Towards Near Real-time Digital Twins of Construction Sites: Developing High LOD 4D Simulation Based on Computer Vision and RTLS

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Abstract –

4D simulation can be used in the planning phase of a project for constructability analysis, which aims to optimize construction processes and improve safety management. The same 4D simulation can be used as a digital twin in the construction phase for progress monitoring and identifying potential safety issues based on micro-schedules. A micro-schedule is a schedule listing tasks of short durations (i.e., days or hours) with the information of the resources assigned to each task (i.e., workers, equipment and materials). The site data can be collected using Computer Vision (CV) or Real-Time Location Systems (RTLS) to identify and recognize the activities of construction resources, as well as to capture the progress of the project. This paper aims to explore the possibility of developing near real-time digital twins of construction sites. The digital twin is developed as a high Level of Development (LOD) 4D Simulation based on CV and RTLS data. A case study is performed to investigate the proposed method.

Keywords –

Digital Twins; 4D Simulation; Computer Vision; RTLS

1. Introduction

4D simulation through Building Information Modeling (BIM) is now widely applied and has been proved to be beneficial throughout the lifecycle of construction projects [3]. According to the results of the survey conducted by Jones and Laquidara-Carr [12], performing 4D simulation can result in reducing project cost by at least 5%. 4D simulation can be used in the planning phase of a project for constructability analysis, which aims to optimize construction processes and improve safety management [6,7,10,15,17,18,25]. The required Level of Development (LOD) of 4D simulation for different purposes are different [2,8,9]. Guevremont and Hammad [9] proposed a guideline for defining 4D-LOD for the construction project simulation based on the requirements. When more details are required, high LODs are required for both the 3D BIM model and the schedule. The highest LOD is required for proximity detection requiring in order to track the equipment movement and their workspaces.

The 4D simulation can be used as a digital twin in the construction phase for progress monitoring and identifying potential safety issues based on micro-schedules. A micro-schedule is a schedule listing tasks of short durations (i.e., days or hours) with the information of the resources assigned to each task (i.e., workers, equipment and materials). A digital twin refers to a digitization technology that integrates cyber space with physical space [1,7,23]. Grieves [7] has defined the digital twin in manufacturing, which has three parts: (a) physical objects in real space, (b) virtual model in virtual space, and (c) connections between virtual space and real space. In a digital twin model, raw data collected from the real world are processed to reveal the reality in the virtual space. Then, further processing is performed to extract useful information for improving the management of the real space. The implementation of the digital twin emerged in the manufacturing industry and became popular as one of the most important technologies toward Industry 4.0. In addition, with the emerging technologies (e.g., IoT, CV, BIM, Big Data), the digital twin becomes applicable in the construction sector [1,14]. In order to improve construction project management, previous researchers have established frameworks of generating digital twins by integrating BIM with other technologies [19,20,21]. The site data can be collected using Computer Vision (CV) or Real-Time Location Systems (RTLS) to identify and recognize the activities of construction resources, as well as to capture the progress of the project.

CV-based activity recognition of resources, such as workers or equipment, is gaining a lot of interest among researchers [5,16,22,24]. Activity recognition can be used for different purposes such as health, safety, productivity analysis, or workspace planning. There are two main challenges for monitoring the progress of construction projects using CV-based methods. The first challenge is the dynamic environment of construction sites, along with the existence of numerous types of equipment and their associated activities. The research in this area has been mainly focused on detecting the activity of workers [24] or a single type of equipment such as excavators (e.g. [5]), with works addressing more than one type of equipment only emerging recently [13]. The second challenge is that CV methods suffer from light conditions and occlusion problems. Therefore, having an additional source of information (other than the video) can help in enhancing the assumptions of the CV processes and providing a reference for tracking the progress of the project.

This paper aims to explore the possibility of developing near real-time digital twins of construction sites. First, the as-planned 4D simulation is used to provide valuable information about the spatio-temporal distribution of activities on the site, which can help focusing the scope of CV/RTLS processes. Then, the as-built digital twin is developed as a high LOD 4D Simulation based on CV and RTLS data. A case study is performed to investigate the proposed method.

2. Proposed Method

A high LOD 4D simulation can provide valuable information about the type and location of objects and activities from the 3D BIM model integrated with a micro-schedule. For example, the information from the as-planned 4D simulation related to the expected durations, locations, number of resources, and output of tasks, can be used to limit the scope of classes used in object detection and activity recognition. The as-planned 4D simulation can be also used to compare with the as-built 4D simulation based on the information extracted from the CV analysis.

The proposed method has three steps as shown in Figure 1. In the first step, the requirements are identified in the planning phase according to the purpose of the simulation. Based on these requirements, the LOD of the 4D simulation is defined. The definition of the LOD can be divided into two parts: defining LOD of the 3D model and defining LOD of the schedule. In the second step, according to the defined LODs, the 3D BIM model and micro-schedule are generated. Then, the 3D BIM model and micro-schedule are linked to generate the high LOD 4D simulation. The third step, which is in the construction phase, the 4D simulation is integrated with monitoring data from CV and RTLS for different types of applications including progress monitoring, delay claim analysis, and safety monitoring.

2.1 Identifying the required 4D LOD based on the requirements

The requirements of 4D simulation vary according to application area. For example, when generating the as-built model for progress monitoring, the focus is on the outcomes of each construction task assigned to the construction team. Therefore, the simulation is required to show the outcomes from each task clearly. For instance, as shown in Figure 2, for the construction of an isolated foundation, the focused outcomes are: (1) building footing formwork, (2) adding footing reinforcement, (3) adding column longitudinal reinforcement, (4) pouring footing concrete, (5) removing footing formwork, (6) adding column stirrup, (7) building column formwork, (8) pouring column concrete, and (9) removing column formwork. The schedule should be developed with outcomes and execution plans on a daily basis to an hourly basis, depending on the required LOD. Table 1 summarizes the requirements of 3D model and schedule for different purposes.

2.2 Developing high-LOD 4D simulation

According to the defined LODs and the corresponding requirements in the 4D simulation, the corresponding 3D model and micro-schedule can be developed. The as-planned micro-schedule can be developed in advance by the project manager or the scheduler. The video monitoring of the site can be used as the ground truth of the as-built micro-schedule. The next step is linking the 3D model with the micro-schedule. It is important to note that multiple adjustments should be performed in order to fit the 3D model with the schedule.

2.3 Integrating 4D simulation with monitoring data from CV and RTLS

2.3.1 Integrating 4D simulation with CV for productivity analysis

CV-based activity recognition approaches focus on atomic activities, such as hammering for workers [24] or digging for excavators [5]. These detailed low-level recognitions cannot be used for productivity analysis, progress tracking, or generating the as-built 4D models. However, combining a series of these atomic activities results into micro-tasks that have longer durations and can give a higher-level understanding of what is happening on the site. For example, a micro-task, such as building footing formwork, consists of a series of atomic activities, such as transporting wooden materials and hammering them, repeated over and over. In this study, the atomic activities for workers (as an example of construction resources) are obtained using YOWO53 [24] and the micro-tasks are obtained by sliding a temporal window of adaptive length on the activity recognition results and comparing the prominent atomic activities laying inside the window to the atomic activity pattern of predefined micro-tasks. The micro-task that matches these atomic activities is chosen for the first frame of the window. If no pattern is matched, the duration of the window is extended until a match is found or until the length of the window exceeds some limits. In addition, if more than a certain portion of the window is occupied by non-value adding activities (e.g. walking or standing), the micro-task is set to idling.

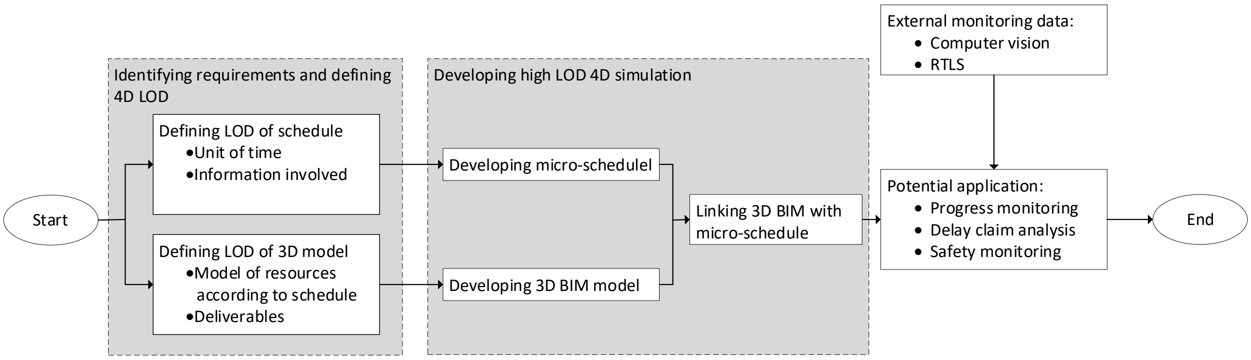


Figure 1. Proposed method

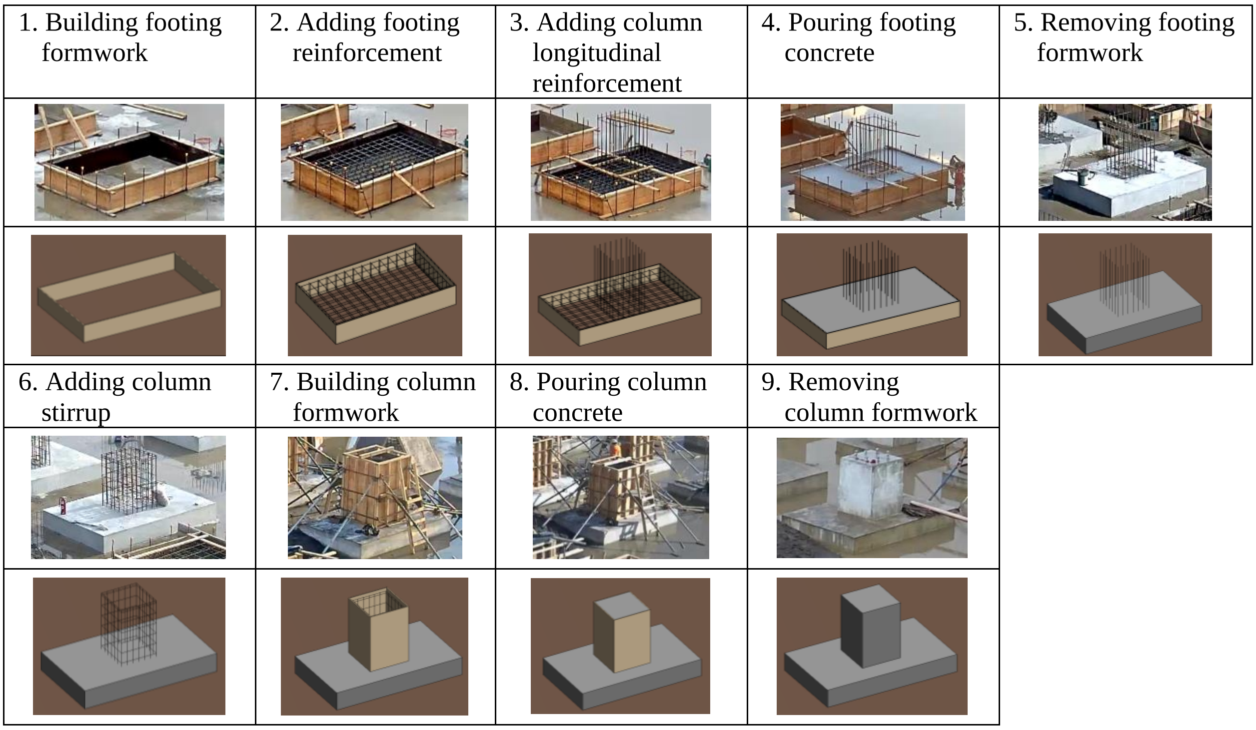


Figure 2. Micro-tasks and the corresponding outcomes

Table 1. Required LOD of 3D model and schedule for different purposes

Purpose	Required 3D BIM LOD	Required schedule LOD	Unit of time
Progress monitoring	• Outcomes after each task	• Tasks	Day to hour
Activity recognition	• Outcomes after each task • Resources (equipment, workers, materials)	• Tasks with related resources	Hour
Safety (Proximity Detection)	• Outcomes after each task • Resources (equipment, workers, materials)	• Tasks with related resources	Hour to minute

Integration of CV-based micro-task recognition and the as-planned 4D simulation helps improving the recognition. CV-based micro-task recognition can give the approximate location of micro-tasks at each frame. The approximate locations of these micro-tasks in the real world can also be derived from the pixel locations using camera calibration matrices. Having this information together with the as-planned 4D simulation helps eliminating recognition errors at different areas of the site. The as-planned 4D simulation also provides a reference for comparing the actual and expected status of the site for productivity analysis and progress tracking. For example, based on the as-planned 4D simulation, the footing formwork construction is scheduled within a specific period ($t1$ to $t2$) by n workers in a specific area of the site, and m completed footing formworks are expected at the end of this duration. CV analysis can provide similar information using micro-task recognition, tracking, and object detection methods. If the CV results do not match the expectation, this can indicate low productivity and requires investigating the underlying reasons for the poor performance. In addition, the results of CV can also be used to update the as-built 4D model with detailed data as the project moves forward, as shown in Figure 3.

2.3.2 Integrating 4D simulation with RTLS for proximity detection

RTLS have been used to collect accurate position data of workers and equipment for proximity detection. However, decreasing the number of unnecessary alerts is still a challenge. One case where proximity alerts can be considered unnecessary is when the workers and equipment belong to the same team [11]. For example, when a worker is loading materials to a telehandler, the worker and the equipment are very close and the movement of equipment is very slow. Besides, the worker and equipment operator should pay attention to each other during this task. In this case, generating alerts is unnecessary and may disturb the worker and the equipment operator, which may eventually lead to ignoring the alerts. By integrating the position data with the 4D simulation based on the micro-schedule, more details can be added to the model. This information can be used to improve the performance of proximity detection by eliminating unnecessary alerts.

3 Case study

The case study is conducted with the data collected from a construction site of an electric substation near Montreal, Canada. The dimensions of the site are 110 m × 70 m. Cameras were installed on four poles to capture the videos of the site, which were used as reference when generating the micro-schedule. In addition, RTLS sensors were installed on the poles to collect the positions of workers and equipment. Multiple isolated foundations are built in the main construction area. In this section, two examples of generating 4D simulation for different purposes are presented. In the first example, the 4D simulation is developed to act as the ground truth of progress monitoring. In the second example, the 4D simulation with high LOD is integrated with CV as the reference in activity recognition.

3.1 Developing high-LOD 4D simulation

Since in this project the simulation is mainly for post analysis, the micro-schedule is developed with site videos captured by the four cameras as ground truth. By observing the videos, the task and activities on the construction site can be identified. The task of constructing an isolated foundation can be divided into multiple micro-tasks as shown in Figure 2. The 3D model of the site is developed using Autodesk Revit based on the 2D drawings provided by the contractor. Then, using the site videos, the progress of the work is used to extract the detailed as-built schedule. Table 2 shows an example of a micro-schedule for the tasks related to building block 1C during the period of September 25 to October 30, 2019. The as-built detailed 4D model is developed using Autodesk Naviswork. Figure 4 shows the example of the 4D high LOD simulation over four days.

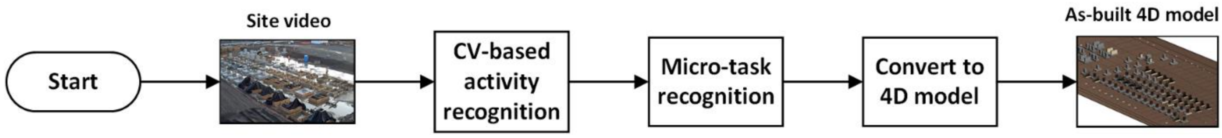


Figure 3. Developing high-LOD as-built 4D model based on activity and micro-task recognition

Table 2. Sample of a simplified micro-schedule for block 1C

Date	Time	Micro Task
2019-09-25	16:00 -17:00	Building footing formwork
2019-09-26	13:00 -14:00	
2019-10-01	11:00 -12:00	Adding footing reinforcement
	15:00 -16:00	Adding column longitudinal reinforcement
2019-10-08	09:00 -10:00	Removing footing formwork
	16:00 -17:00	Adding column stirrup
2019-10-09	07:00 -08:00	
2019-10-28	09:00 -10:00 11:00 -15:00	Building column formwork
2019-10-29	17:00 -18:00	Pouring column concrete
2019-10-30	12:00 -13:00	Removing column formwork
	15:00 -16:00	

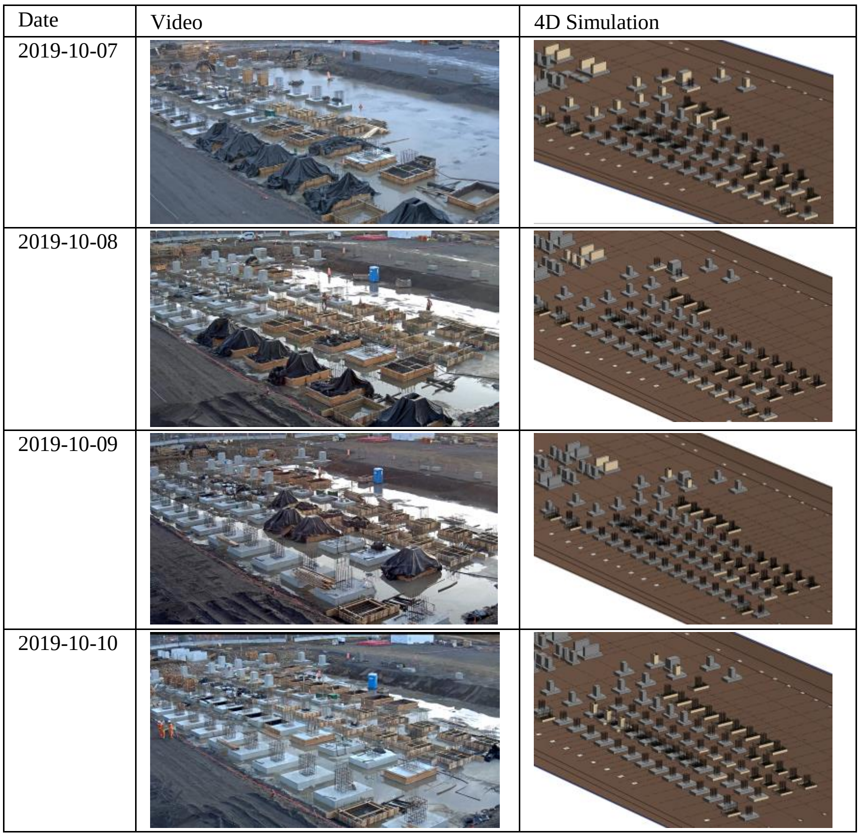


Figure 4. Example of 4D simulation during foundation phase

3.2 Activity and micro-task recognition using CV

Activity recognition using YOWO53 is first applied to two hours of formwork construction to recognized six different atomic activities (i.e., standing, walking, transporting, hammering, drilling, placing/fixing rebars). The video is recorded on 25th of September from 15:00 to 17:00. Frames are extracted at the rate of 3 FPS. The activity recognition processing is almost real-time with inference time of 2.15 hours. The atomic activities that comprise the *building footing formwork* micro-task are hammering and transporting, and the atomic activities that comprise the *adding footing reinforcement* micro-task are placing/fixing rebars and transporting. Table 3 shows the activity recognition results. The atomic activity ratio is computed by dividing the number of recognitions for each atomic activity by the total number of recognitions in the entire duration of the video. Next, micro-tasks are recognized for every non-overlapping one-hour segments of the video and are compared to the ground-truths obtained manually from the video. Table 4 shows micro-task ratios for each hour. The micro-task rates are computed similar to Table 3. The unmatched micro-tasks happen when the maximum number of window extensions is reached without finding a match as explained in Section 2.3.1. Figure 5 shows the location of workers during the same two hours based on CV. It also shows the locations of blocks. The green stars show the blocks are built during the same day, and red stars show the remaining blocks. The figure shows that the site is more congested in the proximity of the blocks that were being constructed at the time. In addition, the congestion near block 2C can be explained by the fact that the materials used for the construction of the formwork are placed at this location and workers travel there frequently.

3.3 Reducing unnecessary RTLS proximity alerts based on micro-schedule information

This test focuses on the alerts generated for the proximities between the workers and three kinds of equipment, which are a boom lift (Equipment-1), a telehandler (Equipment-2), and a crane (Equipment-3). Figure 6(a) and (b) show the images of the site and the map generated by the developed system, respectively, on January 28, 2020, at time 13:47:43. Whenever a worker enters the danger zone of equipment, the IDs of the equipment and the worker are shown on the map. Figure 6(b) shows a detected proximity of 3.21 m (Case 2) between Equipment-2 (telehandler) and Worker-A. As the micro-schedule identified that this worker and the telehandler belong to the same team, the proximity alert is not generated [11].

4 Summary and future work

This paper explored the possibility of developing near real-time digital twins of construction sites as a high LOD 4D Simulation based on CV and RTLS data. The case study shows that the proposed method can be efficient in developing the digital twin, which can be used for productivity analysis or safety management. Future work will focus on the automatic generation of the as-built real-time 4D simulation.

Table 3. Atomic activity ratios for the period of two hours (%)

Standing	Walking	Transporting	Hammering	Drilling	Placing/Fixing rebars
51.6	87.0	19.5	28.1	19.4	0.7

Table 4. Micro-task ratios (%)

Time	Building footing formwork	Adding footing reinforcement	Idling	Unmatched
15:00 -16:00	65.9	2	28.2	3.6
16:00 -17:00	93.3	0	6.4	0.1

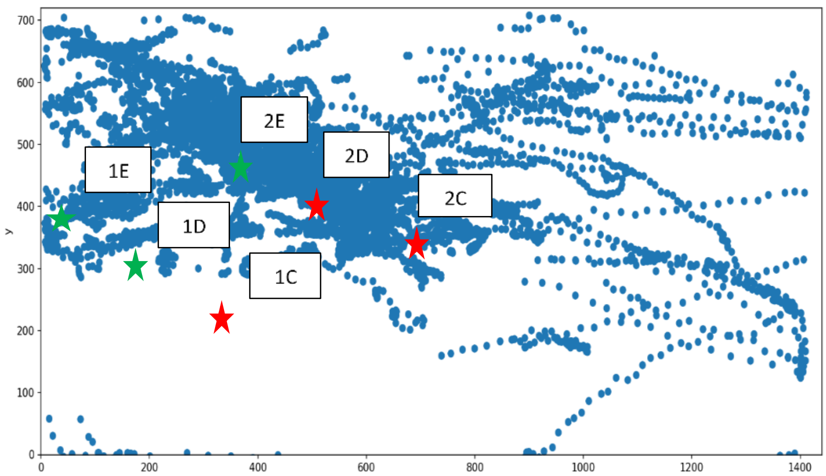
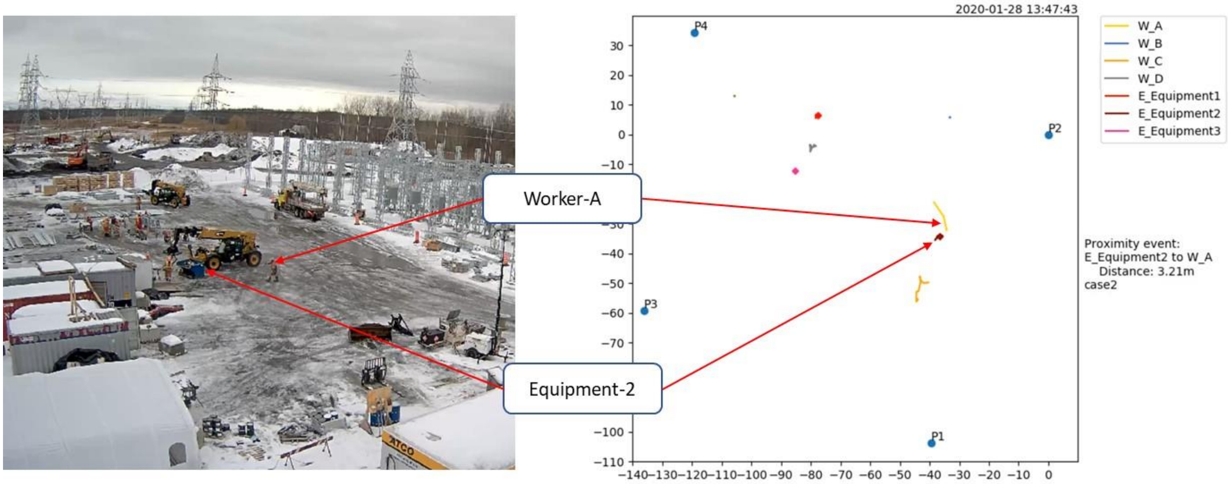


Figure 5. Worker's movement patterns during two hours



(a) Image of the site (b) Map generated by the developed system

Figure 6. Monitoring the positions of equipment and workers

References

[1] Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179, 2020.

[2] Boton, C., Kubicki, S., & Halin, G. The Challenge of Level of Development in 4D/BIM Simulation Across AEC Project Lifecyle. A Case Study. *Procedia Engineering*, *123*, 59–67, 2015.

[3] Charef, R., Alaka, H., & Emmitt, S. Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *Journal of Building Engineering*, *19*, 242–257, 2018.

[4] Chavada, R., Dawood, N., & Kassem, M. Construction workspace management: The development and application of a novel nD planning approach and tool. *Journal of Information Technology in Construction (ITcon)*, *17*(13), 213–236, 2012.

[5] Chen, C., Zhu, Z., & Hammad, A. Automated excavators activity recognition and productivity analysis from construction site surveillance videos. *Automation in Construction*, *110*, 103045, 2020.

[6] Ciribini, A. L. C., Mastrolembo Ventura, S., & Paneroni, M. Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project. *Automation in Construction*, *71*, 62–73, 2016.

[7] Grieves, M. *Digital Twin: Manufacturing Excellence through Virtual Factory Replication*. 2015. https://www.researchgate.net/publication/27521104 7_Digital_Twin_Manufacturing_Excellence_throug h_Virtual_Factory_Replication,

[8] Guevremont, M., & Hammad, A. *Multi-LOD 4D Simulation in Phased Rehabilitation Projects*. In Proceedings of the *17th International Conference on Computing in Civil and Building Engineering*, pp.724-731, Tampere, Finland, 2018.

[9] Guévremont, M. and A. Hammad. Levels of Development Definition for 4D Simulation of Construction Projects, *International Journal of Hydropower and Dams*, 27(4): 76-92, 2020.

[10] Hu, Z., & Zhang, J. BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials. *Automation in Construction*, *20*(2), 167–180, 2011.

[11] Huang, Y., Hammad, A., & Zhu, Z. *Providing Proximity Safety Alerts to Workers on Construction Sites Using Bluetooth Low Energy RTLS*. In Proceedings of the Creative Construction e-Conference, pp. 39-43, 2020.

[12] Jones, S., & Laquidara-Carr, D. (2016, July 27). *New Survey Reveals How GCs, CMs and Subs Engage with BIM*. https://www.enr.com/articles/39935-new-survey-reveals-how-gcs-cms-and-subs-engage-with-bim, Accessed: 05/08/2021.

[13] Jung, S., Jeoung, J., Kang, H., & Hong, T. 3D convolutional neural network-based one-stage model for real-time action detection in video of construction equipment. *Computer-Aided Civil and Infrastructure Engineering*, mice.12695, 2021.

[14] Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J. (2019). Digital Twin: Vision,

Benefits, Boundaries, and Creation for Buildings. *IEEE Access*, *7*, 147406–147419, 2019.

[15] Liu, Y., & Li, S. Research on Virtual Construction in the Construction Phase and Its 4D LOD Analysis. In *Proceedings of International Conference on Construction and Real Estate management 2013*, Karlsruhe, Germany, 289–297, 2013.

[16] Luo, X., Li, H., Yu, Y., Zhou, C., & Cao, D. Combining deep features and activity context to improve recognition of activities of workers in groups. Computer‐Aided Civil and Infrastructure Engineering, 35(9), 965-978, 2020.

[17] Martínez-Aires, M. D., López-Alonso, M., & Martínez-Rojas, M. Building information modeling and safety management: A systematic review. Safety science, 101, 11-18, 2018.

[18] Moon, H., Dawood, N., & Kang, L. Development of workspace conflict visualization system using 4D object of work schedule. *Advanced Engineering Informatics*, 28(1), 50–65, 2014.

[19] Pan, Y., & Zhang, L. A BIM-data mining integrated digital twin framework for advanced project management. *Automation in Construction*, *124*, 103564, 2021.

[20] Qiuchen Lu, V., Parlikad, A. K., Woodall, P., Ranasinghe, G. D., & Heaton, J. Developing a Dynamic Digital Twin at a Building Level: Using Cambridge Campus as Case Study. *International Conference on Smart Infrastructure and Construction 2019 (ICSIC)*, 67–75, 2019.

[21] Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, *1*, 2020.

[22] Sherafat, B., Ahn, C. R., Akhavian, R., Behzadan, A. H., Golparvar-Fard, M., Kim, H., Lee, Y.-C., Rashidi, A., & Azar, E. R. Automated Methods for Activity Recognition of Construction Workers and Equipment: State-of-the-Art Review. *Journal of Construction Engineering and Management*, *146*(6), 03120002, 2020.

[23] Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, *15*(4), 2405–2415, 2019.

[24] Torabi, G., Hammad, A., & Bouguila, N. (2021, July). Joint Detection and Activity Recognition of Construction Workers using Convolutional Neural Networks. *European Council on Computing in Construction*, Rhodes, Greece, 2021.

[25] Yi, S. L., Zhang, X., & Calvo, M. H. Construction safety management of building project based on BIM. Journal of Mechanical Engineering Research and Development, 38(1), 97-104, 2015.