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UAV-enabled Site-to-BIM Automation: Aerial Robotic- and Computer Vision-based Development of As-Built / As-is BIMs and Quality Control

By

**Hesam Hamledari, Shakiba Davari,
Seyed Omid Sajedi, Pouya Zangeneh,
Brenda McCabe, & Martin Fischer**

**CIFE Technical Report #TR230
March 2018**

STANFORD UNIVERSITY

If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
The Jerry Yang & Akiko Yamazaki Environment & Energy Building
473 Via Ortega, Room 292, Mail Code: 4020
Stanford, CA 94305-4020

3.1. Paper I

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ABSTRACT

The automated integration of as-built and as-is conditions into building information models (BIM) remains a primary challenge for unoccupied aerial vehicles (UAV)-enabled facility and construction inspection. Due to the lack of site-to-BIM data pipelines supporting reality capture technologies such as camera-mounted UAVs, BIMs lose their effectiveness over time since they do not accurately reflect the as-built and as-is conditions; the UAV-captured visual data also remains underutilized. This paper proposes and demonstrates a novel industry foundation classes (IFC)-based solution for UAV-enabled as-built and as-is BIM development, quality control, and smart inspections. It first identifies the requirements of UAV-enabled site-to-BIM automation and its framework; then, it elaborates on the proposed solution which aims to: 1) enable automated conformance checking and quality control using data queried from BIMs and UAV-captured reality in the form of images; and more importantly 2) enable the integration of on-site captured reality, including the as-built and as-is conditions, into BIMs. The method leverages the non-proprietary IFC schema, empowering OpenBIM applications, and facilitating interoperability, a core challenge in the information modeling domain. In addition to its support for UAV-enabled applications, the technique can provide the same site-to-BIM functionalities for other types of reality capture and other robotic data collection efforts during construction, commissioning, and facility management.

INTRODUCTION

Construction and facility managers continuously rely on building information models (BIM) for decision making; consequently, BIMs need to be regularly updated to accurately reflect as-built and as-is conditions, ensure situational awareness, and provide a clearer view of actual conditions (Akinci 2015). This has motivated the use of reality capture technologies such as radio frequency identification, laser scanning, 2D image processing, and image-based 3D reconstruction (Lu and Lee 2017) to help automate the BIM updating process. More recently, light weight and rotary unmanned vehicles (UAV) have received increasing attention due to their multi-sensory data collection capabilities and providing an agile and highly maneuverable robotic platform for the reality capture technologies (McCabe et al. 2017).

The UAV use for the inspection of as-built and as-is conditions has been proven efficient, safe, and cost-effective compared to conventional manual practices (Liu et al. 2016). Research studies have focused on various aspects of UAV use including the assessment for feasibility of its construction management applications (Blinn and Issa 2016) and the design of frameworks for the robust utilization of camera-mounted UAVs in construction progress tracking (Hamledari 2016; Han et al. 2015). Recent studies have employed visual data analytics for analyzing UAV-captured images in support of visual construction production management at outdoor sites (Lin and Golparvar-Fard 2017; Siebert and Teizer 2014) and indoor construction progress tracking (Hamledari et al. 2017a).

However, UAV-enabled site-to-BIM (site2BIM) automation still suffers from a primary limitation: the automated integration of UAV-captured reality into BIMs and the development of as-built and as-is models based on design discrepancy analysis. This limitation differs from the superimposition of reality over design or a mere visualization of design versus reality. It refers to the need for project models to be automatically and continuously updated and modified based on quality control results, eliminating the need for manual model updating efforts. In other words, solutions need to be developed to bridge the gap between reality (measured using UAV-based data capture) and virtual models (Chen et al. 2015; Gu and London 2010; Kasireddy and Akinci 2015). This is not limited to the construction stage since the frequent model update remains a core requirement and challenge of BIM-enabled facility management (Akcamete et al. 2009; Quintana et al. 2017; Teicholz 2013).

This paper first reviews the relevant works on model updating and identifies the requirements for UAV-enabled site2BIM workflows. It then proposes a computationally frugal approach toward the automated integration of UAV-enabled visual data analytics results and inspection details into BIMs; this integration results in the development of as-built and as-is models. The work is based on the IFC schema which has been proven to provide reliable support for project management applications. The use of this open data exchange format promotes OpenBIM and interoperability, a core challenge in the site-to-BIM domain.

RELATED WORKS

Regular model updates are rarely achieved due to the time-consuming, expensive, and inaccurate nature of manual updating sessions that heavily rely on modelers (Lopez et al. 2015; McCabe et al. 2017). This lack of site2BIM data transfer automation hampers the practical use of multi-dimensional BIMs among industry practitioners (Lopez et al. 2015). This limitation was identified as the grand challenge of the architectural, engineering, and construction industry (Leite et al. 2016) and a primary barrier to BIM implementation (Teicholz 2013). This section reviews related work on BIM updating and the integration of reality into BIM.

A platform was developed as a central storage of as-built models, aiming to enhance the progress sharing among contractors (Lin et al. 2016); the as-built documentation, however, was achieved manually. To facilitate data linking mechanisms, another study introduced a work breakdown structure-based approach to create documentations of as-built construction records (Park and Cai 2017). The use of the image-based techniques was studied for the verification of as-built documentation for existing buildings (Klein et al. 2012), enabling the comparison of design and reality. The off-the-shelf measurement tools have also been used for the purpose of quality assessment (Kalyan et al. 2016); the results of these studies, however, were not used for automated updating of BIMs and in-BIM documentation.

The IFC-Bridge standards were leveraged to enable the potential integration of inspection data with bridge models (Kasireddy and Akinci 2015). Another work argued that a multi-sensory approach and a progressive data capture plan is necessary for ensuring the completeness and accuracy of as-built point clouds (Liu et al. 2012). In the UAV research domain, an IFC-based approach was introduced to automatically update 4D BIMs in terms of schedule and progress using UAV-captured images (Hamledari et al. 2017b). However, the updates were focused on the BIM's temporal data and the creation of as-built 4D models. There currently exists a need for solutions that can automatically verify design conformance using UAV-captured reality and more importantly integrate the robotic inspection data/reality into BIMs; the regular and robust semantic update of BIMs using UAV data remains a primary concern.

The Requirements of UAV-enabled Site2BIM Automation

Automated integration of UAV-enabled visual data analytics into BIMs. Techniques need to be developed to automatically update an as-designed BIM using UAV-captured reality during the construction stage, hand over, and facility management. Unfortunately, this site2BIM automation capability is not currently offered; existing solutions primarily focus on an understanding of reality or the visualization of perceived reality versus design.

In-BIM documentation of UAV-enabled inspection process. BIM provides a unique opportunity for the communication of inspection details among stakeholders. However, inspection data such as the observed defects, responsible actors, inspection date and time, and captured images are not integrated into models. More focus is needed on integrated model-driven approaches that maximize project members' access to the data and facilitate the integration of project delivery (Fischer et al. 2017).

Interoperability. Many stakeholders are engaged in UAV-enabled applications; this includes the UAV operators, construction and facility managers, authorization bodies, and downstream users of data. The existence of numerous players and software applications necessitates a stronger focus on interoperability. The IFC format can provide a potential solution, eliminating the software-dependent workflows (Hamledari 2017; Hamledari et al. 2018).

THE PROPOSED METHOD

This paper introduces a computationally frugal solution based on IFC schema for automated integration of UAV-captured as-built and as-is conditions and inspection results into BIM. This is provided for inspections during the construction stage, hand over, and facility management.

The proposed technique receives as input 1) the BIM; 2) the as-built and as-is condition of elements, inspected by the UAV during the data collection process (e.g., installed element type or existing defects); and 3) the details of the UAV inspection process. The as-built and as-is element types information are extracted by applying in-house developed computer vision-based techniques on UAV-captured images.

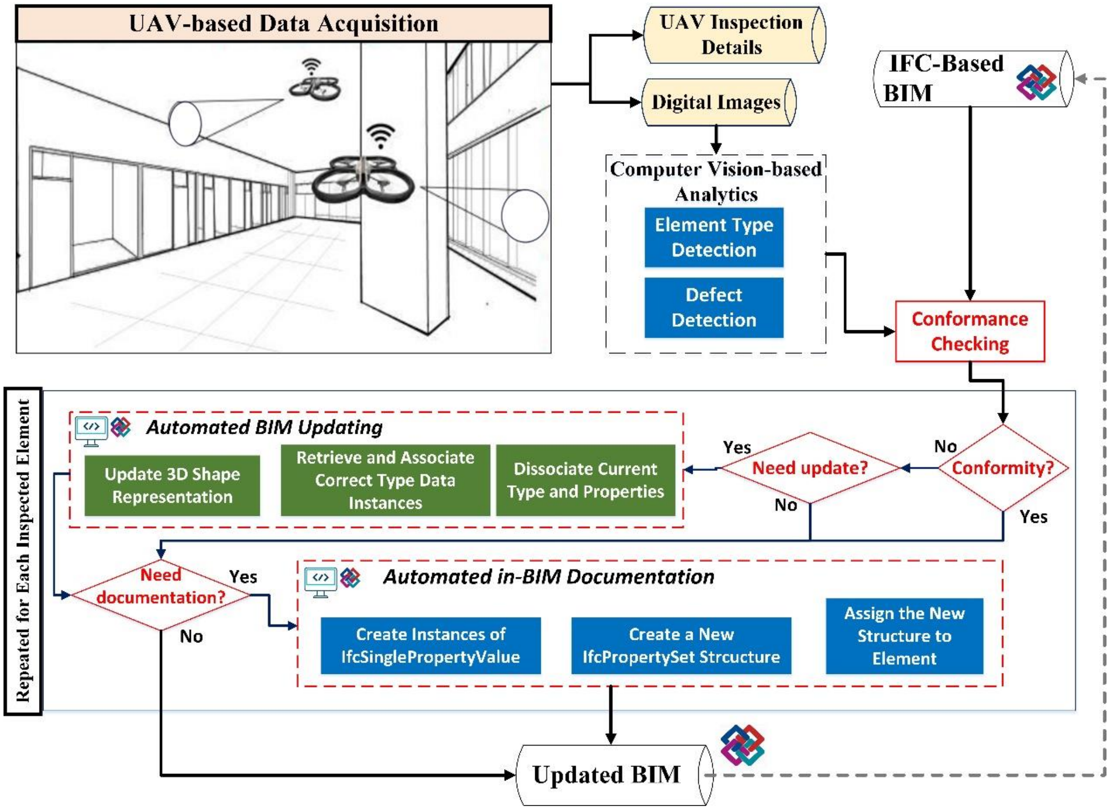


Figure 1. The overview of the proposed UAV-enabled site-to-BIM automation technique

As illustrated in Figure 1, the UAV-captured reality is used to identify the discrepancies between as-designed and as-built element types in BIM-based and automated conformance analysis; for example, an outlet's actual installed type, "standard duplex", can differ from its as-designed type "quadruplex". The conformance analysis identifies this discrepancy by querying the element type information directly from the IFC model. The conformance checking results for each element can be used to provide several functionalities, each of which can be included or forgone based on user's preference.

Semantic and geometrical update. In the case of existing discrepancy between design and constructed (as-built) or existing element (as-is), corrective measures are taken by automatic modification of the IFC data model, resulting in a semantic (i.e., element type and properties) and 3D geometrical update. Figure 2 illustrates this process for an outlet. Using computer vision, the installed outlet type is detected in the images, and the in-BIM element is automatically updated to reflect the observed reality (note the changes in the outlet's appearance). The automated BIM updating process illustrated in the Figure 2 can occur in real time (i.e., during UAV inspection) or after the flight has been completed. The IFC-based implementation will be elaborated in the next section.

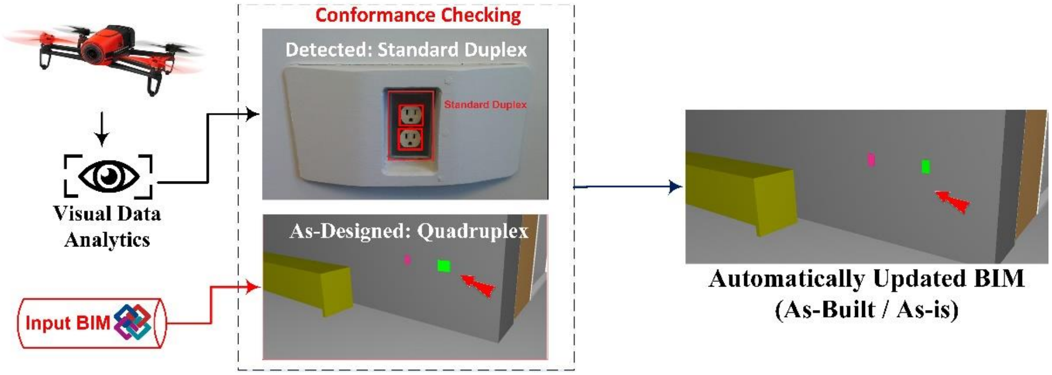


Figure 2. The automated development of as-built and as-is BIM elements using the results of computer vision-based analytics on UAV-captured images

In-BIM documentation of discrepancy analysis and the UAV inspection process. In addition to the element updates, the results of the conformance checking, including the as-designed, as-built, and as-is element types can be integrated directly with the element. This is particularly beneficial for potential diagnostics in the case of updated elements. It helps to retrieve an updated element's as-designed semantics and geometry and prevents data loss.

Other details of the UAV inspection process are also integrated directly with the elements, providing easy access to the information for all stakeholders including the project team, UAV operators, authorities responsible for reviewing UAV inspections, and downstream users of data. The documented data instances include, but are not limited to, UAV-captured images, detected defects, time and date of the inspection, and responsible actors. Figure 3 provides a more comprehensive list of the data instances integrated with BIM elements. The next section elaborates on the IFC-based implementation of introduced functionalities.

The Integration of UAV-Captured Reality into BIM and In-BIM Documentation

Based on the results of conformance checking (Figure 1), the 3D BIM element may need to be updated. If the as-designed and as-built/as-is types do not match and the user requires a model update, the inspected element is semantically and geometrically modified to reflect the actual site conditions; this is realized by a combination of modifications to the existing data instances in the IFC data model and also the generation of new IFC-conformant data structures.

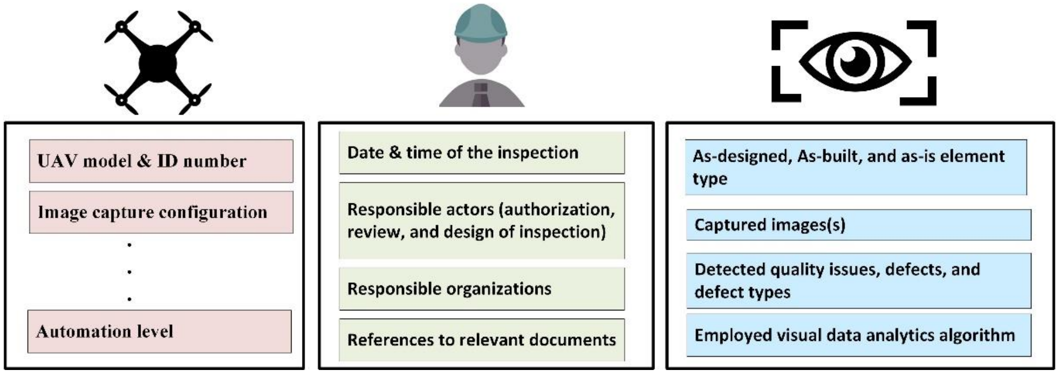


Figure 3. The data instances regarding the UAV inspection process that can be documented within BIM and integrated with the inspected elements

To achieve this, the element's corresponding data instance in the IFC data model (e.g., an instance of *IfcWindow*, representing the inspected window) is dissociated from its current type and property set information. Such data can be automatically queried using respectively the inverse attributes *IsDefinedBy*.*RelatingType* and *IsDefinedBy*.*RelatingPropertyDefinition*. Further, the algorithm iterates over the modeled subtypes of *IfcElement* to retrieve a building element corresponding to the UAV-captured as-built and as-is type; the retrieved element is used to retrieve the geometrical and property set information corresponding to the actual site condition (e.g., electrical outlets of type "standard duplex").

The algorithm populates the IFC data model with new instances of element type (e.g., *IfcOutletType*) and property sets storing common attributes of that type (i.e., *IfcPropertySet*). These modifications ensure the updated element is assigned to correct semantics; however, its geometry still correspond to the as-designed element type. In other words, if selected in a BIM environment, the element's attributes indicate it to be of correct type while its appearance has not undergone any change.

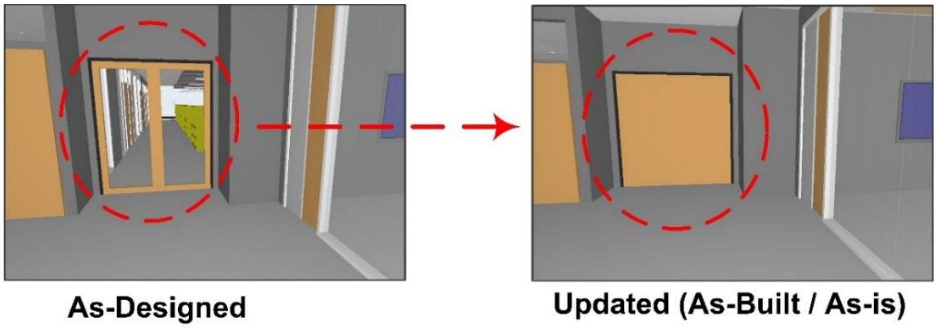
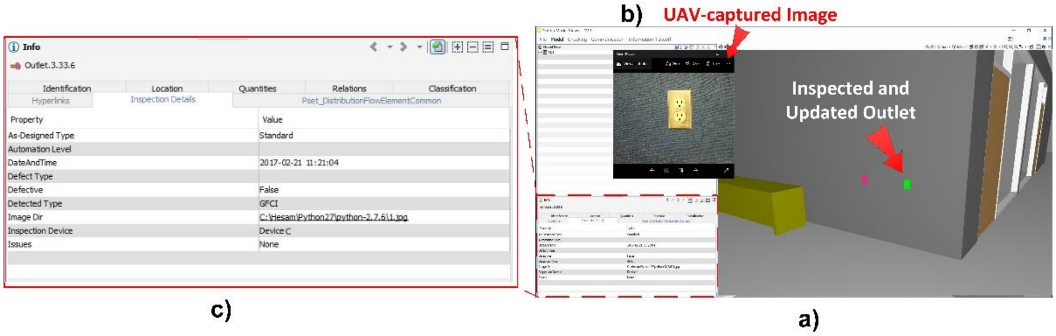


Figure 4. The demonstration of automated BIM updating technique for a door

To address this issue, the inspected element's 3D shape representation (accessible through the *Representation* attribute) is populated with new geometry, previously queried from an element of the same type. As a result, the updated element's appearance is updated to match the as-built and as-is element type (as detected by the UAV). Figure 2 and Figure 4 depict this respectively for an electrical outlet and a door.

To document the UAV inspection results, the algorithm creates new property sets and assigns it to the inspected element; as a result, the users can retrieve the information each time they interact with model elements in BIM environments or model viewers. Each data instance that needs to be documented (i.e., a subset of those listed in Figure 3, specified by users) is stored in a new *IfcPropertySingleValue* (e.g., the time of the inspection or UAV ID number) and assigned to the property set.

The integrated data can be viewed using any IFC-conformant software or directly from the IFC data model. Figure 5 depicts the updated model imported in a model viewer where the inspected (and updated) element is selected by the user; Figure 5c shows a new tab "inspection details" and its corresponding data instances that store the UAV inspection results; please note that this information is accessible due to the proposed method's modifications to the IFC data model and was not previously available in BIM. As discussed previously, a link to the UAV-captured image(s) is also provided in this new property set. This image (Figure 5b) appears if the user clicks on the image directory attribute included in the information section (Figure 5c).



Property	Value
As-Designed Type	Standard
Automation Level	
DateAndTime	2017-02-21 11:21:04
Defect Type	
Defective	False
Detected Type	GFCI
Image Dir	C:\Hesam\Python27\python-2.7.6\1.jpg
Inspection Device	Device C
Issues	None

Figure 5. The in-BIM documentation of inspection details: inspected element selected in a model viewer; b) the UAV-captured image available by clicking on the outlet's attribute; c) the new tab "inspection details" added by the method

Validation and Case Studies

The proposed technique was implemented and tested in real-life case studies for both construction and facility management, two of which are discussed in this section. For more details please see (Hamledari et al. 2018). In one experiment, the technique was employed to automatically integrate UAV inspection details with BIM elements that were photographed during UAV flights, focusing primarily on indoor partitions at a construction site at Toronto, Canada. The proposed solution was successfully tested for over 200 partitions and during two UAV site visits. Further, to evaluate the technique's robust performance in multi-dimensional BIM updates and its effect on model integrity, it was tested in parallel with an automated 4D model updating solution (Hamledari et al. 2017b) and computer vision-based progress assessment (Hamledari et al. 2017a). The method's integration of UAV inspection into BIM did not jeopardize the accuracy of automated 4D model updates for inspected elements.

In another set of experiments at Stanford University's facilities, the introduced technique was tested for both automated in-BIM inspection documentation and the development of as-is BIMs, focusing primarily on electrical outlets. The element types were detected using a computer vision technique developed as part of this study; however, the design of the element type detection is independent of the model updating solution, and it can alternatively be manual or semi-automated. Table 1 summarizes the results of both case studies in terms of model updating accuracy and run time.

Table 1. Summary of the method's performance in real-life case studies

Case study	Stage	Elements	BIM updating accuracy (%)	Run time per element* (s)
I	Construction	Partitions	100	0.04
II	Facility management	Outlets	100	0.05

*****laptop computer: 2.6 GHz core i7 CPU and 16 gigabytes of memory

The updated BIMs generated by this solution can be updated again in future inspections (Figure 1). The method operates regardless of the number of data categories modeled in the input BIMs; 4D and 3D BIMs undergo the same process. The entire workflow is automated and requires no human intervention. The method's reliance on non-proprietary IFC format promotes interoperability, the primary challenge in the construction information modeling (Leite et al. 2016). The integrity of the updated models and their conformance to IFC schema were verified using IFC file validators.

Future work should focus on the use of topological relationships between elements to enable geometry updates for all element types. While, the method provides the fundamental algorithm capable of as-built and as-is element development, it currently does not support geometry updates for elements such as slab, columns spanning multiple floors, and partitions spanning multiple spaces; this is because such elements cannot be updated in isolation and require modification to the other elements.

CONCLUSION

A novel solution was presented for UAV-enabled site2BIM automation and the development of as-built and as-is BIMs. The UAV-captured reality is used to perform conformance analysis, and the inspected elements are semantically and geometrically updated within BIM to reflect their actual site conditions (e.g., element type and defects). The UAV inspection process such as the inspection date, on-site captured images, and the observed defects are also integrated directly with the elements. This computationally frugal approach supports real-time model updates (sub 0.1-second run time per element), and it eliminates the need for manual model updating, a primary barrier to BIM implementation and UAV-enabled smart applications.

ACKNOWLEDGEMENT

The first author is grateful to 1) F. Nietzsche and M. Kundera, for their intellectual guidance; 2) Stanford Bookstore’s Café, for endlessly and still-affordably caffeinating the first two authors; and 3) Stanford University, for its generous financial support. The work is supported by Natural Science and Engineering Research Council (RGPIN-2017-06792) and Center for Integrated Facility Engineering (grant 2017-06).

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