Summary for CIFE Seed Proposals for Academic Year 2017-18

Proposal number:	2017-06
Proposal title:	Using UAVs for Automated BIM-based Construction Progress Monitoring and Quality Control
Principal investigator(s)[1] and department(s):	• Martin Fischer, Civil and Environmental Engineering • Silvio Savarese, Computer Science
Research staff:	• Hesam Hamledari, Graduate Student, Civil and Environmental Engineering • Forest Flager, Research Associate, Civil and Environmental Engineering
Total funds requested:	$ 66,381
Project URL for continuation proposals	Not Applicable
Project objectives addressed by proposal[2]	Buildable, Operable
Expected time horizon	2 to 5 years
Type of innovation	Breakthrough
Abstract (up to 150 words)	The problem: The construction of our built environment today is often managed without a current and accurate understanding of as-built condition on site, leading to poor project cost and schedule conformance. The proposed solution: A method to automatically update objects in the Building Information Model (BIM) to reflect the as-built condition and to inform stakeholders of potential quality control and schedule issues associated with current site conditions so that necessary corrections can be made at a highly accelerate rate. The proposed research approach: We propose to create an automated workflow integrating three technologies: unmanned aerial vehicles (UAVs), computer vision and BIM. First, UAV will be used to efficiently capture a point cloud representation of the as-built condition. Second, computer vision will identify constructed objects from the point cloud geometry and automatically update their position in the BIM. Finally, the as-built and as-designed BIMs will be compared to update the project schedule and to inform stakeholders of potential quality control issues.

[1] The PI(s) must be academic council member(s) at Stanford.
[2] For this and the next points, delete the answers that don't apply to your proposal.

1. ENGINEERING OR BUSINESS PROBLEM

The vast majority of Architecture, Engineering, and Construction (AEC) projects run over budget and schedule (Yang et al. 2015). Reworks are a primary source of overruns, and the 6% of costs during the construction phase have been associated with this activity (Josephson and Hammarlund 1999). The main cause of reworks is the lack of access to reliable data with respect to the as-built conditions at sites (Akinci et al. 2006; Love and Li 2000). The robust identification of defects and communication of their status to project teams can significantly improve quality, cost, and schedule, the three key performance indicators of a project (Chan and Chan 2004).

Building information modeling (BIM) can provide information-rich documentations of design data and can potentially facilitate the efficient communication of as-built conditions. According to the US National Building Information Model Standard Project Committee "A BIM is a shared knowledge resource of information about a facility forming a reliable basis for decisions during its *lifecycle*." (Committee 2017). Currently, the vast majority of BIMs, however, reflect only the design status of a building and not the other phases of a building's life cycle such as construction or operation (Akcamete, Akinci, and Garrett 2009). As such, they cannot form a reliable basis for decision making througout the building's lifecycle (Akinci 2015).

Although some physical characteristics related to the as-built status are currently obtained manually or using data capture tools, limitations exist with respect to the automated detection and in-BIM modeling of construction and operation status, as well as functional characteristics. As-designed BIMs lose their effectiveness over time due to design inconformity and schedule/cost variations (Ding, Zhou, and Akinci 2014). Hence, they do not accurately reflect the as-built and as-is conditions (Lu and Lee 2017). The timely identification of state of construction progress and design inconformity facilitates situational awareness (Akinci 2015; Yang et al. 2015). More importantly, the integration of such information into the as-designed BIMs ensures reliable access to a project's data and supports integrated model-based approaches.

There is a need for solutions that not only ensure timely acquisition and analysis of as-built conditions, but also provide a reliable and interoperable means of updating as-designed BIMs. In fact, recent studies have identified the lack of robust site data integration into BIMs as a main barrier to BIM implementation (Ding, Zhou, and Akinci 2014; Volk, Stengel, and Schultmann 2014) and one of the grand challenges of the construction industry (Leite et al. 2016).

The existence of integrated model-driven solution for automated measurement and in-BIM modeling of construction status can enhance the manmade structures in terms of Buildability. It facilitates processes such as construction progress monitoring, the identification of deviations between as-designed and as-built statuses, and robust integration of site data into models which are vital to reducing cost and schedule overruns (Yang et al. 2015; Akinci et al. 2006). This research also has the potential to support Operability and Sustainability in future (please see section 8: Next Steps). The in-BIM as-built documentation can potentially guide the operation and maintenance of a facility by providing information about visible and hidden elements, and the timeline of modifications; it also ensures continuous use of BIM throughout the project's life cycle due to its integration of reality into virtual models.

2. THEORETICAL AND PRACTICAL POINTS OF DEPARTURE

2.1. UAV-Based Reality Capture

The recent improvements in the design of low-weight unmanned aerial vehicles (UAV) has increased their popularity among AEC researchers and practitioners. These devices are easily available at relatively low costs and provide high maneuverability, suitable for data capture at construction sites. Because of this, they provide fast, low-cost, and easy access to actual sites data (Ham et al. 2016). The use of UAVs can increase the coverage and completeness of collected data (McCabe et al. 2017) and automate some of the processes associated with reality capture solutions such as terrestrial laser scanning, manual image capture, and radio frequency identification (RFID).

The use of UAVs can potentially streamline the site-to-BIM data transfer and facilitate both the analysis and in-BIM documentation of the captured data. This is because UAVs can act as robust multi-sensory platforms and provide support for the construction monitoring methods which are based on photogrammetry, laser scanning/LiDAR, and RFID. Hence, the use of both off-the-shelf and custom-designed UAVs has been studied for various applications such as vision-based quality inspections (Roca et al. 2013), infrastructure monitoring (Yan et al. 2016), photogrammetry-based surveying (Siebert and Teizer 2014), and computer vision-based construction monitoring (Hamledari et al. 2017c; Lin, Han, and Golparvar-Fard 2015).

This has created a unique opportunity for the integration of this data capture platform with BIM- and virtual design and construction (VDC)-based solutions. With this regard, frameworks and formalisms have been developed in support for the UAV's robust use in support of computer vision-based construction monitoring and quality control practices (Hamledari 2016; Lin, Han, and Golparvar-Fard 2015). Despite these developments, the UAV-based construction monitoring is still in its infancy and suffers from a series of limitations. A holistic and life cyclic view should be employed to design an integrated UAV-based platform which facilitates the robust integration of data capture, visual data analytics, automated model update, and model-based communication of results.

To reduce data lost and ensure high utilization of information-rich project models, different reality capture techniques need to be evaluated on the UAV platform in terms of suitability for computer vision-based object recognition and other downstream applications such as automated 3D and 4D BIM updates. In this regard, the accuracy of the object localization within BIMs should also be investigated since it is crucial to accurate geometry update.

2.2. Automated BIM Update

Both researchers and practitioners have been interested in achieving regular model updates. This is partly due to the current need for solutions that are capable of integrating site data into BIMs, and also due to the high costs and level of effort associated with manual updates. Conventionally, modelers need to manually detect the discrepancies, identify the corresponding elements, and update them. This is a time-consuming, inefficient, and costly process, proven to hamper BIM use (Becerik-Gerber et al. 2011).

To address this issue, some studies have focused on integrating progress assessments into the models by updating the schedule using proprietary solutions and importing the results into CAD/BIM (Kim, Kim, and Kim 2013; Son, Kim, and Kwon Cho 2017). Others have focused on directly updating IFC-based BIMs using UAV-captured images and without reliance on proprietary solutions (Hamledari, McCabe, and Davari 2017a; Hamledari et al. 2017b).

Despite these advancements, the automated BIM updating is still far from maturity (Teicholz 2013; Hamledari et al. 2017b); The lack of robust site data integration into models has proven to discourage industry practitioners from fully adopting BIMs (Lopez et al. 2015). This necessitates the development of automated solutions in this domain. Further, the existence of reliable data acquisition and BIM updating techniques can potentially increase life-cyclic use of BIM, particularly in the facility management (Becerik-Gerber et al. 2011).

While some of the existing industry solutions (e.g., Skur and Verify 1.0) offer comparison between as-built point clouds and as-designed models, the results are underutilized due to the lack of automated modeling techniques. In other words, the design discrepancy analysis should not only be used for the communication of detected issues, but more importantly to automatically update the as-designed BIMs; more importantly, such results should be used for automated in-model documentation of schedule and quality, crucial to life-cyclic use of BIM. The modeling and documentations of such data facilitates the model-based communication of site conditions, increases transparency, and enhances the accuracy of models.

Additionally, the use of UAV-captured data for automated updating of as-designed BIMs needs to be investigated. For example, the geometrical or temporal deviations from design data should automatically be reflected into BIMs. In developing such techniques, effort needs to be concentrated on the design of interoperable and non-proprietary solutions that facilitate data communication between stakeholders and during different stages of a project's life cycle. The costs associated with the lack of interoperability is estimated at $15.8 billion per year in United States (Gallaher et al. 2004) and has been recognized as the most important challenge in the construction information modeling domain (Leite et al. 2016). Currently, most solutions rely on proprietary data formats, while the IFC data model can support most project management applications (Froese and Yu 1999).

3. RESEARCH METHODS AND WORK PLAN

The proposed research will be performed in two phases: (1) the identification of reality capture method and (2) the development of BIM-based construction progress monitoring and quality control method.

3.1. The Identification of Reality Capture Method

The objective is to determine which UAV-based reality capture method is best suited to support an automated construction monitoring and identifying quality control issues. Photogrammetry and LiDAR methods will be compared on the basis of:

- Data suitability for automated object recognition using computer vision
- Relative and absolute accuracy of object spatial localization within BIM
- Time and costs associated with data capture and computing

This phase consists of the following tasks:

3.1.1. Compare data capture methods

The following data capture technologies will be compared: 1) photogrammetry with various megapixel cameras and sensor sizes and 2) airborne LiDAR. Automated flight plans will be used to compare the photogrammetry and LiDAR data capture technologies according to the metrics described in the Section 3.1. At the conclusion of this task a preferred data capture technology will be selected.

3.1.2. Develop and validate the point cloud alignment method

This step aims to automatically geo-rectify the on-board photogrammetry or Lidar Scan data with RTK GPS data for the purpose of accurate geometry alignment with previous surveys and as-designed BIMs.

3.2. The Development of BIM-based Construction Progress Monitoring and Quality Control Method

This phase aims to:

- Effectively document and communicate actual versus planned construction of building elements and to automatically update the project schedule, semantics, and geometry accordingly

- Identify potential issues resulting from the object's as-built position, including objects that are outside of the acceptable construction tolerances in a timely fashion, so the most cost effective remediation can be performed

This phase consists of the following tasks:

3.2.1. Develop / apply object recognition method

This step automatically transforms raw point cloud data into objects (e.g., core walls, embedments, openings) which have meaning relevant to the required tasks. This task involves *structuration* of the input data using machine learning and/or computer vision to identify classifiers that can accurately and robustly parse the point cloud input data to identify the desired objects.

3.2.2. Develop 4D work progress reporting system

This objective is to effectively document and communicate actual versus planned construction of building elements in 3D over time. The system will be implemented to complement existing construction management workflows and software tools used by our industry partners (e.g., Synchro, Primavera P6).

3.2.3. Develop model-based QC system

This step automatically identifies constructed objects that are outside of acceptable tolerances by comparing the object’s as-built position with the design model and/or trade model. The system will be implemented on the same platform as the 4D work progress reporting system discussed previously.

3.2.4. Case study validation

To quantitatively compare the efficiency and effectiveness of the new methods and technology that have been developed to conventional surveying and construction management methods. Comparison metrics be developed in consultation with our industry partners and will benchmark against traditional survey methods and/or laser scanning with manual processing.

4. EXPECTED RESULTS

4.1. Findings and Contribution

4.1.1. Quantitative comparison of UAV-based reality capture methods

Providing a quantitative comparison of the selected data capture methods based on their suitability for automated object recognition, accuracy, data processing time and total cost. The report will recommend a data capture method and describe the preferred method for point cloud alignment to facilitate automated object recognition.

4.1.2. An automated BIM-based construction progress monitoring and quality control method

An automated means of monitoring the status of work and comparison with as-designed models will be provided. This system will be designed to reflect as-built conditions into the model without the need for human involvement.

4.1.3. Validation of proposed method compared to conventional practice

The effectiveness of the proposed method will be evaluated in terms of progress tracking, model updating, quality control; various metrics will be employed in evaluations such as the level of effort, the degree of automation, amount of data loss, and the run time.

4.2. Impact on Practice

The impacts of the proposed solution on AEC practices can be primarily categorized as:

4.2.1. Automation of the tedious data collection processes

Manual data capture is expensive, inaccurate, time-consuming, and is not frequent enough to support progress monitoring solutions. The proposed solution not only has the potential to reduce the data collection durations, but it also increases their frequency, completeness, and accuracy. The use of agile UAVs provides a flexible means of data capture from areas with high level of risks; hence, it will also reduce the exposure of inspectors to safety hazards.

4.2.2. Automation of the data analysis and condition assessments

Using the proposed system, site superintendents do not need to spend resources on the acquisition of as-built conditions, but instead focus on data-driven decision making and model-based collaborations.

4.2.3. Life-cyclic modeling of building information

The continuous and automated integration of site data into the models encourages the practitioners to utilize the models throughout the project's life cycle, including facility management. This way, the updated models can be used as the primary source of data transfer and documentation of actual conditions.

4.2.4. Maximizing stakeholders' involvement

The system's reliance on developing interoperable techniques increases stakeholders' involvement by (1) eliminating reworks associated with the use of proprietary data formats (e.g., the need for re-modeling due to compatibility issues), and (2) the semantic enrichment of the BIM to increase their utility throughout the life cycle of the facility.

5. INDUSTRY INVOLVEMENT

We have identified three industry partners that are interested in supporting the proposed research: DJI, Mortenson Construction and Louis Berger. The contribution of each partner in delivering the proposed research is summarized below. There is opportunity for additional CIFE members to become involved in the project – please contact the research team if this is of interest.

5.1. DJI

- Providing the UAV platform(s) and associated data capture equipment
- Performing the initial flights and engineering support to establish optimal flight paths for data capture

5.2. Mortenson and Louis Berger

- Providing access to case study site and necessary project information (e.g., drawings and BIM for relevant building systems)
- Piloting or hiring a third party to pilot subsequent UAV flights after DJI has established optimal flight paths for data capture as discussed above
- Defining requirements for 4D work progress reporting and model-based QA systems (in collaboration with CIFE)
- Developing case study validation metrics to compare the efficiency and effectiveness of the methods and technology developed to conventional surveying and progress reporting methods (in collaboration with CIFE)

6. RISKS

The risks are primarily associated with the inter-dependency of different milestones; for example, the progress toward the development of 4D-based progress tracking system is affected by the accuracy and degree of maturity of the object recognition techniques. To mitigate such risks, multiple strategies will be employed including:

- Researchers will focus on developing the different components of the system in parallel, relying on valid sets of assumptions about the structure of the input data at each milestone.
- Some of the automated model updating algorithms previously developed by the team (Hamledari et al. 2017b; Hamledari et al. 2017c; Hamledari, Rezazadeh Azar, and McCabe 2017d) will be used to streamline the development of the proposed solution.

Other risks include the restrictions and regulations with respect to UAV operation/flights; fortunately, efforts have already been focused on mitigating this risk as our industry partner DJI has closely coordinated the legal processes with Mortenson and Louis Berger in order to obtain all necessary permissions.

7. RESEARCH MILESTONES

The estimated schedule for achieving the research milestones is provided:

#	*Milestone*	*Estimated Completion*
1	Complete comparison of reality capture methods and select preferred method	Fall 2017
	Development / application of automated object recognition method	Fall 2017
2	Develop 4D work progress reporting system	Winter 2018
3	Develop model-based QA / QC system	Winter 2018
4	Complete case study validation	Spring 2018

8. NEXT STEPS

The proposed solution will contribute to the robust and life-cyclic use of BIMs, and hence it will also be of interest to stakeholders in the facility management, operation, and maintenance. Previous research associates approximately 54% of defects in the facility management to the construction stage (Josephson and Hammarlund 1999).The continuous integration of data into BIMs during construction will enable future applications in other phases due to the information-rich data structures embedded into the models. For example, facility manager can query customized information and historical data using the updated BIMs, obtaining a clearer view of as-is conditions. Therefore, there is funding opportunity in post-construction stages. Future research should also explore the use of various reality capture technologies on the proposed platform. Automated model updating techniques can hugely benefit from multi-sensory data fusion applications (Hamledari et al. 2017b); hence, future works need to identify robust data fusion pipelines for the generation of more accurate and complete input progress using various data sources.

10. REFERENCES

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