ACE Architecture, City and Environment

E-ISSN 1886-4805

Emerging Dimensions of Unmanned Aerial Vehicle's (UAV) 3D Reconstruction Modeling and Photogrammetry in Architecture and Construction Management

Ali Keyvanfar [1] | Arezou Shafaghat [2]

Received: 2021-05-13 | Final version: 2021-10-23

Abstract

In recent decades, the versatility of virtual reality (VR) and augmented reality (AR) have made the Unmanned Aerial Vehicle (UAV) technology widely applied in diverse disciplines, such as architecture, civil engineering, and construction management. UAV is employed in diverse dimensions to obtain essential information from the construction sites, a feasible analysis in condition assessment, and progress monitoring and visualization. The current research has aimed to investigate the dimensions UAV' 3D modeling by applying the literature content analysis method. The research found that UAV technology has been merged into seven dimensions; included, 3D Modeling, Safety, Surveying, Monitoring, Transportation, Contour crafting, Inspection. Amongst, 3D modeling is the primary dimension and dramatically growing in architecture and civil engineering. The research found that UAV' 3D modeling has merged into nine (9) dimensions; D1. Quality management, D2. Risk Management, D3. Site monitoring, D4. Project performance and progress control, D5. Facilities Management, D6. Building Measurement, D7. On-Site Information Analysis, D8. Team Collaboration and communication, and D9. Workers Training. The research found that building measurement and quality management are the most rapidly growing dimensions. Also, the research has indicated thirty-six (36) sub-dimensions, where using inspection tools, using web-based VR, image-based 3D reconstruction and meshing, and using AR have been mostly grown in the UAV's 3D modeling. Accordingly, several 3D reconstruction software has been developed.

Keywords: Unmanned Aerial Vehicle; 3D reconstruction modeling; construction site mapping and visualization; photogrammetry

Citation

Keyvanfar, A. & Shafaghat, A. (2022). Emerging Dimensions of Unmanned Aerial Vehicle (UAV) Technology's 3D Reconstruction Modeling and Photogrammetry in Architecture and Construction Management. *ACE: Architecture, City and Environment*, *16*(48), 10492. DOI: http://dx.doi.org/10.5821/ace.16.48.10492

Dimensiones emergentes del modelado de reconstrucción 3D y fotogrametría de vehículos aéreos no tripulados (UAV) en la gestión de la arquitectura y la construcción

Resumen

En las últimas décadas, la versatilidad de la realidad virtual (VR) y la realidad aumentada (AR) han hecho que la tecnología de vehículos aéreos no tripulados (UAV) se aplique ampliamente en diversas disciplinas, como la arquitectura, la ingeniería civil y la gestión de la construcción. El UAV se emplea en diversas dimensiones para obtener información esencial de los sitios de construcción, un análisis factible en la evaluación de la condición y el monitoreo y visualización del progreso. La investigación actual ha tenido como objetivo investigar las dimensiones del modelado 3D de UAV aplicando el método de análisis de contenido de la literatura. La investigación encontró que la tecnología UAV se ha fusionado en siete dimensiones: Modelado 3D, Seguridad, Topografía, Monitoreo, Transporte, Elaboración de contornos, Inspección. Entre ellos, el Modelado 3D es la dimensión principal y está creciendo dramáticamente en arquitectura e ingeniería civil. La investigación encontró que el modelado 3D de UAV se ha fusionado en nueve (9) dimensiones; D1. Gestión de la calidad, D2. Gestión de riesgos, D3. Monitoreo del sitio, D4. Control de avance y ejecución del proyecto, D5. Gestión de instalaciones, D6. Medición de edificios, D7. Análisis de información in situ, D8. Colaboración y comunicación en equipo, y D9. Formación de trabajadores. La investigación encontró que la D6 y la D1 son las dimensiones de crecimiento más rápido. Además, la investigación ha indicado treinta y seis (36) subdimensiones, en las que el uso de herramientas de inspección, el uso de VR basada en la web, la reconstrucción y el mallado 3D basado en imágenes y el uso de AR se han desarrollado principalmente en el modelado 3D del UAV. En consecuencia, se han desarrollado varios softwares de reconstrucción 3D.

Palabras clave: Vehículo aéreo no tripulado; modelado reconstructivo 3D; visualización y mapeo de sitios de construcción; fotogrametría

[1] Ph.D., Department of Construction Management, College of Architecture and Construction Management, Kennesaw State University (KSU), Marietta, Georgia, USA (ORCiD: 0000-0003-0059-274X; Scopus Author ID: 55326089900); [2] Ph.D., Department of Construction Management, and Department of Architecture, College of Architecture and Construction Management, Kennesaw State University (KSU), Marietta, Georgia, USA (ORCID: 0000-0002-6439-936X; WoS ResearcherID: B-8011-2016; Scopus ID: 55326539000). Contact e-mail: ashafagh@kennesaw.edu

E-ISSN 1886-4805

1. Introduction

Unmanned Aerial Vehicle (UAV) is known as Remotely Piloted Vehicle (RPV), Micro Aerial Vehicles (MAV), Small UAV (SUAV), Remote Controlled (RC) Helicopter, Remotely Operated Aircraft (ROA), and Model Helicopter (Siebert and Teizer, 2014). In recent decades, the versatility of virtual reality (VR) and augmented reality (AR) have made UAVs widely applied in diverse disciplines, such as architecture, engineering, transportation, archaeology, and geology (Muñoz Salinas and Garcia-Almirall, 2010; Dib *et al*., 2013; Marques *et al*., 2017). UAV usage in each discipline varies, depending on the requirements; for example, in archaeology, UAV is used to capture 3D geometry information of heritage monuments, while survey, mapping, and safety are widely used in transportation (Keyvanfar *et al*., 2021).

The focus of the current study is the usage of UAVs in architecture and construction management projects. Laser scanning, Robotic Total Station (RTS), labor-intensive GPS are such space-borne applications in construction management. However, they are limited in labor-intensive, time-consuming, costly, limited range and area size to cover, high measurement errors of monitoring projects (Tang *et al*., 2011). In turn, obtaining essential information from the construction sites, a feasible analysis in condition assessment, and progress monitoring need an intuitive information visualization under the capacity of UAV (Abd Majid *et al*., 2012; Majid *et al*., 2012; Barsantia *et al*., 2013; Ham *et al*., 2016). Architects and civil engineers see the UAV as the must-have technology due to its micro/meso size, easy handling mechanism, and simple attached camera. The versatility of the UAV and its capabilities for messy and complicated works make it widely used. UAVs can handle the limitations of space-borne-based technologies through air-borne solutions. Using drones has been dramatically grown for construction mapping and visualization. Although we can use either drones or satellites for geospatial imagery and analysis of the construction projects, several concerns affecting our technology selection (Murugan *et al*., 2016; Báez *et al*., 2020). The following describes these concerns briefly.

i) *Efficiency in progress tracking and monitoring:* Although the spatial and spectral resolution of the remote sensing satellites has been substantially enhanced, using UAVs is highly demanding since it can track the progress by flying closer to the ground and capturing centimeter-level spatial resolution images. Hence, drones can generate centimeter-level resolution images, while 30cm would be the best deliverable resolution by commercial satellites. This issue highlights the differences between the accessibility of the information of drones and satellite imagery techniques.

ii) *Type of construction activity:* Measuring every construction activity needs a specific level of spatial detail. For instance, the drone can measure the placement of girders or grading of earthworks in detail and provide a high-resolution visual perspective. At the same time, these abilities are oversight to the satellite.

iii) *Covering scale of construction projects:* Drone is a cost-effective method suggested for 10 or fewer square kilometers area size projects. However, unlike commercial satellite constellations, drone technology cannot cover the wide areas beyond this limit, such as a synoptic view for monitoring complex ecosystems. Also, unlike commercial satellite constellations, the drone does not have the long-term archived data of years and decades; for example, monitoring the weather effects, climate changes, sea-shore development, or desert swamping during an El Nino year.

iv) *Capturing Invisible Environmental Conditions:* Satellites can capture hyperspectral and multispectral data in diverse sizes and locations (such as subtle stress in water bodies and vegetation) in the infrared portion of the spectrum; however, the drone cannot do it.

v) *The project phases:* Although both drone and satellite technologies can be used for every phase of the project (i.e., design, construction, operation, demolition, etc.), using the drone is much cost-efficient even for daily exercises.

E-ISSN 1886-4805

vi) *Type and size of information needed to capture:* The projects need a combination of data sources. The main difference between drones and satellite is the machine learning resolution techniques, which strongly depend on the object's size. For example, satellites can capture the construction sites even in low-resolution; however, the drone can help efficiently capture high-resolution imagery of the whole site and the objects (such as the wall, windows, facade of buildings, etc.) the width of at least 10px. For instance, Quadcopter Geoscan 401 can take high-quality aerial photos at 4 cm/pix high resolution and 1 cm / Pix for the altitude of 60m of air scan.

vii) *Collision avoidance technology:* Drones are equipped with several types of object detection sensors to avoid collision accidents to objects and even fly safely in zigzagging paths of the construction site or indoor environments.

viii) *Data Processing Capabilities*: The drone processing software is affordable, powerful, user-friendly, self-learning, and sometimes cost-free, while satellite imagery software is complicated and expensive, and hence, needs a more advanced computing system.

ix) *Cost of project:* In general, we can track long-term changes (for instance, the earth's surface) for free through historical data by satellite imageries, while the drones cannot. Using drones would be a good solution for cloudy days when satellite data may not be complete enough.

To sum up, using satellite imagery data can be very useful for analyzing the long-term changes, while multispectral cameras have a higher resolution at a reasonable cost. The size of the projects would be a key driver in selecting the means; UAVs can handle the required imagery works for medium to small projects, while satellites are mainly recommended for large to mega-scale projects (such as sea-shore development). Therefore, the trade-off among the concerns mentioned above can help users achieve their desired goals.

UAV technology is predominantly used in architecture and construction management, merging into several aspects, included, 3D modeling, safety, surveying, monitoring, contour crafting, and inspection. For example, UAV will be attached with a thermal camera to collect the thermal picture; later, the 3D model of that building will be created that shows the thermal details using the data obtained from the UAV. Reviewing literature shows that 3D modeling is the primary dimension growing very fast. Accordingly, UAV has significant capabilities in site mapping and aerial photogrammetry for 3D modeling the construction projects (i.e., buildings, bridges, tunnels, etc.). The images were taken by UAV Will then be used for progress and performance monitoring of the construction projects. Accordingly, this research has aimed to investigate the UAV’s 3D modeling dimensions and applications. The research has conducted two objectives. Objective one is to investigate and identify the UAVs’ 3D reconstruction modeling dimensions in architecture and civil engineering. Objective two is to synthesize the 3D reconstruction modeling state-of-the-art based on their Features of Photogrammetry Reconstruction Generation, Capabilities in Reconstructing site elements, and the required computational System Specification. In addition, the research has applied the content analysis method as one of the well-established literature review analysis methods. The content analysis method will help explore the dimensions and sub-dimensions of the UAVs’ 3D reconstruction modeling and measure the impact degree of each based on frequency. To conduct the content analysis, the research has investigated the available sources (i.e., books, journal articles, conference proceedings, etc.) across diverse research fields and searching the combination of two or three following codes (i.e., keywords); Unmanned Aerial Vehicle (UAV), 3D reconstruction modeling, photogrammetry, construction management, architecture, site mapping, site visualization, dronography, and automated project monitoring.

2. Applications of the UAVs' 3D Reconstruction Modeling in architecture and Civil Engineering

3D reconstruction modeling is the most referenced dimension of UAV technology and is dramatically growing. The '3D Reconstruction of Generic House Roofs from Aerial Images of Urban Areas' is one of the earlier research projects conducted by 1997. This research focuses on the method that automatically generates the 3D model of the roof house of the residential areas in the urban site based on the aerial images. Later in 2007, another research was done by Jin and Xu (2007) entitled 'Reconstruction of the Building Objects from Multi-aspect High-resolution SAR Images.' They have used multi-aspect metric-resolution SAR images to reconstruct the 3D model of the building's objects automatically. Recently, in 2011, another research was conducted with the title 'Automatic Alignment of 3D Reconstruction Using a Digital Surface Model' by Wendel *et al*. (2011). In this research, they present the alignment of Structure from Motion (SfM) of the 3D reconstruction models, then use GPS information to create an overhead Digital Surface Model (DSM). Indeed, 3D reconstruction modeling emerged in different dimensions helping architects and civil engineers in project monitoring and management through either mapping or visualization techniques. The following presents these dimensions in detail.

i. *Quality Management:* UAVs' 3D reconstruction modeling has emerged for quality management in architecture and construction projects. It especially aids in detecting defects in the earlier phase of the project lifecycle (Zhao and Lucas, 2015). The 3D model of quality management has great advantages than 2D images, mainly overlooking issues, real-time checking, saving cost, and time of exploring issues (Portalés *et al*., 2018). In this regard, Hou *et al*. (2015) have emerged AR technology for quality management, enhancing performance and productivity while reducing cognitive workloads. Fazel and Izadi (2018) designed an interactive multi-marker AR system for building quality and accurate free form prefabricated surfaces. Tavares *et al*. (2019) have developed a combined, coordinated AR-BIM (Building Information Modeling) system that the operator can use to track welding in beam joints and make sure highest flexibility throughout the beam assembling. In addition, some researchers have studied how to control construction quality through inspection devices. For instance, Portalés *et al*. (2018) have designed an AR-based tool for inspecting the pre-fabrication building process and documenting it through manual measurements and 3D data. Also, Kwon *et al*. (2014) have designed an AR-BIM combined system to enhance construction defect management.

ii. *Building Measurement:* UAVs have been widely used to conduct as-built project monitoring through a field-realistic system (Biljecki *et al*., 2015). For instance, Siebert and Teizer (2014) developed such a system focusing on the extent of the UAV photogrammetry errors for ground truth measurements of the construction site (Colomina and Molina, 2014). Recently, a few researchers have studied the geometric accuracy of the 3D model of the site. For instance, Shazali and Tahar (2019) have investigated the minimum possible errors (less than 4cm) while generating the 3D model of the actual measurement of the as-built project. Freimuth and Konig (2018) have improved the as-built data generation process through UAV's automatic data acquisition of the structural objects. Their system can guide and control the flight around building structures capturing the required as-built information of the objects. Moon *et al*. (2019) have investigated data integration and data processing through photogrammetry and developed a new method to merge hybrid point cloud data obtained from UAV-based image processing and laser scanning. They could achieve a good result in comparing original blueprints of the projects and surveyed geometry. Recently, Kim *et al*. (2017) have conducted UAV-driven hybrid image-processing for crack identification, obtaining cracks thicker than 0.1 mm with 7.3% Maximum length-estimation error.

E-ISSN 1886-4805

Ficapal and Mutis (2019) developed a system for facade thermal bridges detection, assessment, and diagnosis using UAV-driven infrared thermography. Their system can analyze the building envelope's performance regarding energy consumption, the actual state of deterioration, functionality, and then offers possible scenarios for the best use of the existing structure. Freimuth and Konig (2018) have integrated UAV and BIM technologies to automatically trigger inspections through a visual inspection task in a 3D environment.

iii. *Risk Management:* Regarding risk management through 3D modeling, the researchers have emerged in diverse disciplines, such as workers' safety, risk of accidents, and hazardous situations (e.g., unprotected openings or edges, the proximity of overhead power lines, the proximity of boom vehicles or cranes, etc.). For instance, de Melo and Costa (2019) have applied UAVs in collecting visual assets to evaluate the compliance of safety rules and regulations on the construction site. Their system integrates UAV technology and resilience engineering (RS) to sustain the construction project's safety planning and control (SPC) process. Kim *et al*. (2017) developed a UAV-assisted visual monitoring system to assess the safety intervention against struck-by hazards in the construction site by quantifying the proximities automatically among construction entities, enhancing safety for laborers and workers. Liu *et al*. (2019) have integrated UAV and BIM technologies and developed a new web-based dynamic safety-inspection technique which combines safety information (i.e., videos) of the real environment and virtual camera parameters in the BIM platform, an update the off-site risk managers and executive managers for better transparency and accurate decision making

iv. *Site Monitoring:* Monitoring the construction site and workers is critical during the construction phase. Architects and civil engineers, and coordinators need several rounds of job-site progress monitoring inspections and safety inspections in the construction site while sticking to an on-time and planned budget. However, there are a few studies about borrowing UAVs for progress monitoring. In general, UAVs can do all these jobs more accurately, faster, and without human-error distractions. Using UAVs can generate a panorama of a construction site, identify the layered design, generating the as-built point cloud data, simulating aerial photogrammetry point cloud, etc. For instance, Bang *et al*. (2017) has applied a UAV and image stitching technique for developing the panorama based on high-quality image data; Kim and Kim (2018) have developed the First Personal View (FPV) to monitor on-site condition and status by a quadcopter drone to share the reports to construction project managers and other members.

v. *Project Performance and Progress Control:* The immersive technologies aid construction processionals in comparing virtually as-built progress against planned schedules. The AR on PC, tablet, or mobile is the advanced technology for construction control and monitoring through facilitating the real-time estimation and visualization of on-site construction jobs (Ratajczak *et al*., 2019). Reviewing literature determines that very few researchers have studied project scheduling through 3D reconstruction modeling. Kim et al. (2017) have developed an AR-driven 4D CAD method linking AR's 4D and 5D objects in the site with the real images and then implements schedule information for revisions if needed. Recently, Ratajczak *et al*. (2019) developed a new system by integrating AR and BIM with a location-based management system (LBMS), which can explore scheduling deviations and report the context-specific progress data and project managers.

vi. *Facilities Management:* Facilities management through 3D modeling has focused on dynamic data integration. For instance, Sampaio *et al*. (2012) have developed a VR-driven system for controlling the performance of periodic inspections of the interior and exterior wall maintenance. In addition, Williams *et al*. (2015) have designed an automated BIM2MAR process to convert a complex geometry on a mobile computational platform, which aids facility managers in accessing real-time and updated information through AR technology.

E-ISSN 1886-4805

Finally, Carreira *et al*. (2018) have integrated the game engine technologies and VR for building management flexible and dynamic facilities management system.

vii. *On-Site Project Information Analysis:* 3D reconstruction modeling can combine digital data with an on-site physical view. For instance, Yeh *et al*. (2012) developed a wearable device for engineers that stores all construction information and drawings. As a result, no one needs to carry the massive construction drawings to the site while saving time and energy in correcting drawings. Kim *et al*. (2017) have designed a camera-equipped mobile device called HD4AR to exchange project information precisely to the construction stakeholders and engineers for task management purposes (e.g., visualizing task location through AR). Chu *et al*. (2018) have developed a cloud-based BIM-AR system to enhance the information retrieval process for task efficiency during construction.

viii. *Team Collaboration and Communication:* Several project stakeholders are collaborating in a construction project; contractors, managers, designers, etc. Good collaboration can guarantee the project's success and complete the project according to the planned budget and on time. However, all team members (design team, risk management team, etc.) are not on the site simultaneously, and any immediate actions and changes need confirmation by all parties. Hence, 3D modeling techniques can provide a platform to share and check the real-time and updated notes and imagery data and take the required actions in actual time. The 3D modeling techniques have significantly improved the on-site project information accessibility and effective communication (Pejoska *et al*., 2016). Goulding *et al*. (2012) have created a collaborative design team through a web-based VR game environment to expedite decision-making. Du *et al*. (2018) have developed a real-time synchronized BIM-VR system, called collaborative virtual reality (VR), used for collaborative decision-making. It is such cloud-based metadata interpreting the VR data automatically to update the BIM model.

ix. *Workers Training:* Using 3D modeling techniques, avoid exposure to hazardous job sites while providing a safer and effective training environment with reduced risk of injury. For example, by using VR technologies, we can train construction professionals and operators to learn to work with many tools and machinery in a safe environment (Pedro *et al*., 2016). Recently, the researchers have developed 360 VR for training purposes which simulates virtual construction safety challenges of the real construction site (Portalés *et al*., 2018). Also, the 3D modeling techniques have improved the quality and speed of training while the experts can supervise the trainees. Furthermore, the researchers have applied AR technology, which provides the employee a simulated virtual environment to understand construction processes and even teach them the building construction courses (e.g., González, 2018).

Table 1 has synthesized different dimensions and sub-dimensions of UAVs' 3D reconstruction modeling in architecture and civil engineering. According to Table 1, Building Measurement (F_{D6}=27) and then Quality Management (F_{D1}=26) are the most grown dimensions of UAV's 3D reconstruction modeling in architecture and civil engineering. In contrast, the Facilities Management, and Workers Training were not grown as much as other dimensions (F=9).

The research found that researchers regarding the sub-dimensions have mostly studied the sub-dimension using inspection tools (FD1.5=12). Afterward, Three sub-dimensions, D3.3. Using web-based VR, D6.1. Image-based 3D reconstruction and meshing, and D7.3. Using AR system have been investigated mostly grown in the UAV's 3D modeling (F=11).

In contrast, several sub-dimensions have room to grow, included: Using a WLAN-based AR system, using integrated AR and BIM, Using BIM2MAR, Using Game engine technologies, Geo-referencing, and Using GPS data, Image segmentation and Orthophoto mapping, Using the wearable device, and Using HD4AR system.

E-ISSN 1886-4805

Table 1. Applications of UAV's 3D Reconstruction modeling in Architecture and Civil Engineering

Citation	D1. Quality Management					D2. Risk Management			D3. Site monitoring			D4. Project performance control				D5. Facilities Management					D6. Building Measurement						D7. On-Site Information Analysis				D8. Team Collaboration			D9. Workers Training		
	D1.1.Using AR system	D1.2.Using BIM	D1.3.Integrating AR and BIM	D1.4.Integrating AR, BIM, and image-matching system	D1.5.Using inspection tools	D2.1.Risk of accidents	D2.2.Risk of hazardous situations	D2.3.Safety for laborers and workers	D3.1.Using a WLAN-based AR system	D3.2.Using image stitching technique	D3.3.Using web-based VR	D4.1.Using AR for virtual scheduling	D4.2.Using an AR-based 4D CAD system	D4.3.ntegrating location-based management system (LBMS) into BIM and AR	D4.4.Image-based 3D & 4D reconstruction	D5.1.Using BIM	D5.2.Using VR technology	D5.3.Using integrated AR and BIM	D5.3.Using BIM2MAR	D5.4.Using Game engine technologies	D6.1.Image-based 3D reconstruction and meshing	D6.2.Geo-referencing and using GPS data	D6.3.3D mapping	D6.4.using RGB sensors and 3D rotating laser scanners	D6.5.Image segmentation and Orthophoto mapping	D6.5.Using AR for digital fabrication	D7.1.Using wearable device	D7.2.Using HD4AR system	D7.3.Using AR system	D7.4.Integrating BIM and AR system	D8.1.Integrating game technology with web-based VR cloud	D8.2.Applying MR technologies	D8.3.Integrating BIM and VR systems	D9.1.Applying VR-based training simulators	D9.2.Using 360 VR system	D9.3.Integrating VR and MR
Goulding et al. (2012)																					▪										▪			▪		
Sampaio et al. (2012)	▪				▪											▪										▪										
Yeh et al. (2012)			▪										▪														▪			▪						
Xie et al. (2018)					▪			▪		▪	▪										▪								▪							
Sacks et al. (2013)					▪	▪	▪																											▪		
Park and Kim (2013)								▪				▪								▪											▪	▪	▪	▪		
Kwon et al. (2014)				▪						▪	▪	▪		▪															▪	▪						
Zollmann et al. (2014)															▪								▪						▪							
Siebert and Teizer (2014)										▪											▪	▪	▪	▪					▪							
Hou et al. (2015)	▪								▪		▪		▪				▪												▪						▪	▪
Williams et al. (2015)																		▪	▪											▪						
Lin et al. (2015)											▪	▪	▪		▪														▪				▪			
Zhao and Lucas (2015)						▪	▪																											▪		
Han et al. (2015)													▪		▪																▪	▪	▪			
Irizarry and Costa (2016)	▪				▪			▪				▪									▪									▪						
Pedro et al. (2016)					▪			▪															▪	▪										▪		
Zhou et al. (2016)																					▪				▪											
Bang et al. (2017)										▪	▪				▪														▪							
Kim et al. (2017)					▪		▪	▪																				▪								
Chu et al. (2018)			▪				▪			▪	▪			▪															▪	▪			▪			
Fazel and Izadi (2018)	▪										▪						▪									▪			▪		▪					
Kim and Kim (2018)										▪	▪																		▪							
Chalhoub and Ayer (2018)											▪																			▪		▪				
Du et al. (2018)	▪				▪						▪										▪										▪	▪				
Portalés et al. (2018)					▪																▪		▪			▪									▪	

Carreira et al. (2018)																▪														▪					
Freimut and König (2018)					▪																▪		▪			▪			▪	▪						
Zaker and Coloma (2018)		▪									▪										▪					▪					▪		▪			
Liu et al. (2019)		▪			▪		▪	▪						▪		▪																				
Ratajczak et al. (2019)												▪	▪	▪							▪										▪		▪			
Mirshokraei et al. (2019)			▪	▪												▪														▪						
de Melo and Costa (2019)		▪			▪	▪	▪	▪																												
Wu et al. (2019)																																				▪
Moon et al. (2019)	▪				▪					▪											▪		▪	▪												
Sub-Frequency	6	3	3	2	12	3	6	7	1	7	11	5	5	4	4	3	3	1	1	1	11	1	6	3	1	5	1	1	11	8	8	4	6	5	2	2
Frequency	26					16			19			18				9					27						21				18			9		

Note: AR: augmented reality, BIM: building-information modeling

Source: Authors.

3. The 3D Reconstruction modeling state-of-the-art (SOTA)

3D reconstruction modeling is one of the established state-of-the-art (SOTA) 3D modeling techniques. 3D reconstruction deals with diverse parameters tuning, automatization, and customization features, using dense (depth-map oriented) or sparse (key-point oriented) algorithms (Stotko and Golla, 2015; Jiang *et al*., 2020). 3D reconstruction also copes with the close-up scenes, key-point oriented approach, camera poses, the trajectory of key points, and sparse 3D features. Several 3D reconstruction modeling software has been developed to evaluate and analyze their performance and reliability on large and heterogeneous datasets (see Table 2).

The most well-established 3D reconstruction modeling software are COLMAP pipeline (Schönberger and Frahm, 2016), AgiSoft Photoscan (2016), 3DF+Zephyr (2016), Autodesk Recap (2017), 3D Survey (Guidi *et al*., 2014), DroneDeploy (2018), Photomodeler (1997), VisualSfM (Wu, 2013), and Pix4D (2017).

COLMAP is one of the 3D reconstruction pipelines mostly applied for 3D reconstruction in architecture projects. The 3D reconstruction modeling programs constitute a series of SfM and MVS (Multi-View-Stereo) algorithms. They have an intuitive graphical interface with special capacities to generate accurate, robust, and scalable 3D reconstruction. They have a key-point-oriented algorithm that works accurately and robustly on any scale and camera movements (even recognizing the drone's minor shakes) (Maxence *et al*., 2019).

These programs store the project information in the database format and export the sparse and dense reconstruction to other pipelines. For instance, COLMAP implements the SIFT algorithm and has the GPU option and a long list of feature matching options (like transitive matching, exhaustive matching, spatial matching, sequential matching, custom matching, and vocabulary tree (Maxence *et al*., 2019).

For these reasons, COLMAP needs more time to gradually create the 3D scene graph because it verifies the image pairs if they have a valid geometric mapping (i.e., fundamental matrix or homography) (Schönberger and Frahm, 2016). The 3D reconstruction modeling programs conduct bundle adjustment through Cere's solver and global bundle adjustment (BA) to enhance the points and estimations step-by-step and reconstruct the MVS using the probabilistic patch-based stereo method. For instance, COLMAP enhances completeness through multi-scale geometric consistency, also disseminates depth measurements based on lower resolution levels (Maxence *et al*., 2019).

E-ISSN 1886-4805

Agisoft Photoscan is the other 3D reconstruction software that can provide inter-the-camera calibration data (i.e., initial parameters or fixed values) after loading the images. VisualSFM is a 3D reconstruction software with incremental SfM pipeline while having less flexibility than other techniques due to using one algorithm set for reconstruction modeling (Wu *et al.*, 2019; Wu, 2013).

Like COLMAP, the VisualSFM has an intuitive graphical user interface and can generate the dense clouds directly using Furukawa's dense reconstruction tool for image-processing functions. Pix4D is an SfM pipeline that automatically recovers the sparse reconstruction orientation and camera positions from the series of images. It can calculate depth information for each camera involved in the dense point cloud and converts scenes into 3D meshes to develop high-quality digital models.

Table 2 summarizes the features and specifications of those mentioned above top-tier 3D reconstruction modeling software. According to Table 2, we may follow either of the following approaches to selecting the most appropriate software for our project:

i. Software selection based on functionalities; we may have a trade-off among point counts, overlaps, and errors generated by the software. The software induces different types of errors in calculating geometric measurement or distance computation (such as, Distant computing error, Final RMS (root-mean-square) error, Distant computing standard deviation, etc.), which affect our software selection; for example, PhotoModeler usually develops a dense point cloud, but with high Std. Dev. for distance computation.

ii. Software selection based on technical capabilities; although most software can generate the 3D models of the flat surfaces (like tree and landscape), some are not able to recognize curved surfaces (like site topography and contours), such as COLMAP, which impact on the software selection as well, iii) Software selection based on specification: software users need to plan for the type of output meets their project goal as each software produces some or a few types of the 3D model; for instance, LiMapper cannot generate the Orthomosaic and Triangulation and Bundle Adjustment. Software users also need to plan for an Educational or Commercial License before starting the project, as each license has a specific cost chart. In addition, the software users need to provide a suitable computational system able to handle the huge amount of data processing and analysis.

Table 2. Features and Specifications of the Selected Top-tier 3D reconstruction modeling software

Software	Features of Photogrammetry Reconstruction Generation							System Specification			Capability in Reconstructing site elements			
	Point Cloud	Dense Cloud	Surface Mesh	Textured model	DEM*	Orthomosaic	Triangulation and Bundle Adjustment	Software Output format	Software Platform	Software License type	Flat surfaces	Curved surfaces	Tree and Landscaping	Topography and Contours
Dronedeploy	▪	▪	▪	▪		▪	▪	ply, obj, fbx, pdf 3D, u3d, dae, pts, ptx, xyz, txt,	Windows, Linux, Mac OS	Stand-alone, Educational, Commercial	▪	▪	▪	▪
COLMAP	▪	CUDA only	CUDA only	▪			▪	ply, vrml	Windows, Linux, Mac OS	Stand-alone	▪		▪	
3DF+Zephyr	▪	▪	▪	▪			▪	ply, obj, fbx, pdf 3D, u3d, dae, pts, ptx, xyz, txt, las, e57	Windows	Stand-alone, Educational, Commercial	▪	▪	▪	▪
Autodesk Recap		▪	▪	▪	▪	▪	▪	asc, cl3, clr, e57, fls, fws, isproj, las, pcg, ptg, pts, ptx, rds, txt, xyb, xyz, zfs, zfprj	Windows	Web-based, Educational, Commercial	▪	▪	▪	▪
LiMapper	▪	▪	▪	▪				Ply, Obj, Las	Windows	Stand-alone	▪		▪	

PhotoModeler	■	■	■	■			■	3ds, 3dm, dxf, igs, kml, kmz, las, ma, ms, obj, pts, , facet, iv, ply, stl, txt, wrl	Windows	Web-based, Educational, Commercial	■	■	■	
3D Survey	■	■	■	■		■		obj, rcm, rcp/rcs	Windows, Linux, Mac OS	Stand-alone	■	■	■	
AgiSoft	■	■	■	■	■	■	■	obj, rcm, rcp/rcs, Geo-TIFF	Windows, Linux,Mac OS	Stand-alone, Floating, Educational	■	■	■	■
Pix4D Mapper	■	■	■				■	obj, fix, dxf, las, las, kml, tif, osgb, slpk, shp	Windows, macOS, Android, iOS	Stand-alone, Floating, Educational, Commercial	■	■	■	

Source: Authors.
Note: *DEM stands for Digital Elevation Model.

4. Discussion and Conclusion

Applying the UAV technology is dramatically growing and expanding in various sectors, such as geology, archeology, disaster management, particularly architecture and construction management. Meanwhile, UAV technology is applied for various dimensions, included, 3D modeling, safety, inspection, transportation, survey, etc. Among these dimensions, 3D modeling is the principal function of the UAV.

UAV's 3D modeling has become demanding since it is more convenient, affordable, and cost-efficient than satellites. Moreover, with a lot of software being developed, the 3D model can be created in a short duration of time.

The 3D reconstruction modeling software conducts a series of evaluation procedures to create the ground truth geometry of the reconstructed model and ground truth camera pose. According to Huang *et al*. (2018), the accuracy assessment, the standard deviation of unit weight, the standard deviation of object coordinates, averaged residuals of image coordinates, completeness, and accuracy of independent references are the essential metrics for photogrammetry analysis. In this regard, they perform specific steps; i) Alignment and registration, ii) Sparse point cloud Evaluation, iii) Camera pose Evaluation, and iv) Dense point cloud Evaluation. However, the implementation details and limitations of 3D modeling pipelines may vary, leading to the results' drastic strengths and weaknesses. Hence, it is recommended to employ a series of the pipeline using the same set of input images as the control variable. Indeed, the 3D reconstruction software can generate the quality 3D model of the construction site if they impute images by the UAV that have acceptable qualities. On the other hand, if the 2D image is not of good quality (like the contrast of the image or the image's completeness), it will later affect the quality of the 3D model. The thing that leads to this problem is the lighting intensity and the distance of the captured image. In this regard, the researchers conduct trajectory analysis on the device. The researchers use trajectory controllers to manage the drone's hover conditions to guarantee its convergence and stability against the reasonably small roll, pitch, yaw angles, and so on. Some dynamic factors that make a trajectory are minimum and maximum speed, minimum and maximum maneuvering radius, terrain collision avoidance, obstacle accident avoidance, air pressure, airspeed, temperature, turbulence, and erratic behaviors. Handling these factors forces researchers to optimize the UAV's trajectories through trajectory analysis techniques (such as cubic polynomials and linear functions with parabolic blends) or acceleration analysis techniques (such as trigonometric and exponential mathematical functions).

The research has investigated the UAVs' 3D reconstruction modeling applications and found out they can be clustered into nine (9) dimensions as follow; D1. Quality management, D2. Risk Management,

E-ISSN 1886-4805

D3. Site monitoring, D4. Project performance and progress control, D5. Facilities Management, D6. Building Measurement, D7. On-Site Information Analysis, D8. Team Collaboration and communication, and D9. Workers Training. The content analysis determined that building measurement and quality management were the most expanded dimensions of UAV's 3D reconstruction modeling in architecture and civil engineering. On the contrary, the facilities management and workers training are the dimensions that remain oversight and need major improvement and knowledge growth. In addition, the research found that building measurement and quality management are the most rapidly growing dimensions. These dimensions involve thirty-six (36) sub-dimensions. According to the content analysis results, using inspection tools, using web-based VR, image-based 3D reconstruction and meshing, and using AR are the most developed sub-dimensions. However, the following sub-dimensions have substantial room for growth, using a WLAN-based AR system, using integrated AR and BIM, using BIM2MAR, using game engine technologies, Geo-referencing, and using GPS data, Image segmentation and Orthophoto mapping, Using the wearable device and Using HD4AR system.

Furthermore, the research has reviewed the top-tier 3D reconstruction modeling software (included COLMAP, AgiSoft Photoscan, 3DF+Zephyr, Autodesk Recap, DroneDeploy, Photomodeler, VisualSfM, and Pix4D), and synthesized them based on features of photogrammetry reconstruction generation, capabilities in reconstructing site elements, and the required computational system specification. As each software has specific series of features and specifications, the users need to make a proper software selection before starting their project. Therefore, the research has imposed a set of software selection scenarios that significantly aid architects and contrition managers on the most appropriate software selection that fits their project plan, budget, and contract schedule.

The main approaches on software selection are i) Software selection based on functionalities, ii) Software selection based on technical capabilities, and iii) Software selection based on specification. Finally, by having the quality output from the software, the construction professionals can input them in project management software (such as BIM (Building and Information Modeling), Primavera, etc.) for further analysis and more accurate progress monitoring and scheduling.

Acknowledgments

The authors would like to thank Professor Dr. Hasanuddin Lamit for his advice in conducting this research.

Authorship

To prepare this manuscript, the authors have involved and contributed significantly. The first author has contributed to the research methodology of the manuscript, and the second author has conducted the fundamental study and literature review, and data analysis of the research. Both authors have involved for reviewing the manuscript and wrapping it up.

Conflict of interest: The authors declare that they have no conflict of interest.

References

3DF+Zephyr (2016). [Computer software]. http://www.3dflow.net/

Abd Majid, M. Z., Zakaria, W. Z., Lamit, H., Keyvanfar, A., Shafaghat, A., & Bakti, E. S. (2012). Construction Information Systems for Executive Management in Monitoring Work Progress. *Advanced Science Letters, 15*(1), 169-171. DOI: https://doi.org/10.1166/asl.2012.4096

Agisoft (2016). Agisoft PhotoScan (Version 1.2). [Computer software]. Retreived from https://www.agisoft.com/

Autodesk ReCap. (2017). (Version 3.12) [Computer software]. Retrieved from http://help.autodesk.com/view/RECAP/2018/ENU/GUID-91810DA7-71F5-4C6C-989C790455B7C847

Báez, M. C., Zambrano, A. M. A., Gutierrez, B. L., Stokes, G., Chavez, J., Montero-Alvarez, P., ... & Broadbent, E. N. (2020). Comparing High-Resolution Satellite and GatorEye UAV Lidar Data for Trail Mapping in Mixed Pine and Oak Forests in Central Florida Using a Participatory Approach.

Bang, S., Kim, H., & Kim, H. (2017). UAV-based automatic generation of high-resolution panorama at a construction site with a focus on preprocessing for image stitching. *Automation in construction*, *84*, 70-80. DOI: https://doi.org/10.1016/j.autcon.2017.08.031

Barsantia, S. G., Remondino, F., Visintini, D. (2013). 3D Surveying and Modelling of Archaeological Sites-some critical issues. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* Volume II-5/W1. DOI: https://doi.org/10.5194/isprsannals-II-5-W1-145-2013

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Çöltekin, A. (2015). Applications of 3D City Models: State of the Art Review. *International Journal Geo-Information ISPRS*, 4(4), 2842–2889. DOI: https://doi.org/10.3390/ijgi4042842

Carreira, P., Castelo, T., Gomes, C. C., Ferreira, A., Ribeiro, C., & Costa, A. A. (2018). Virtual reality as integration environments for facilities management. *Engineering, Construction and Architectural Management*. 25(1), 90-112. DOI: https://doi.org/10.1108/ECAM-09-2016-0198

Chalhoub, J., & Ayer, S. K. (2018). Using Mixed Reality for electrical construction design communication. *Automation in Construction*, *86*, 1-10. https://doi.org/10.1016/j.autcon.2017.10.028

Chu, M., Matthews, J., & Love, P. E. (2018). Integrating mobile building information modelling and augmented reality systems: an experimental study. *Automation in Construction*, *85*, 305-316. DOI: https://doi.org/10.1016/j.autcon.2017.10.032

Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. *Journal of Photogrammetry and Remote Sensing ISPRS*, *92*, 79–97. DOI: https://doi.org/10.1016/j.isprsjprs.2014.02.013

de Melo, R. R. S., & Costa, D. B. (2019). Integrating resilience engineering and UAS technology into construction safety planning and control. *Engineering, Construction and Architectural Management*. 26 (11), 2705-2722. DOI: https://doi.org/10.1108/ECAM-12-2018-0541

Dib, H., Adamo-Villani, N., Issa, R. R. (2013). A GIS-based visual information model for building construction project management. *International Journal of Construction Management, 13*(1), 1-18. DOI: https://doi.org/10.1080/15623599.2013.10773202

DroneDeploy (2018). [Computer software]. Retrieved from https://www.dronedeploy.com/

Du, J., Shi, Y., Zou, Z., & Zhao, D. (2018). CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users. *Journal of Construction Engineering and Management*, *144*(2), 04017109. DOI: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426

Fazel, A., & Izadi, A. (2018). An interactive augmented reality tool for constructing free-form modular surfaces. *Automation in Construction*, *85*, 135-145. DOI: https://doi.org/10.1016/j.autcon.2017.10.015

E-ISSN 1886-4805

Ficapal, A., & Mutis, I. (2019). Framework for the detection, diagnosis, and evaluation of thermal bridges using infrared thermography and unmanned aerial vehicles. *Buildings*, *9*(8), 179. DOI: https://doi.org/10.3390/buildings9080179

Freimut, H., & König, M. (2018). Planning and executing construction inspections with unmanned aerial vehicles. *Automation in Construction*, *96*, 540-553. DOI: https://doi.org/10.1016/j.autcon.2018.10.016

González, N. A. A. (2018). Development of spatial skills with virtual reality and augmented reality. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *12*(1), 133-144. DOI: https://doi.org/10.1007/s12008-017-0388-x

Goulding, J., Nadim, W., Petridis, P., & Alshawi, M. (2012). Construction industry offsite production: A virtual reality interactive training environment prototype. *Advanced Engineering Informatics*, *26*(1), 103-116. DOI: https://doi.org/10.1016/j.aei.2011.09.004

Guidi, G., Russo, M., & Angheleddu, D. (2014). 3D survey and virtual reconstruction of archeological sites. *Digital Applications in Archaeology and Cultural Heritage*, *1*(2), 55-69. DOI: https://doi.org/10.1016/j.daach.2014.01.001

Ham, Y., Han, K. K., Lin, J. J., Golparvar-Fard, M. (2016). Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works. *Visualization in Engineering, 4*(1), 1. DOI: https://doi.org/10.1186/s40327-015-0029-z

Han, K, Lin, J, Golparvar-Fard, M. A. (2015). Formalism for Utilization of Autonomous Vision-Based Systems and Integrated Project Models for Construction Progress Monitoring. In David J. White, Ahmad Alhasan, and Pavana Vennapusa (Eds.), *Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure* (pp. 118-131). Retrieved from https://intrans.iastate.edu/app/uploads/2015/08/CARCI-proceedings.pdf

Hou, L., Wang, X., & Truijens, M. (2015). Using augmented reality to facilitate piping assembly: an experiment-based evaluation. *Journal of Computing in Civil Engineering*, *29*(1), 05014007. DOI: https://doi.org/10.1061/(ASCE)CP.1943-5487.0000344

Huang, R., Zou, D., Vaughan, R., & Tan, P. (2018). Active image-based modeling with a toy drone. In *2018 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 6124-6131). Retreieved from https://www.ieee-ras.org/component/rseventspro/event/570-icra-2018-ieee-int-conf-on-robotics-and-automation/

Irizarry, J., & Costa, D. B. (2016). Exploratory study of potential applications of unmanned aerial systems for construction management tasks. *Journal of Management in Engineering*, *32*(3), 05016001. DOI: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000422

Jiang, W., Zhou, Y., Ding, L., Zhou, C., & Ning, X. (2020). UAV-based 3D reconstruction for hoist site mapping and layout planning in petrochemical construction. *Automation in Construction*, 113, 103-137. DOI: https://doi.org/10.1016/j.autcon.2020.103137

Jin, Y. Q., & Xu, F. (2007). Reconstruction of the building objects from multi-aspect high-resolution SAR images. In 2007 IEEE International Geoscience and Remote Sensing Symposium (pp. 555-558). IEEE. Retrieved from https://ieeexplore.ieee.org/document/4422854/citations#citations

Keyvanfar, A., Shafaghat, A., & Awanghamat, M. A. (2021). Optimization and Trajectory Analysis of Drone's Flying and Environmental Variables for 3D Modelling the Construction Progress Monitoring. *International Journal of Civil Engineering*, 1-26. DOI: https://doi.org/10.1007/s40999-021-00665-1

E-ISSN 1886-4805

Kim, H., Lee, J., Ahn, E., Cho, S., Shin, M., & Sim, S. H. (2017). Concrete crack identification using a UAV incorporating hybrid image processing. *Sensors*, *17*(9), 2052. DOI: https://doi.org/10.3390/s17092052

Kim, S., & Kim, S. (2018). Opportunities for construction site monitoring by adopting first personal view (FPV) of a drone. *Smart Structures and Systems*, *21*(2), 139-149. DOI: https://doi.org/10.12989/sss.2018.21.2.139

Kwon, O. S., Park, C. S., & Lim, C. R. (2014). A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. *Automation in construction*, *46*, 74-81. DOI: https://doi.org/10.1016/j.autcon.2014.05.005

LiMapper (2019). [Computer software]. Retrieved from https://candrone.com/products/limapper

Liu, M., Lee, S., & Kamat, V. R. (2019). Remote proximity monitoring between mobile construction resources using camera-mounted UAVs. *Automation in Construction*, *99*, 168-182. DOI: https://doi.org/10.1016/j.autcon.2018.12.014

Majid, M., Lamit, H., Keyvanfar, A., & Shafaghat, A. (2012). Conceptual intelligent building (IB) design framework to improve the level of user comfort towards sustainable energy efficient strategies: proposal validation. *OIDA International Journal of Sustainable Development*, 4(01), 11-18. Retrieved from http://www.ssrn.com/link/OIDA-Intl-Journal-Sustainable-Dev.html

Marques, L. F., Tenedório, J. A., Burns, M., Romão, T., Birra, F., Marques, J., & Pires, A. (2017). Cultural Heritage 3D Modelling and visualisation within an Augmented Reality Environment, based on Geographic Information Technologies and mobile platforms. *ACE: Architecture, City, and Environment,* 11(33), 117-136. DOI: https://doi.org/10.5821/ace.11.33.4686

Maxence, R., Uchiyama, H., Kawasaki, H., Thomas, D., Nozick, V., & Saito, H. (2019). Mobile photometric stereo with keypoint-based SLAM for dense 3D reconstruction. In *2019 International Conference on 3D Vision (3DV),* 574-582. Retrieved from https://www.computer.org/csdl/proceedings/3dv/2019

Mirshokraei, M., De Gaetani, C. I., & Migliaccio, F. (2019). A web-based BIM–AR quality management system for structural elements. *Applied Siences*, *9*(19), 3984. DOI: https://doi.org/10.3390/app9193984

Moon, D., Chung, S., Kwon, S., Seo, J., & Shin, J. (2019). Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning. *Automation in Construction*, *98*, 322-331. DOI: https://doi.org/10.1016/j.autcon.2018.07.020

Muñoz Salinas, F., & Garcia-Almirall, M. P. (2010). Methodology to reconstruct virtual cities from the past. *ACE: Architecture, City and Environment,* 5(13), 223-236. DOI: https://doi.org/10.5821/ace.v5i13.2501

Murugan, D., Garg, A., Ahmed, T., & Singh, D. (2016). Fusion of drone and satellite data for precision agriculture monitoring. In *2016 11th International Conference on Industrial and Information Systems (ICIIS)* 910-914. Retrieved from https://www.aconf.org/conf_81847.2016_11th_International_Conference_on_Industrial_and_Information_Systems.html

Park, C. S., & Kim, H. J. (2013). A framework for construction safety management and visualization system. *Automation in Construction*, *33*, 95-103. DOI : https://doi.org/10.1016/j.autcon.2012.09.012

Pedro, A., Le, Q. T., & Park, C. S. (2016). Framework for integrating safety into construction methods education through interactive virtual reality. *Journal of professional issues in engineering education and practice*, *142*(2), 04015011. DOI: https://doi.org/10.1016/j.autcon.2012.09.012

Pejoska, J., Bauters, M., Purma, J., & Leinonen, T. (2016). Social augmented reality: Enhancing context-dependent communication and informal learning at work. *British Journal of Educational Technology*, *47*(3), 474-483. DOI: https://doi.org/10.1111/bjet.12442

Photomodeler (1997). [Computer software]. Retrieved from www.photomodeler.com

Pix4D (2017). (Pix4Dmapper version 4.1) [Computer software]. Retrieved from https://support.pix4d.com/hc/en-us/sections/360003718992-Manual

Portalés, C., Casas, S., Gimeno, J., Fernández, M., & Poza, M. (2018). From the paper to the tablet: on the design of an AR-based tool for the inspection of pre-fab buildings. Preliminary results of the SIRAE project. *Sensors*, *18*(4), 1262. DOI: https://doi.org/10.3390/s18041262

Ratajczak, J., Riedl, M., & Matt, D. T. (2019). BIM-based and AR application combined with location-based management system for the improvement of the construction performance. *Buildings*, *9*(5), 118. DOI: https://doi.org/10.3390/buildings9050118

Sacks, R., Perlman, A., & Barak, R. (2013). Construction safety training using immersive virtual reality. *Construction Management and Economics*, *31*(9), 1005-1017. DOI: https://doi.org/10.1080/01446193.2013.828844

Sampaio, A. Z., Rosário, D. P., & Gomes, A. R. (2012). Monitoring interior and exterior wall inspections within a virtual environment. *Advances in Civil Engineering*, *2012*. DOI: https://doi.org/10.1155/2012/780379

Schönberger, J. L., & Frahm, J. M. (2016). Structure-from-motion revisited. In *Proceedings of the IEEE conference on Computer Vision and Pattern Recognition (CVPR),* 4104-4113. Retrieved from https://ieeexplore.ieee.org/document/7780814

Shazali, A. S. A. Tahar, K. N. (2019), Virtual 3D model of Canseleri building via close-range photogrammetry implementation. *International Journal of Building Pathology and Adaptation*, 38(1). 217-227. DOI: https://doi.org/10.1108/IJBPA-02-2018-0016

Siebert, S. Teizer, J. (2014), Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system. *Automation in Construction,* 41, 1-14. DOI: https://doi.org/10.1016/j.autcon.2014.01.004

Stotko, P., Golla, T. (2015). Improved 3D Reconstruction using Combined Weighting Strategies. In *Proceedings of CESCG 2015: The 19th Central European Seminar on Computer* Graphics (pp. 135-142). Retrieved from https://www.worldcat.org/title/proceedings-of-the-19th-central-european-seminar-on-computer-graphics-cescg-2015-april-20-22-2015-smolenice-slovakia/oclc/911526632

Tang, P., Huber, D., Akinci, B. (2011). Characterization of laser scanners and algorithms for detecting flatness defects on concrete surfaces. *Journal of Computing in Civil Engineering*, *25*(1), 31-42. DOI: https://doi.org/10.1061/(ASCE)CP.1943-5487.0000073

Tavares, P., Costa, C. M., Rocha, L., Malaca, P., Costa, P., Moreira, A. P., ... & Veiga, G. (2019). Collaborative welding system using BIM for robotic reprogramming and spatial augmented reality. *Automation in Construction*, *106*, 102825. DOI: https://doi.org/10.1016/j.autcon.2019.04.020

Wendel, A., Irschara, A., & Bischof, H. (2011). Automatic alignment of 3D reconstructions using a digital surface model. In *CVPR 2011 WORKSHOPS,* 29-36. Retrieved from https://www.computer.org/csdl/proceedings/cvprw/2011/12OmNwJPMYe

E-ISSN 1886-4805

Williams, G., Gheisari, M., Chen, P. J., & Irizarry, J. (2015). BIM2MAR: An efficient BIM translation to mobile augmented reality applications. *Journal of Management in Engineering*, *31*(1), A4014009. DOI: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000315

Wu, C. (2013). Towards linear-time incremental structure from motion. In *2013 International Conference on 3D Vision-3DV 2013*, 127-134. Retrieved from https://www.computer.org/csdl/proceedings/3dv/2013/12OmNyaXPPL

Wu, W., Hartless, J., Tesei, A., Gunji, V., Ayer, S., & London, J. (2019). Design assessment in virtual and mixed reality environments: Comparison of novices and experts. *Journal of Construction Engineering and Management*, *145*(9), 04019049. DOI: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001683

Xie, R., Yao, J., Liu, K., Lu, X., Liu, Y., Xia, M., & Zeng, Q. (2018). Automatic multi-image stitching for concrete bridge inspection by combining point and line features. *Automation in Construction*, *90*, 265-280. DOI: https://doi.org/10.1016/j.autcon.2018.02.021

Yeh, K. C., Tsai, M. H., & Kang, S. C. (2012). On-site building information retrieval by using projection-based augmented reality. *Journal of Computing in Civil Engineering*, *26*(3), 342-355. DOI: https://doi.org/10.1061/(ASCE)CP.1943-5487.0000156

Zaker, R., & Coloma, E. (2018). Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. *Visualization in Engineering*, *6*(1), 1-15. DOI: https://doi.org/10.1186/s40327-018-0065-6

Zhao, D., & Lucas, J. (2015). Virtual reality simulation for construction safety promotion. *International Journal of Injury Control and Safety Promotion*, *22*(1), 57-67. DOI: https://doi.org/10.1080/17457300.2013.861853

Zhou, Z., Gong, J., & Guo, M. (2016). Image-based 3D reconstruction for post hurricane residential building damage assessment. *Journal of Computing in Civil Engineering*, *30*(2), 04015015. DOI: https://doi.org/10.1061/(ASCE)CP.1943-5487.0000480