EVM-3664

Evolving Technological Trends for Automated Construction Progress Monitoring

Dr. Bahadir V. Barbarosoglu, CCP EVP PSP

Abstract–Individuals traditionally capture construction progress data through manual efforts such as taking notes on a schedule print-out during site-walks. The quality and accuracy of the progress data collected manually depend on individuals' skills, experiences, and semi-quantitative interpretations. In the absence of supportive visual progress data such as photos and videos, the manually collected data cannot be peer-reviewed or audited by others, thus remaining as the single source of truth. In addition to being open to human errors and subjective interpretations, the traditional process of capturing construction progress data and updating project status can be complicated, time-consuming, and misleading towards incorrect conclusions, regardless of project size, type, and delivery method. Even though commercially available hardware and software technologies offer automation in construction progress monitoring, they possess limitations due to lack of standardization and are not widely adopted. This paper reviews academic research and applications in the industry for new technological developments and the recent evolution of existing technologies related to automated construction progress monitoring. The paper synthesizes parallelism between academia and the industry and finally discusses the future trends.

Table of Contents

Introduction

Most construction contracts require schedule updates at predetermined intervals to assure timely project completion. Schedule update refers to a status assessment for a project that is currently ongoing. Documents such as schedule reports and narratives are considered vital communications between the contractor and the owner. The owner must approve the schedule update process to prevent potential confusion, ambiguities, and disagreements regarding the project's status and forecasts. Disagreements caused by unapproved schedule update processes may result in cost overruns and disputes. Through continuous progress monitoring, schedule updates must maintain the expected level of quality and completeness in terms of an accurate reflection of work sequence, constructability considerations, durations, crew flows, and resource constraints [1]. Construction progress monitoring is a crucial phase in the construction project life cycle to execute project schedules successfully. It includes but is not limited to the critical tasks such as timely and accurate as-built data collection and robust analysis of the data. Changes in activity status, activity logic, activity duration, the occurrence of unplanned events, unforeseen constraints, and changes in resource calendars and availability are among the as-built data that are expected to be captured by monitoring progress to have a healthy schedule update and execution plan. While efficient progress monitoring significantly impacts a construction project's success, it is often regarded as a challenging task, especially when the level of project complexity and schedule activity interdependencies are high [1], [2]. Even under challenging circumstances, the construction progress monitoring process is expected to be carried out periodically.

The project status captured at the activity level as an outcome of the progress monitoring process is compared against the baseline schedule and baseline cash flow projections. The comparison identifies how much the status deviates from the plan regarding schedule and cost [3]. The comparison also aims to assure that the project proceeds according to the plan, the project forecasts on time and budget at completion, and risks related to cost and schedule are identified and mitigated throughout the project [4]. Construction progress monitoring does not only track time and cost requirements but also measures quality performance. Efficient progress monitoring, time management, cost control, and quality performance are correlated at a level of statistical significance. Timely project control decisions to take preventive and corrective actions require an efficient progress monitoring mechanism that reflects the most current state of quality, schedule, and cost performances [2]. Unfortunately, the current practice of construction progress monitoring is inefficient due to manual effort and reliance on individuals' experience and dedication.

In the current practice, the construction progress monitoring and reporting are carried out by the different construction industry practitioners. Construction progress interpretations made by individuals are often infrequent, subjective, and may require excessive manual effort [4], [5], [3]. The unsystematic and low-quality outcomes of the conventional construction progress monitoring method do not generate the prompt and clear communication required to identify issues and take remedial actions [2]. Lack of capturing real-time construction progress data results in imprecise and less accurate schedule updates. Schedule inaccuracy leads to allocating budget and workforce in the wrong place at the wrong time [6], [7]. A significant amount of construction projects is behind schedule and over budget due to inability of systematic and accurate progress monitoring [8], [6]. Contractors are often paid based on periodic progress reports (i.e., weekly, monthly, quarterly) that are the output of questionable progress monitoring processes [4]. Considering how much impact progress monitoring and reporting have on contractors' periodic payments, relying on individuals' interpretations may be insufficient and misleading, and it jeopardizes the overall project success.

The time consumption and inefficiencies of manual construction progress monitoring increase as construction projects become more complex and dynamic. Construction progress must be monitored more accurately and timely to minimize waste and increase project success. Deployment of automated progress monitoring systems is inevitable to gain and maintain a competitive advantage in the construction industry [3]. Commercially available hardware and software technologies promise automated, timely, and accurate construction project monitoring methods and systems. However, the potential benefits of automated construction progress monitoring over conventional manual efforts have not been well understood or explored by the construction industry [2]. The construction industry's current state does not allow feasible outcomes from using such technologies in most cases. Inconsistent construction processes differing from one project to another prevents standardized data collection and require heavy involvement in manual data collection. The nonstandard data collection is currently a bottleneck towards efficient and economical use of automated construction progress monitoring systems [7].

Literature Review

Technology Adoption in the Construction Industry

Mobile devices such as smartphones and tablets are commonly used in day-to-day operations. Over 90% of the industry uses smartphones, and around 65% of the industry uses tablets for work purposes daily. 63% of the industry uses 3 to 6 mobile applications to document and communicate field construction data that used to be documented manually. Building information modeling (BIM), time management, and scheduling are among the most common reasons for mobile application usage in the field [9].

Many construction projects carry out planning efforts and risk identification processes using a BIM model that is an accurate virtual model of a construction project. Construction projects can now be simulated in a 4D virtual environment that visualizes design, procurement, fabrication, and construction efforts necessary for project delivery [10]. 4D refers to an integration of a 3D model and a schedule. Terms such as 4D BIM, 4D model, 4D schedule, and 4D simulation are often used synonymously to refer to the same concept [11]. A 4D BIM model can be used to demonstrate the whole life cycle of a project, and it can also be used in the phase of operation and maintenance [10]. BIM-centric project management is a well-established method that facilitates and enhances project delivery. Real-time data, including actual performance and construction progress status at the activity level, are captured timely and accurately and better understood using BIM [12]. 26% of mobile BIM usages in the field relates to scheduling and construction progress monitoring [9]. Even though BIM, in some context, is referred to like a technology or a tool, it is a much broader concept that integrates technologies, automation, and innovations to capture big data and use it for better project and operations management.

More than half of the construction companies have a defined process, dedicated employees, and allocated budget for testing and implementing innovative technologies that integrate with 4D BIM and construction progress monitoring. Unmanned aerial vehicles (UAV), robotics, laser scanners, and augmented reality goggles are among the most used innovative technologies for construction progress monitoring. These innovative technologies allow big data to be automatically captured by advanced hardware and transformed into meaningful information by advanced software and algorithms. Over 20% of the construction industry has benefited from visual status monitoring technologies with artificial intelligence and machine learning. 46% of the industry believe technological adaptations will impact future profitability [9]. Even though the construction industry has been criticized for lagging other industries on adopting technologies, the construction industry's status shows that the industry has invested and adopted technologies that aim to eliminate manual efforts and human errors by automating construction progress monitoring and status update processes. Safety and security, hardware, schedule, standardization in capturing data and communication are primary factors to consider while deploying automated construction progress monitoring technologies.

Recommended Practices to Deploy Progress Monitoring Technology

Hardware type (i.e., laser scanner, digital camera, smartphone, tablet), integration with other technologies, owning and operating costs, zoom capability (i.e., optical, digital), image resolution levels, geotagging feature (i.e., GPS coordinates), timestamp, and safety regulations are among the factors to consider while selecting hardware technology for construction progress monitoring. Safety regulation must be reviewed in advance and must not be violated while capturing project status. Necessary permissions regarding proprietary information protection must be obtained before capturing project status visuals [13].

Computerized and automated methods are very efficient and accurate to monitor construction progress. They are more effective than the frequently used narratives on communicating the project status. However, critical important status and progress information is not captured when there is a lack of standardized progress monitoring approaches. The project's schedule should determine the scope of progress monitoring for standardization. The critical areas and look-ahead activities outlined by the schedule must be covered during visual progress monitoring. The status of building elements should be visually captured multiple times at similar coordinates to provide transparent information of status and progress. Taking visual media repeatedly over time in a sequential manner (i.e., according to schedule time and logic) establishes a significant portion of as-built construction progress documentation [13]. Successful implementation of an automated construction progress monitoring system requires standardized data collection procedures, progress monitoring, activity monitoring, and reporting. The construction progress data collected in the field can be visuals, sensor readings, and semantics, and they can be in terms of photos, videos, and point clouds. The data collection can be done using phones, drones, and laser scanners. Considering progress data are captured in several different formats, and various hardware are used to collect the data, the data collection process should be standardized for data quality and completeness [14].

Common Technological Methods of Construction Progress Data Acquisition

Most technological developments regarding automated construction progress monitoring systems aim to capture the as-built status of projects from point clouds generated by visual methods such as laser scanning, photogrammetry, and videogrammetry technologies (Kopsida et al., 2015; [15].

The term photogrammetry is composed of the following words: photos, gramma, and metron. These Greek words mean light, description, and measurement, respectively. Photogrammetry is the science of obtaining measurements from photos [16]. In photogrammetry, three-dimensional coordinates are calculated using multiple pictures of an element from different positions [17].

Videogrammetry is a branch of photogrammetry. Videogrammetry obtains three-dimensional coordinates of an object by using images extracted from video frames. Videogrammetry can be more advantageous on moving elements compared to photogrammetry [18]. Videogrammetry can be very useful in some 3D model generation cases, such as generating as-built 4D construction models because video frames are captured sequentially and progressively [19].

Generating point clouds using the laser scanning method is usually more expensive than its alternatives, and it requires skilled operators and a relatively longer duration to process the point cloud data. Videogrammetry requires long data processing duration and may result in lower quality images due to a higher number of noises. Considering the time, quality, and cost constraints, photogrammetry is often the most feasible method of generating as-built point cloud data than laser scanning and videogrammetry [15]. However, the construction progress data acquisition method should be selected based on the specific nature and dynamics of projects.

Laser Scanning and BIM

Deploying a laser-based automated progress monitoring system requires capital investment to acquire the hardware and translate the raw data into meaningful information. The system's feasibility and usefulness should be evaluated case-by-case and according to the project needs [3]. Integration of laser scanning and BIM models is a common approach to laser-based automated progress monitoring. In this approach, construction progress is captured by multiple laser scans over time. The as-built data obtained by laser scanning are in terms of point clouds. The progress data are compared against a performance measurement baseline that is digitally structured using a 4D BIM platform based on the critical path method (CPM) schedule. The comparison between the as-built point clouds and the as-planned 4D BIM model quantitatively analyzes the construction progress and the project's status. An early case study of automating construction progress monitoring by integrating laser scanning and 4D BIM indicated 80-90% accuracy [5]. A recent case study conducted on a construction project used a similar system with laser scanners and a 4D BIM model. The system successfully automated every step of the schedule update process, including obtaining as-built progress data from the field and updating the schedule accordingly [8].

Laser-based automated progress monitoring systems can involve cameras in addition to the laser scanning hardware. The main goal of using laser scanning and cameras is to capture project status and progress of the areas that are not within the coverage of laser scanning hardware. The progress of the areas that are not visible to the laser scanning hardware is documented by taking pictures. The 2D pictures are translated to point clouds and combined with the point clouds of the laser's areas scanned. The point clouds reflecting the project's status and progress are aligned with the 4D BIM model by georeferencing. The point clouds that are not within the 4D BIM model's scope are identified as noise and removed from the data set to prevent misinterpretation. The automated system quantitatively and semantically analyzes the construction progress by comparing the point clouds and the 4D model in terms of geometries and texture using color-based object recognition methods. A recent case study conducted on commercial and industrial projects using a laser scanner and UAV-mounted cameras showed that a laser-based automated progress monitoring system could achieve 90% accuracy in capturing real-time as-built construction progress [6].

Fixed Cameras, Photogrammetry, and BIM

Using fixed cameras to capture progress data and analyze the data by image processing algorithms is a common photogrammetric approach of automated construction progress monitoring. In this approach, fixed cameras capture construction progress images at predetermined intervals. The images are normalized to disregard uninterested effects (i.e., light, shadow, fog, rain, snow). The images are then evaluated to whether the detected changes are within the plan indicated by the 4D BIM model. The schedule accuracy in terms of reflecting the status and forecasting the future sequence of activities is highly correlated with the accuracy of this automated progress monitoring approach. An early example of this approach was tested through a case study conducted on a school building project where the automated system took progress pictures of columns at three different elevations every 20 minutes during the shift for four months. The accuracy of progress detection achieved in the case study suggested that automated construction progress monitoring with the integration of 4D BIM model, fixed cameras, photogrammetry, and image processing algorithms is feasible and robust [4].

Point cloud generation using cameras like laser scanners also falls in the research area of photogrammetry. Using a crane-mounted fixed camera is an approach to automated construction progress monitoring. In this approach, the system is set to take pictures every time the crane boom moves. The image processing algorithm converts pictures to 3D point clouds.

The non-building elements within the point clouds are identified and removed by the algorithm. The remaining point clouds reflecting the building elements are laid over the 3D BIM model by georeferencing, and the automated system determines construction progress. Automated construction progress monitoring using a crane-mounted fixed camera and point clouds was experimented in a recent case study of a high-rise construction project. The experiment showed that the system is very accurate and precise in distinguishing building and non-building elements, aligning as-built 3D point clouds and 3D BIM models using georeferencing and updating construction activity status (i.e., form and rebar concrete slab). However, the study indicated that the full coverage of construction projects is not possible with fixed cameras and timely processing of large amounts of 3D point cloud data requires high computational power [7].

Image processing using two fixed cameras covering the same area is another photogrammetric method of construction progress monitoring, and it is often referred to as stereo vision. Image processing with stereo vision systems refers to using multiple sensors to capture 3D data from the same perspective (i.e., right image vs. left image). Stereo vision systems capture 2D images and 3D spatial data. Values that are not found in both data sets are considered noise. Noises are reduced using image improvement processes. The remaining data are converted to an as-built 3D model. The as-built 3D model generated by the proposed system is compared against the as-planned 3D BIM Model [3]. A recent case study using commercially available cameras to capture construction progress from a stereo vision perspective validated the robustness of the approach for both interior and exterior construction activities. The quantities calculated by the automated system were compared with the quantities obtained from the as-planned 3D BIM model. The case study showed that the system could automatically capture real-time construction progress with 99% accuracy [15].

Moving Cameras, Photogrammetry, and BIM

Construction pictures captured by moving cameras, such as mobile phone cameras, are also used for photogrammetric analyses of construction progress. The semantic data captured along visual data are processed by image processing and deep learning algorithms. For example, an automated progress monitoring system using mobile phones can use a mobile application (i.e., Android OS) to capture progress in visuals and semantic data. The progress data include but are not limited to location (i.e., unit number), picture, task (i.e., schedule activity, work package, trade), and status (i.e., not started, in-progress, completed). The system feeds the deep learning algorithm with the photos and progress data captured using the mobile application. A system using mobile phone cameras, image processing, and deep learning algorithms to automate construction progress monitoring was tested through a case study on real-time bathroom and kitchen renovation projects that spanned multiple renovation stages. The case study showed that the current image processing technologies' accuracy in detecting construction progress depends on data labeling quality. It was suggested that the feasible and commercial deployment of such technologies requires standardized data collection processes [7].

Cameras mounted on UAVs are another example of moving camera application in automated construction progress monitoring systems. Progress pictures captured by UAVs can be processed using image processing and optimization algorithms and integrated with 4D BIM platforms. UAVs can be programmed for monitoring specific targets (i.e., areas, building elements) determined by parametric inputs. The initial parametric inputs to the system compose an accurate description outlining the scope and targets of progress monitoring and addressing 4Ws and 1 H (i.e., what, when, where, why, and how). The scope and targets of progress monitoring can be defined using parametric filters such as building element geometry and type, schedule activities, schedule performance index, resources, date and time of progress inspection, landing, take-off locations, and information related to 3D geofencing and safety requirements. The system reviews the 4D model and extracts 3D data and semantics that satisfy the parametric filters' scope and target criteria. The system then identifies coordinates that provide the UAV a full coverage of progress monitoring for the defined scope and target requirements. UAV monitors the progress of the scope and target by UAV taking 2D pictures. Such a system was recently tested through case studies containing different scopes and targets for progress monitoring. The case studies validated that the system can successfully conduct automated progress monitoring for specific targets meeting parametric criteria such as schedule performance index (i.e., partitions behind schedule), building element type (i.e., standard duplex), resources (i.e., subcontractor A), and scheduled activities (i.e., Activity ID 1020-1040) [20].

Moving Cameras, Videogrammetry, and BIM

Some projects still heavily rely on 2D CAD plans even though BIM adoption has been increasing [9]. With the advancement of technologies, accurate as-planned 3D models are generated by integrating 2D CAD and geographic information system (GIS) platforms even if the project lacks a 3D model. Construction progress monitoring can be automated using a system that integrates image processing and optimization algorithms, UAVs, CAD plans, and GIS. The system monitors the progress through a video recorded by a UAV. The video frames are then converted to 2D pictures that compose an as-built 3D model. The as-built 3D model is georeferenced to the as-planned 3D model obtained by integrating CAD models and GIS. The point clouds existing in both as-built and as-planned 3D models are identified, and their density is analyzed to determine whether it indicates construction progress on a binary base (i.e., built, not-built) [21].

Industry Applications

The research conducted in academia and technologies and adopted in the construction industry is significantly correlated, especially in the methods used in image processing. The construction industry has been recently testing autonomous technologies such as drones and robots that can be used for automated construction progress monitoring.

A software solution by Pix4D automates construction progress monitoring using drones. Autonomously flying drones take progress pictures uploaded to the cloud for image processing and photogrammetric analysis that measure and determine the project's status and progress. The analysis result is also uploaded to a 4D software program such as Synchro Pro for as-built and as-planned schedule comparison [22].

Boston Dynamics' Spot is an autonomous quadruped robot used mainly by general contractors in the industry for automated construction progress monitoring. 3rd party hardware such as cameras and laser scanners are mounted to the robot and integrated with the existing information and communication systems. The robot is programmed for custom autonomous missions using the software development kit [23]. Boston Dynamics has recently partnered with companies like HoloBuilder, FARO, Hilti, and Trimble to integrate BIM platforms like Revit, Trimble Connect, and BIM360 with their robot to maximize real-time autonomous and automated construction progress monitoring abilities. The robot walks the site through a path, collects and documents progress information using artificial intelligence provided by HoloBuilder. The robot is mounted with FARO's laser scanning technologies to maximize the amount of progress data captured by the robot during site walks. The robot is also equipped with Trimble and Hilti's reality capture devices that sync the robot with cloud-based construction management platforms and communicate real-time as-built progress data [24]. However, general contractors deploying the robot as an automated construction progress monitoring system do not have to use Boston Dynamics' partners' hardware and software.

In a case study by Swinerton, one of the top general contractors in the US, the robot was equipped with a laser scanner produced by Kaarta and integrated with a BIM-based cloud platform for construction management offered by Avvir. The case study was conducted in a medical office building construction. The robot was programmed to walk the site autonomously. The point clouds captured by the laser scan during the site walk were optimized by the robot's on-board image processing capabilities. The processed point clouds are communicated to the Avvir platform, where scans were analyzed and compared against the BIM model containing metadata such as BIM element ID, schedule activity ID, material type, and system type. The comparison immediately produced and communicated reports of current project progress and quantities of installed materials to the project team. The case study indicated that the automated construction progress monitoring system using the robot and its integrated systems contributed significantly to project management, especially in payment applications, schedule updates, and cost forecasts [25].

The partnership between Oracle and Reconstruct is another example of an application on automated construction progress monitoring. The integration of Oracle Aconex, Primavera P6, and Reconstruct composes a platform where construction progress data, documentation, quality control, drawings, BIM models, and schedule are united. The progress data are captured using any camera. The platform creates a digital presentation of project status using real-time data. The schedule impacts of both planned changes and unforeseen events are visually distinguished in the platform [26].

Discussion and Conclusion

The review of the current research conducted in academia and the industry trends within the past 15 years indicates that image processing technologies are the most researched and promising method for automated construction progress monitoring systems. BIM integration is a must-have feature. The findings of the case studies and recent industry applications reviewed in this paper suggest that construction projects will soon commonly deploy automated progress monitoring systems with the following technological features and capabilities.

- Automated progress monitoring with specific scope and target
- Progress monitoring scope and target extraction from 4D BIM model
- Building element recognition with deep learning and optimization techniques
- Image-based as-built data collection and as-built 3D model creation
- As-built and as-planned 4D BIM model comparison
- Schedule update with as-built 4D BIM model
- Parametric and semantic variance analyses between as-planned and as-built
- Programmable all-terrain robot mounted with sensors, GPS, LIDAR, and cameras

Commercially available hardware and software are advanced enough to meet the technical infrastructure required to deploy efficient automated construction monitoring systems. However, the nonstandard data collection and processing procedures are the bottlenecks towards efficient and economical use of automated construction progress monitoring systems. Academia and the construction industry should continue working collaboratively to establish best practices and standards for automated construction monitoring systems.

References

1. AACE International, Recommended Practice No. 53R-06, Schedule Update Review–as Applied in Engineering, Procurement, and Construction, AACE International, 2008.
2. S. Alizadehsalehi and I. Yitmen , "A Concept for Automated Construction Progress Monitoring: Technologies Adoption for Benchmarking Project Performance Control," *Arabian Journal for Science and Engineering,* vol. 44, no. 5, pp. 4993-5008, 2019.
3. N. Choi, H. Son, C. Kim, C. Kim and H. Kim, "Rapid 3D Object Recognition for Automatic Project Progress Monitoring Using a Stereo Vision System," in *Proceedings of the 25th ISARC*, Vilnius, Lituania, 2008.
4. T. C. Lukins and E. Trucco, "Towards Automated Visual Assessment of Progress in Construction Projects," in *British Machine Vision Conference*, Warwick, UK, 2007.
5. F. N. Bosche, C. Haas and P. Murray, "Performance of automated project progress tracking with 3D Data fusion," in *Annual Conference of the Canadian Society for Civil Engineering*, Québec, Canada, 2008.
6. K. Han, J. Degol and M. Golparvar-Fard, "Geometry- and Appearance-Based Reasoning of Construction Progress Monitoring," *Journal of Construction Engineering and Management,* vol. 144, no. 2, 2018.

7. O. Seppänen, Y. Xiao, M. K. Masood, P. Byshev, T.-A. Pham, A. Aikala and P. Lundström, "Reality Capture (RECAP) Project Final Report," Aalto University, Espoo, Finland, 2020.
8. H. Son, C. Kim and Y. K. Cho, "Automated Schedule Updates Using As-Built Data and a 4D Building Information Model," *Journal of Management in Engineering,* vol. 33, no. 4, 2017.
9. JBKnowledge, "The 9th Annual Construction Technology Report," JBKnowledge, Station, TX,, 2020.
10. S. Azhar, "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry," *Leadership and Management in Engineering,* vol. 11, no. 3, 2011.
11. J. Jupp, "4D BIM for Environmental Planning and Management," *Procedia Engineering,* vol. 180, pp. 190-201, 2017.
12. S. Tang, D. R. Shelden, C. M. Eastman, P. Pishdad-Bozorgi and X. Gao, "A review of building information modeling (BIM) and the Internet of Things (IoT) Devices Integration: Present Status and Future Trends," *Automation in Construction,* vol. 101, pp. 127-139, 2019.
13. AACE International, Recommended Practice No. 95R-18, Construction Photography to Document Project Status, AACE International, 2019.
14. J. J. Lin and M. Golparvar-Fard, "Construction Progress Monitoring Using Cyber-Physical Systems," in *Cyber-Physical Systems in the Built Environment*, Berlin, Germany, Springer, 2020, pp. 63-87.
15. H. Mahami, F. Nasirzadeh, A. H. Ahmadabadian and S. Nahavandi, "Automated Progress Controlling and Monitoring Using Daily Site Images and Building Information Modelling," *Buildings,* vol. 9, no. 3, p. 70, 2019.
16. J. Valença, E. Santos Julio and H. J. Araújo, "Applications of Photogrammetry to Structural Assessment," *Experimental Techniques,* vol. 36, no. 5, pp. 71-81, 2012.
17. W. Linder, "Example 3: Some Special Cases," in *Digital Photogrammetry*, Berlin, Germany, Springer, 2009, pp. 111-140.
18. A. Gruen, "Fundamentals of Videogrammetry — A review," *Human Movement Science,* vol. 16, no. 2-3, pp. 155-187, 1997.
19. I. Brilakis, H. Fathi and A. Rashidi, "Progressive 3D Reconstruction of Infrastructure with Videogrammetry," *Automation in Construction,* vol. 20, no. 7, pp. 884-895, 2011.
20. H. Hamledari, B. McCabe, S. Davari, A. Shahi, E. Rezazadeh Azar and F. Flager, "Evaluation of Computer Vision and 4D BIM-Based Construction Progress Tracking on a UAV Platform," in *6th CSCE/ASCE/CRC International Construction Speciality Conference*, Vancouver, Canada, 2017.
21. J. R. Bognot, . C. G. Candido, A. C. Blanco and J. R. Y. Montelibano, "Building Construction Progress Monitoring Using Unmanned Aerial System (UAS), Low-Cost Photogrammetry, and Geographic Information System (GIS)," *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences,* vol. 4, no. 2, 2018.
22. Pix4D, "Boosting 4D Project Management with Drone Mapping," Pix4D, 11 June 2020. [Online]. Available: https://www.pix4d.com/blog/boosting-4D-project-management-with-drone-mapping. [Accessed 28 January 2021].
23. G. Wood, "Construction Site Mobility Robot Spot 2.1 Released," For Construction Pros, 23 November 2020. [Online]. Available: https://www.forconstructionpros.com/construction-technology/press-release/21204245/boston-dynamics-construction-site-mobility-robot-spot-21-released. [Accessed 28 January 2021].

24. Boston Dynamics, "Unlocking Jobsite Data with SPOT," Boston Dynamics, 19 November 2019. [Online]. Available: https://www.bostondynamics.com/11-19-2019. [Accessed 28 January 2021].
25. Swinerton, "Spot Robot Dog Spotted in Redwood City," Swinerton, 5 August 2020. [Online]. Available: https://swinerton.com/blog/swinerton-healthcare-and-innovations-team-partner-with-avvir-and-kaarta-on-new-technology/. [Accessed 28 January 2021].
26. R. Roske, "Oracle-Reconstruct Integration Enhances Visual Construction Progress Tracking, Remote Monitoring," Oracle, 14 April 2020. [Online]. Available: https://blogs.oracle.com/construction-engineering/oracle-reconstruct-integration-enhances-visual-construction-progress-tracking,-remote-monitoring#:~:text=Oracle%2DReconstruct%20Integration%20Enhances%20Visual%20Construction%20Progress%20Tracking%2C%20Rem. [Accessed 28 January 2021].

Dr. Bahadir V. Barbarosoglu, CCP EVP PSP
Aegis Project Controls
bvbarbarosoglu@gmail.com