potential safety hazards in BIM, and 4) conducting field trials that explore and validate the opportunities of using the proposed pro-active technology based approaches in the future and its application to traditional construction safety risk analysis.

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References

[1] Rozenfeld, O., Sacks, R., and Rosenfeld, Y. (2009). ‘CHASTE’: construction hazard assessment with spatial and temporal exposure, *Construction Management and Economics*, Taylor & Francis, Vol. 27, No. 7, 625-638.

[2] Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M. and Venugopal, M. (2013). Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules, *Automation in Construction*, Elsevier, Vol. 29, 183–195.

[3] Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C.M., and Teizer, J. (2015). BIM-based Fall Hazard Identification and Prevention in Construction Planning, *Safety Science*, Elsevier, Vol. 72, p. 41-45.

[4] Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*, 2nd Ed. John Wiley and Sons, Hoboken, NJ, 2011.

[5] Benjaoran, V., and Bhokha, S. (2010). An integrated safety management with construction management using 4D CAD model, *Safety Science*, Elsevier, Vol. 48, No. 3, 395-403.

[6] Vasenev, A., Pradhananga N., Bijleveld, F., Ionita, D., Hartmann T., Teizer, J., and Dorée, A. (2014). Information Fusion Approach to Increase the Quality of GNSS Data Sets in Construction Equipment Operations, *Advanced Engineering Informatics*, Elsevier, 28(4), 297-310.

[7] Thabet, W.Y. and Beliveau, Y.J. (1994). Modeling Work Space to Schedule Repetitive Floors in Multystroy Buildings, *Journal of Construction Engineering and Management*, 120(1), 96-116.

[8] Riley, D. R., and Sanvido, V. E. (1997). Space planning method for multistory building construction, *Journal of Construction Engineering and Management*, Vol. 123, No. 2, 171–180.

[9] Akbaş, R. (2003). Geometry-based modeling and simulation of construction processes, Dissertation, Department of Civil and Environmental Engineering, Stanford University, Stanford, California.

[10] Akinci, B., Fischer, M., Kunz, J. and Levitt, R. (2002). Representing Work Spaces Generically in Construction Method Models, *Construction Engineering and Management*, 128(4), 296-305.

[11] Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002). Formalization and automation of time-space conflict analysis, *Journal of Computing in Civil Engineering*, Vol. 16, No. 2, 124-134.

[12] Haque, M. E., and Rahman, M. (2009). Time-Space-Activity Conflict Detection Using 4D Visualization in Multi-storied Construction Project. In *Visual Informatics*: Bridging Research and Practice. Springer Berlin, 266-278.

[13] Riley, D. R., and Sanvido, V. E. (1995). Patterns of construction-space use in multistory buildings, *Journal of Construction Engineering and Management*, Vol. 121, No. 4, 464-473.

[14] Hallowell, M. R., and Gambatese, J. A. (2009). Activity-based safety risk quantification for concrete formwork construction, *Journal of Construction Engineering and Management*, Vol. 135, No. 10, 990-998.

[15] Rozenfeld, O., Sacks, R., Rosenfeld, Y., and Baum, H. (2010). Construction job safety analysis, *Safety Science*, Elsevier, Vol. 48, No. 4, 491-498.

[16] Teizer, J., Caldas C.H., and Haas, C.T. (2007). Real-Time Three-Dimensional Occupancy Grid Modeling for the Detection and Tracking of Construction Resources, *Journal of Construction Engineering and Management*, Vol. 133, No. 11, 880-888.

[17] Teizer, J., Allread, B.S., Fullerton, C.E., and Hinze, J. (2010). Autonomous Pro-Active Real-time Construction Worker and Equipment Operator Proximity Safety Alert System, *Automation in Construction*, Elsevier, Vol. 19, No. 5, 630-640.

[18] Park, C. S., and Kim, H. J. (2012). A framework for construction safety management and visualization

system. *Automation in Construction*, Elsevier, Vol. 33, 95-103.

[19] Cheng, T. and Teizer, J. (2013). Real-time Resource Location Data Collection and Visualization Technology for Construction Safety and Activity Monitoring Applications, Automation in Construction, Elsevier, Vol. 23, 3-15.

[20] Teizer, J., Lao, D., Sofer, M. (2007), Rapid automated monitoring of construction site activities using ultra-wideband, Proceedings of the 24th International Symposium on Automation and Robotics in Construction, Kochi, India, 19-21.

[21] Cheng, T., Venugopal, M., Teizer, J., and Vela, P.A. (2011). Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments, *Automation in Construction*, Elsevier, Vol. 20, No. 8, 1173-1184.

[22] Zhang, C., Hammad, A., and Rodriguez, S. (2013). Crane Pose Estimation Using UWB Real-Time Location System, *Journal of Computing in Civil Engineering*, Vol. 26 No. 5, 625-637.

[23] Maalek, R., and Sadeghpour, F. (2013). Accuracy assessment of Ultra-Wide Band technology in tracking static resources in indoor construction scenarios, *Automation in Construction,* Elsevier, Vol. 30, 170-183.

[24] Pradhananga, N., and Teizer, J. (2013). Automatic spatio-temporal analysis of construction site equipment operations using GPS data, *Automation in Construction*, Elsevier, Vol. 29, 107-122.

[25] Teizer, J., Venugopal, M., and Walia, A. (2008). Ultra Wideband for Automated Real-time Three-Dimensional Location Sensing for Workforce, Equipment, and Material Positioning and Tracking. *Transportation Research Record: Journal of the Transportation Research Board*, Washington D.C., No. 2081, 56-64.

[26] Cheng, T., Mantripragada, U., Teizer, J., and Vela, P. A. (2012). Automated trajectory and path planning analysis based on ultra wideband data, *Journal of Computing in Civil Engineering*, Vol. 26, No. 2, 151-160.

[27] Melzner, J, Zhang, S., Teizer, J., and Bargstädt, H.-J. (2013). Quantification and Visualization of U.S. and German Fall Protection Standards using Automated Safety-Rule Checking in Building Information Models (BIM), *Construction Management and Economics*, Taylor & Francis, Special Issue on Occupational Health and Safety in the Construction Industry, Vol. 31, No. 6, 661-674.

[28] U.S. Bureau of Labor Statistics (2011). Incidence rates of nonfatal occupational injuries and illnesses by industry and case types, http://www.bls.gov/iif/oshwc/osh/os/ostb3191.pdf, Washington, DC.

[29] Sacks, R., Barak, R., Belaciano, B., Gurevich, U., and Pikas, E. (2012). KanBIM Workflow Management System: Prototype implementation and field testing. *Lean Construction Journal*, 19-35.

[30] Grau, D., Caldas, C.H., Haas, C.T., Goodrum, P.M., and Gong, J. (2009). Assessing the impact of materials tracking technologies on construction craft productivity, *Automation in Construction,* Elsevier, Vol. 18, No. 7, 903-911.

[31] Guo, H. L., Li, H., and Li, V. (2012). VP-based safety management in large-scale construction projects: A conceptual framework, *Automation in Construction*, Elsevier, Vol. 34, 16-24.

[32] Durovic, Z. and Kovacevic, B. (1999). Robust estimation with unknown noise statistics, *IEEE Transactions on Automatic Control*, Vol. 44, No. 6, 1292–1296.

[33] Cheng, T., Teizer, J., Migliaccio, G.C., Gatti, U.C. (2013). Automated Task-level Productivity Analysis through Fusion of Real Time Location Sensors and Worker's Thoracic Posture Data, *Automation in Construction*, Elsevier, Vol. 29, 24-39.

[34] Cheng, T., Migliaccio, G.C., Teizer J., Gatti, U.C. (2013). Data Fusion of Real-time Location Sensing (RTLS) and Physiological Status Monitoring (PSM) for Ergonomics Analysis of Construction Workers, *Journal of Computing in Civil Engineering*, 27(3), 320-335.

[35] Pradhananga, N. and Teizer, J. (2015). Cell-based Construction Site Simulation Model for Earthmoving Operations using Real-time Equipment Location Data, *Visualization in Engineering*, Springer.