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A SYSTEMATIC REVIEW OF UNMANNED AERIAL VEHICLE APPLICATION AREAS AND TECHNOLOGIES IN THE AEC DOMAIN

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SUMMARY: *The recent increase in the integration of unmanned aerial vehicles (UAVs) in civilian usage stems mainly from modern technological advancements and the devices' abilities to accomplish civilian tasks in a quick, safe, and cost-efficient manner. One sector that witnessed tremendous UAV impact is the Architecture, Engineering, and Construction (AEC) industry. Among several AEC applications, UAV technology is currently being implemented for building and bridge inspection, progress monitoring, and urban planning. The following review aims at thoroughly classifying all AEC-related UAV applications within the past decade, extending the understanding of the current state of UAV implementation in the AEC domain, and outlining relevant research trends in this setting. The review follows a systematic literature assessment methodology in which peer-reviewed bibliographical databases were queried, based on specific search keywords, for AEC-related UAV applications. This study also discusses the technological components (flying styles, types of platforms, onboard sensors) to assist in better developing, integrating, and understanding the technology implemented in the AEC industry. Our search query yielded 228 articles, of which 86 met our inclusion criteria and were therefore analyzed. Seven categories of structural and infrastructure inspection, transportation, cultural heritage conservation, city and urban planning, progress monitoring, post-disaster, and construction safety were identified and fully analyzed in this study. The study revealed that UAV integration in the AEC domain might exhibit equal, if not, higher outcomes compared to conventional methods as to time, accuracy, safety, and costs. In terms of technology, the control styles reported were mostly autonomous and manual. Rotary wing vehicles were the predominant type of platforms in the literature. Of the rotary wing type, quadcopters were most commonly employed. Readily available, or "off-the-shelf" video recording cameras and thermal cameras were most frequently mounted on UAVs, followed by LiDAR and laser scanning devices. Other sensors included Radio Frequency Identification and Ultrasonic Beacon System. The outcome of this study would benefit both AEC researchers and professionals to recognize the potentials of UAVs and understand the requirements and challenges for their successful integration.*

KEYWORDS: *Unmanned Aerial Vehicle, UAV, AEC Industry, Technology, Application, Systematic Review, UAS.*

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1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are pilotless airborne systems, controlled through ground control stations (Hallermann and Morgenthal, 2014). These systems had mainly been designed for military applications (Pajares, 2015; Siebert and Teizer, 2014; Zhou and Gheisari, 2018) but over the years and with tremendous improvements in their technologies, civilian applications of UAVs have gained wide popularity (Zhou and Gheisari, 2018). Specifically, civilian applications range from remote sensing or precision agriculture (Gonzalez-Dugo et al., 2013) to delivery of goods and medical supplies (Howell et al., 2016), as well as search and rescue domains (Mccormack, 2008). The growth of UAV applications has had a strong economic impact as well, generating more than 70,000 job opportunities in the United States (Jenkins and Vasigh, 2013). By 2025, this technology is anticipated to positively influence the American economy with unprecedented growth of more than $82 billion (Jenkins and Vasigh, 2013).

The Architecture, Engineering, and Construction (AEC) industry in particular is primed for a growth in UAV applications (Eiris Pereira and Gheisari, 2017; Ham et al., 2016). UAVs are an ideal technology for many AEC applications, since they can access spaces that are unsafe, hard-to-reach, or inaccessible by human workers. UAVs are also capable of doing some AEC-related tasks faster and at a lower cost. They can also be equipped with a variety of onboard sensors as needed by the task. Moreover, the new generation of commercial UAVs and flight platforms are inexpensive and require minimal human involvement to conduct the flights which might lead to more usage and fewer safety challenges on site (Zhou and Gheisari, 2018). These features together with technological advancement in battery life, flight and data collection sensors, and the integration of flight autonomous capabilities, have made UAVs a more popular and reliable platform for AEC-related applications.

A few researchers have published review papers regarding UAV applications in construction: Pajares (2015) presented an overview of the status of UAVs in remote sensing applications; Ham et al. (2016) discussed UAV application in the visual inspection of civil infrastructure systems; Duque et al. (2018a) presented UAV implementation for post-construction infrastructure inspection with specific focus on applications within the Departments of Transportations (DOTs). However, no prior reviews have examined the entirety of the AEC domain to identify and categorize UAV applications related to the design, engineering, and construction phases of a project. The goal of this paper is to systematically review peer-reviewed academic studies on UAVs across the entire AEC domain to identify trends in their application and technological components (e.g., UAV types, styles of control, sensor). Specifically, this study seeks to answer the following research questions: (1) *What is the status of the UAV adoption in the AEC domain?* (2) *What are the current applications of UAVs in the AEC domain?* (3) *What types of UAV technologies are being used in the AEC domain?*

2. RESEARCH METHOD

To answer these questions, this study performed a systematic review of extant literature. The systematic review is a structured analysis that reports topic-specific studies in a replicable, objective, transparent, and comprehensive manner (Denyer and Tranfield, 2009; Kitchenham and Charters, 2007). Initially employed in the medical field, this type of review has been increasingly applied in AEC research (Abdirad and Dossick, 2016; Eiris Pereira and Gheisari, 2017; Khallaf et al., 2018; Martínez-Aires et al., 2017).

2.1 Search Terms

The first step of a systemic review is to operationalize the research questions into search terms and syntax that will identify as many potentially relevant publications as possible. For this study, the research questions were broken down to individual concepts, and related keywords, which were then arranged into the following search syntax for study retrieval: ("Unmanned Aerial Vehicles" OR "Unmanned Aerial System" OR "UAV" OR "Drone" OR "UAS") AND ("Construction" OR "Engineering" OR "Architecture OR "Applications" OR "Civil Uses" OR "AEC").

2.2 Search Procedure

A systematic search, using the search syntax, was performed in the Google Scholar database. This database is a freely accessible web-based search engine capable of identifying full text and multi-disciplinary publications (Bar-Ilan, 2008; Zientek et al., 2018). It offers the advantage of entering a specific syntax query, which instantly generates an exhaustive list of papers unique to a specific topic and may be indexed in other alternative databases (Shultz, 2007; Zientek et al., 2018). A total of 222 papers were collected using the search syntax. A review of the references in these papers allowed for the manual identification of 6 additional articles for consideration in the review. The titles and abstracts of all 228 publications were reviewed to determine whether they satisfied the inclusion criteria in the systematic review. To be included in the review, the publication was required to be a peer-reviewed journal or conference paper, issued within the last decade (2008 to 2018) and focusing on UAV applications within the AEC domain. Other types of studies such as literature reviews, research reports, dissertations, and industry trade articles were excluded.

To document this procedure, we followed a systematic paper selection procedure, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2009) as shown in Fig. 1. In the identification stage, 228 potentially relevant publications were identified. After screening to remove duplicate entries, records that were not published within 2008 to the 2018 year range and non-peer-reviewed articles, 197 publications were carried forward for eligibility analysis. To determine eligibility, the full-text of articles were reviewed and 114 were excluded, since they were either not related to the AEC domain or were not describing UAV applications. After the eligibility check, a total of 86 articles became the foundation of our systematic literature review.

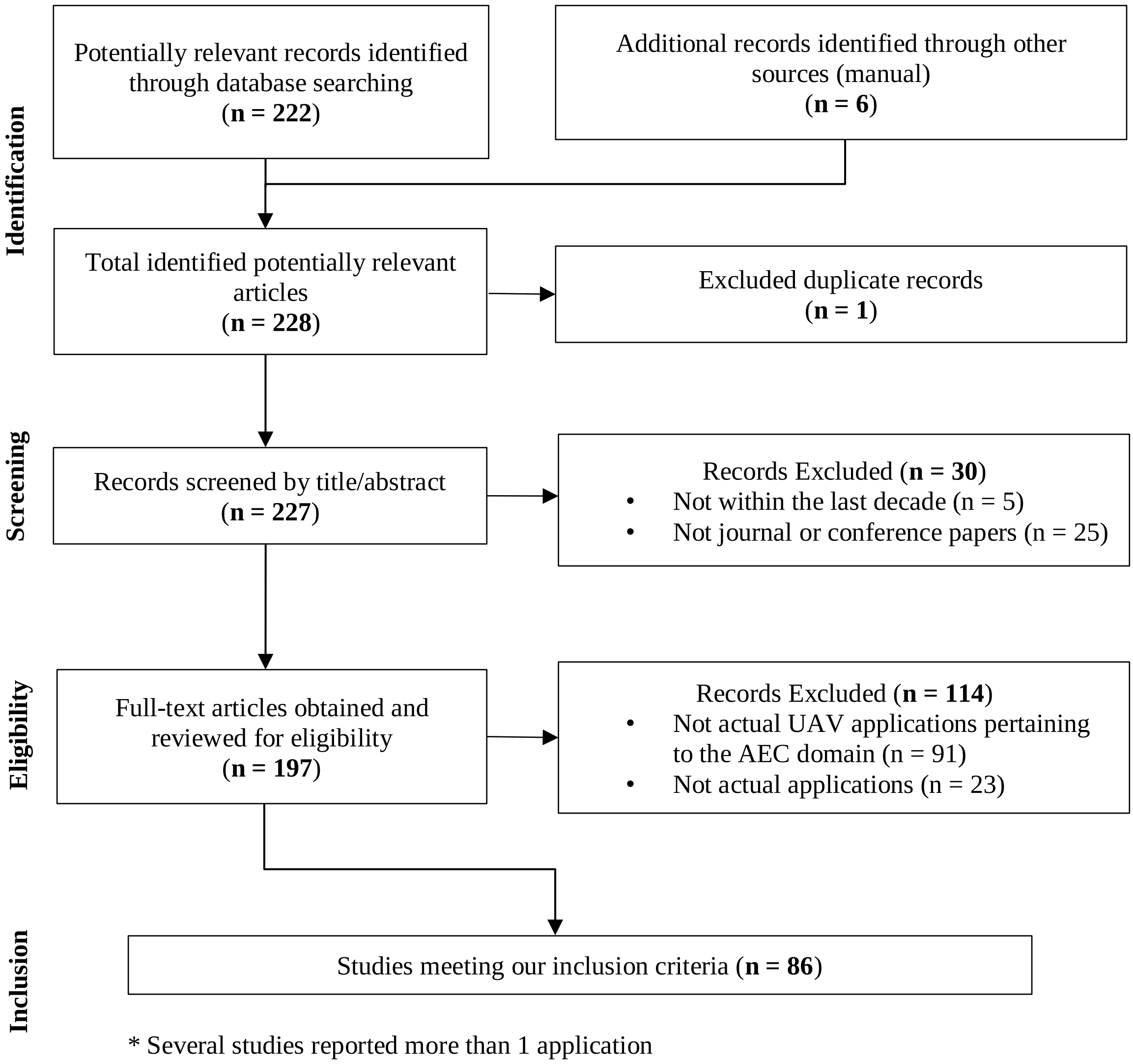

FIG. 1: PRISMA flowchart of article screening

3. CURRENT STATUS OF UAVS IN THE AEC RESEARCH

The annual number of publications on UAV applications in the AEC domain is illustrated in Fig. 2. During the last decade, the mean number of annual publications in the AEC field was 7.8. This period was characterized by an increasing trend of publications. Overall, there were approximately threefold more papers between 2014 and 2018 than there were between 2008 and 2012 (55 versus 20, respectively). The lowest numbers of articles were recorded in 2008, 2009, and 2010 with five studies in total, whereas the highest number of studies were recorded in the year 2014 with 16 studies, and both 2015, and 2013, with 13 studies each. This increase reflects the growing interest of researchers on using UAVs for various applications within the AEC domain.

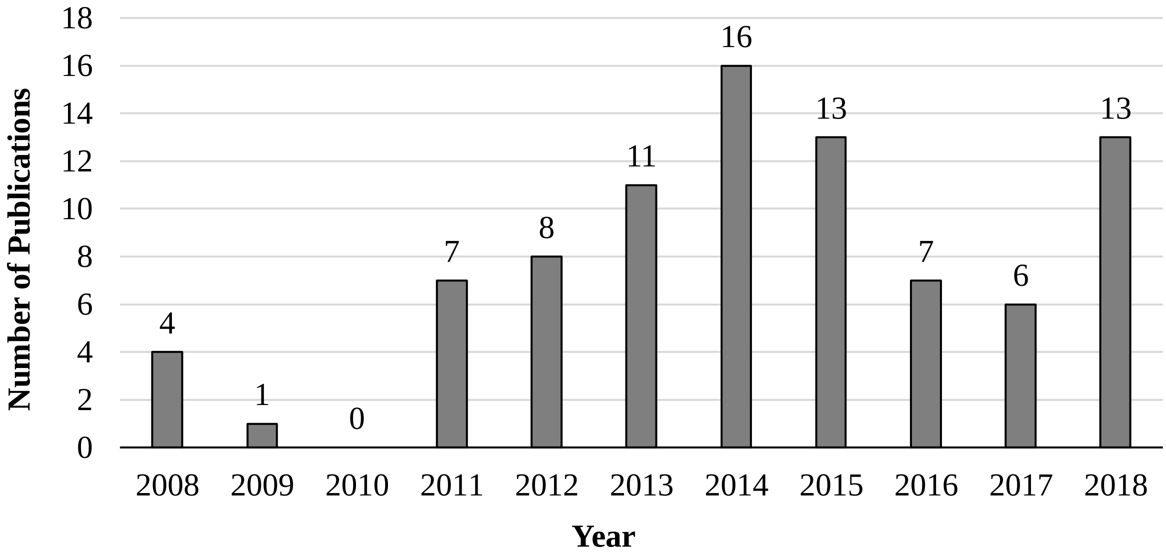

FIG. 2: Annual number of publications on UAV applications in the AEC domain (2008-2018)

Furthermore, publications were categorized based on their sources and corresponding years of publication. A complete list of the venues that published two or more papers on UAV applications in the AEC domain is summarized in Table 1.

TABLE 1: Number of Publications by Journal or Conference on Year Range

Peer-Reviewed Journal or Conference Venue	**Year Range**	**No. of Publications (Percentage)**
International Conference on Unmanned Aerial Vehicle in Geomatics	2011-2013	6 (6.98%)
International Society for Photogrammetry and Remote Sensing (ISPRS) Congress Meeting	2008-2016	4 (4.65%)
International Conference on Construction Applications of Virtual Reality (ConVR)	2018	4 (4.65%)
Annual International Symposium on Automation and Robotics in Construction (ISARC)	2015-2017	3 (3.49%)
IEEE International Workshop on Safety, Security and Rescue Robotics (SSRR) Annual Meetings	2008-2012	2 (2.33%)
Annual International Conference on Unmanned Aircraft Systems (ICUAS)	2013-2014	2 (2.33%)
International Association for Bridge and Structural Engineering (IABSE) Annual Symposium	2013-2014	2 (2.33%)
Proceedings of Associated Schools of Construction	2015-2016	2 (2.33%)
Journal of Automation in Construction	2013-2014	2 (2.33%)
Journal of Computer-Aided Civil and Infrastructure Engineering	2012-2018	2 (2.33%)
Computing in Civil and Building Engineering Conference	2014	2 (2.33%)
Journal of Infrastructure Systems	2008-2015	2 (2.33%)
CIB W78 Conference: IT in Design, Construction, and Management	2018	2 (2.33%)
Others (venues with a single publication)	2008-2018	51(59.3%)
Total Publications:	2008-2018	86 (100%)

The International Conference on Unmanned Aerial Vehicle in Geomatics contributed most publications (6.98%) with 6 articles from 2011 to 2013, followed *by International Society for Photogrammetry and Remote Sensing (ISPRS) Congress Meeting* (4.65%), *The International Conference on Construction Applications of Virtual Reality* (4.65%), and *Annual International Symposium on Automation and Robotics in Construction (ISARC)* (3.49%). Publication sources suggest that papers related to UAV applications in the AEC domain are mainly published in technology-related journals and conferences within the general area of engineering and construction management. The diversity of these venues also shows the multidisciplinary research opportunities offered by UAV applications.

An analysis of the institution and authorship of the retrieved articles revealed that the top contributing institution is Bauhaus University in Germany (Authors: Guido Morgenthal and Norman Hallermann), with six peer-reviewed manuscripts published from 2013 to 2015. This was followed by Drexel University (Andrew Ellenberg, Antonios Kontsos, and Ivan Bartoli) and Georgia Institute of Technology (Javier Irizarry), both with four publications. Countries that conducted relevant studies were also analyzed in this part of the study. The top contributing country was the United States with 34 manuscripts followed by Germany (15), Italy (7), and Spain (5).

4. CONTEXTS OF APPLICATION AND THEIR TECHNOLOGY USE

Seven distinct categories of UAV applications in the AEC domain were identified by the authors to provide a framework for discussing prior work. These categories (see Table 2) are not presented as a statement of fact, but rather as the authors' interpretation of the applications found across the searched publications. They serve as a structure, around which the review of prior work is organized and discussed. Each of the seven categories was intended to be exclusive. That is, an example of a UAV application should fit in one and only one category. These categories were: structural and infrastructure inspection, transportation, cultural heritage conservation, city and urban planning, progress monitoring, post-disaster, and construction safety. Applications that described road condition assessment or maintenance inspection were labelled as structural and infrastructure inspection; otherwise, they were categorized under transportation. Articles discussing damage assessment of buildings or structures affected by disastrous events were considered as reporting post-disaster applications.

TABLE 2: Application areas of UAV uses and examples in the AEC domain

Application area	**Examples from articles**
Structural and infrastructure inspection	Building inspection Bridge inspection Other inspections (roads, photovoltaic cells, dams, retaining walls, microwave tower)
Transportation	Landslide monitoring and mapping Earthwork Traffic surveillance
Cultural heritage conservation	Historic preservation and reconstruction Monitoring historic monuments 3D modeling of heritage buildings Landscape preservation
City and urban planning	Land policy monitoring Cadastral surveying City and building modeling Cartography updating
Progress monitoring	Construction progress monitoring Tracking material on complex jobsites
Post-disaster assessment	Assessing damages (including structural) of cities/buildings after disastrous events
Construction safety	Construction safety inspection Monitoring safety hazards of equipment in construction sites

4.1 Structural and Infrastructure Inspection

Multiple authors have investigated UAVs performing structural and infrastructure inspections during the last decade. The assessments covered buildings, bridges, as well as several other structures (e.g., retaining walls, roads, windmill and dams). Thirty-nine of the 86 articles evaluated (45.3%) reported structural and infrastructure inspection uses for UAVs. These articles are summarized shown in Table 3.

TABLE 3: UAV Applications for Structure and Infrastructure Inspection

Building inspection	Liu et al., 2016; Eschmann et al., 2012; Morgenthal and Hallermann, 2014; Mauriello and Froehlich, 2014; Roca et al., 2013; Sankarasrinivasan et al., 2015; Wefelscheid et al., 2011; Pratt et al., 2008; Eschmann et al., 2013; Ellenberg et al., 2015; Ellenberg et al., 2014; Daftry et al., 2015; Hallermann et al., 2015b; Vetrivel et al., 2015; Hallermann and Morgenthal, 2013; Mutis and Romero, 2018; Kang and Cha, 2018; Merz and Kendoul, 2011
Bridge inspection	Duque et al., 2018b; Khan et al., 2015; Khaloo et al., 2018; Ellenberg et al., 2016; Hallermann and Morgenthal, 2014; Gillins et al., 2016; Ellenberg et al., 2015; Kim et al., 2015; Brooks et al., 2017; Xu and Turkan, 2018; Kasireddy et al., 2018; Seo et al., 2018; Zekkos et al., 2018
Other inspections	
▪ Roads	Zhang, 2008; Dobson et al., 2013; Zhang and Elaksher, 2012; Rathinam et al., 2008; Ho and Kubota, 2018
▪ Dams	Hallermann et al., 2015b; Henriques and Roque, 2015; Zekkos et al., 2018
▪ Retaining walls	Hallermann and Morgenthal, 2014; Hallermann et al., 2014; Hallermann et al., 2015b; Zekkos et al., 2018
▪ Photovoltaic cells	Tyutyundzhiev et al., 2015
▪ Microwave tower	Merz and Kendoul, 2011

Building inspection. Of the 39 articles reporting structural and infrastructure inspection, 18 (46.2%) discussed UAV applications for building inspection. Of those, only one tethered their UAV to inspect a parking garage. However, it was proved to be ineffective in terms of efficiency and safety reliability (Pratt et al., 2008). Several studies relied upon light detection and ranging (LiDAR) surveying techniques to conduct their comparative analyses. Wefelscheid et al. (2011) presented the possible application fields that UAVs offer by reconstructing a digital three-dimensional (3D) building model using UAV visualizations. Results were evaluated based on benchmark datasets and exhibited a highly accurate model comparable to the LiDAR surveying method. After conducting a comparison with the latter scanning technique, Roca et al. (2013) assessed the feasibility of mounting a Microsoft Kinect sensor on a UAV as a standalone technique or as a terrestrial complementary method in surveying building facades. The authors noted that the UAV-generated model demonstrated good quality results that could be used for energy and structural analyses. A more recent study assessed the existing state of a building curtain walls by comparing LiDAR and UAV-generated point clouds (Liu et al., 2016). The research team advocated drone usage for such tasks, emphasizing the advantages associated with this new technology, in terms of improved safety and cost savings. Other researchers employed different technical methods to evaluate the drones' efficacy in their experiments. Vetrivel et al. (2015) developed a 2-step segmentation algorithm to automatically recognize buildings and their sub-elements. Their proposed method consists of defining the region of interest by performing a delineation of the studied area, as well as performing the image space segmentation by using UAV spectral image information and geometric features generated by the 3D model. This methodology permitted a successful segmentation of the tested buildings and sub-elements, and outperformed other techniques solely based on 3D geometric features.

All of the aforementioned studies discussed UAV applications in an outdoor global positioning system (GPS)-enabled environment. On the other hand, a recent pioneering study evaluated the potential application of autonomous UAVs for building inspection by using an ultrasonic beacon system (UBS) in GPS-deprived locations (Kang and Cha, 2018). The authors aimed at assessing the feasibility of using UAV videos with deep learning-based automatic damage detection and geo-tagging for concrete crack detection and localization, respectively. After adequate firmware and hardware adjustments to allow UBS integration, indoor tests revealed that UAV-acquired images were accurate and precise for damage detection and localization. Several other articles discussed damage assessment and crack detection in buildings. Combining high-resolution cameras with UAVs were found to be a suitable method for building digital monitoring and automated crack detection while allowing damage and crack observations to the millimeter range (Eschmann et al., 2012). Environmental factors (mainly wind speed and direction) that may affect UAV image acquisition were discussed in a more recent analysis, which developed a technique that successfully quantifies damage assessment quality (Morgenthal and Hallermann, 2014). Buildings were also inspected with infrared thermography. This technique was relied upon to inspect a facade, determine thermal bridges and quantify their magnitude (Mutis and Romero, 2018). Guided by baseline temperature values, the authors concluded that this technique would assist the architecture, engineering, and construction realm in establishing subsequent retrofitting thresholds.

Bridge inspection. UAV bridge inspection was discussed in 13 of 39 (33.3%) peer-reviewed publications, the majority of which emphasized the advantages of UAVs over manual inspection. The most prominently discussed topics were bridge damage detection and quantification. Khan et al. (2015) assessed the capacity and efficacy of UAV-captured multispectral images using RGB and thermal cameras in delimiting deterioration signs in road bridge decks. According to their findings, this non-contact technology is effective in detecting and localizing cracks and delamination, as well as overcoming traditional traffic control and/or roadway closure. In another study, field tests were conducted on bridges using aerial platforms to assess a proposed automatic crack detection and width calculation system (Kim et al., 2015). Despite some differences between measured and analyzed crack widths, the research team argued that such discrepancies fall within the allowable 0.1 mm surveying error range. Similarly, Ellenberg et al. (2016) evaluated the use of UAV-captured and computer-processed images to assist inspection managers quantify bridge damages. A recent analysis evaluated the effectiveness of UAV as a supplementary bridge damage quantification tool (Duque et al., 2018b). By developing a four-stage UAV-enabled timber arch bridge damage quantification protocol involving image quality assessment, the authors found that their technique was accurate and precise with small differences in results retrieved regarding crack length, thickness, and rust stain area, compared to conventional manual field measurements. An analysis of a bridge located in South Dakota was recently performed and noted that technical advancements and weather conditions played vital roles in achieving an accurate alternative for bridge inspection, allowing the identification of different damage types and reducing safety concerns commonly encountered with other previous inspection methods (Seo et al., 2018). Another report aimed at using UAV images combined with a structure from motion algorithm to generate a 3D model of the Alaskan Placer River Trail Bridge (Khaloo et al., 2018). This study associated the technology with enhanced quality and accuracy compared to models generated from traditional inspection methods. The advantages included the ability to collect images from all possible points of view due to the system's flexibility and flight path planning. Although limited by a demonstrative mockup, the authors guaranteed that the model replicates exact outdoor conditions and confirmed the ability of the generated images to accurately assess bridge-related damages. The structure from motion algorithm was also performed on a collapsed bridge as part of a 26-field analysis to reflect UAV-related applications in geotechnical engineering (Zekkos et al., 2018). After obtaining a 3D model of the bridge, the research team was able to adequately perform several measurements and recommended this technique for geotechnical applications.

Other inspections. Additional specific inspections were found for roads (5 articles), dams (3 articles), retaining walls (3 articles), photovoltaic (PV) cells (1 article), and a microwave tower (1 article). Several researchers considered applying drones to determine road condition and specifically distresses found on unpaved roads. One such study used the structure from motion algorithm on a set of aerial images to generate a 3D model for an unpaved road condition assessment (Dobson et al. 2013). Despite being limited by vegetation interference, the authors were capable of successfully detecting and classifying distresses. Similarly, another study validated UAV-captured photogrammetric images as a mean to survey unpaved road conditions and successfully established the ability to collect vital road condition parameters (Zhang, 2008). With the aid of a real-time detection algorithm that allows localization and identification of various structures, Rathinam et al. (2008) studied infrastructures that encompassed both canals and highways. Although not tested, one of the proposed recommendations consisted of using gimbaled and downward looking cameras mounted on a UAV while hovering for these types of inspections. A research team operated a camera-mounted UAV on a PV rooftop to assist inspectors in large PV field inspection and monitoring (Tyutyundzhiev et al., 2015). They noted that recent UAV hardware and software advancements easily permitted rooftop PV cells inspections while being limited by sunlight-related image distortions. Other authors were more interested in deploying drones to inspect concrete dams. In this context, Henriques and Roque (2015) showed that image-generated 3D model and/or orthomosaics are precise and can be relied upon as a reference in conducting measurements and further investigations. A concrete dam as well as a retaining wall were also visually monitored by Hallermann et al. (2014, 2015b), who validated a non-destructive and precise approach that exhibited great potential in 3D model reconstruction and surveying.

In summary, almost half of the AEC-related UAV studies were performed in the context of structural and infrastructure inspections applications. UAVs were used mainly to conduct building and bridge inspections as well as roads assessment and surveying. Other applications included visual monitoring of dams, retaining walls, photovoltaic cells, and a microwave tower. UAV-generated 3D models were either compared to conventional techniques to evaluate their effectiveness and accuracy, or used as a damage quantification and assessment tool for crack observations, quantification, and thermal leak detection. Road assessments were accomplished by acquiring UAV photogrammetric visuals and processing them through image algorithms. In GPS-deprived locations, UBS technology was an efficient substitute to ensure adequate navigation. Overall, UAVs were efficient in assessing cracks and thermal leaks, as well as evaluating the conditions of roads and other structures. Discussed advantages included this technology's flexibility when compared to traditional methods, and its ability to perform tasks in a safe and cost-efficient manner. Environmental factors (e.g., wind speed, wind direction, and sunlight reflectivity) were challenges that some of the authors reported in their analyses. Future studies are warranted to design and enhance onboard sensors that could potentially overcome GPS-related interferences. Also, there is a need to improve the platforms' hardware components and the processing algorithms to account for the environmental challenges.

4.2 Transportation

Transportation applications were discussed in 16 articles (18.6%) and encompassed landslide monitoring and mapping, earthwork volume calculations, and traffic surveillance (Table 4).

TABLE 4: UAV Applications for Transportation

Landslide monitoring and mapping	Niethammer et al., 2012; Ruggles et al., 2016; Zekkos et al., 2018; Candigliota and Immordino, 2013b; Carvajal et al., 2011; Carvajal et al., 2013; Lucieer et al., 2014; Nizam Tahar et al., 2011; Car et al., 2016
Earthwork volume calculations	Siebert and Teizer, 2014; Hugenholtz et al., 2015; Kim et al., 2015
Traffic surveillance	Hart and Gharaibeh, 2011; Xiao-Feng et al., 2013; Wierzbicki, 2018; Brooks et al., 2017

Landslide monitoring and mapping. Out of these 16 articles, 9 (56.3%) examined UAV usage in landslide monitoring and mapping. Different authors validated their results by comparing them to conventional field measurements. Results of terrestrial laser scanning (TLS) were either compared to those generated by UAVs (three articles) or integrated with the photogrammetry analysis (1 article). Niethammer et al. (2012) used camera-equipped UAVs and compared their results with traditional TLS in landslide fracture monitoring and surface movements. Overall, by yielding high-quality ortho-mosaics and digital terrain models, the authors endorsed the former technique as a landslide surveying tool. A similar approach testing distinct camera types and UAV configurations revealed that rotary platforms outperformed fixed wings in terms of model resolution, whereas the model accuracy was primarily impacted by the camera type and quality, regardless of the UAV type deployed (Ruggles et al., 2016). Twenty-six field applications, which included landslides monitoring, were presented by Zekkos et al. (2018), to highlight the impact of UAV-enabled structure from motion photogrammetry in geotechnical engineering applications. Similar results with a small margin of error were obtained with UAV and TLS. Despite lacking details pertaining to their experimental setup, both techniques were integrated within a larger study, improving the understanding and control of landslide movement-associated potential hazards (Candigliota and Immordino, 2013b).

Four articles evaluating landslide-related UAV applications compared their results with other traditional surveying methods, including geodetic GPS receivers (3 studies), and tachymetry (1 study). A landslide in Spain was surveyed with both UAV and geodetic GPS receivers (Carvajal et al., 2011; Carvajal et al., 2013). The study revealed that the former technique constitutes an efficient tool for landslide characterization with minor measurement discrepancies (<0.12 meters) between both methods. In another report, Lucieer et al. (2014) noted that geodetic GPS receivers outperformed algorithm-processed UAV visuals in mapping the main scarp retreat but did not surpass them in terms of flexibility and effectiveness for landslide monitoring. 3D generated models through UAV photogrammetry helped a Malaysian research team perform automatic area and volume calculations, study the contour line behavior, and have a better understanding of a landslide's direction and magnitude (Nizam Tahar et al., 2011). Compared to tachymetric surveying, the results obtained favored the implementation of UAV as a mapping tool, mainly in projects with budget and time limitations.

Lastly, while not including any comparative analysis, Car et al. (2016) did apply UAVs to locate landslides and gauge their slopes for instability and potential hazards, thereby highlighting the importance of using drones for landslide mapping and debris flow control. This study relied upon drone images to generate a measurable high-resolution 3D model from which contour lines, cross sections, as well as volumes and areas could all be retrieved.

Earthwork. Earthwork projects accounted for 3 out of 16 (18.8%) articles reporting transportation applications. Their main emphasis was in comparing earthwork volume calculations retrieved from UAVs with the ones generated by conventional techniques. One analysis evaluated drones for earthmoving applications in three different test areas and proposed a new UAV path planning software for automated surveying applications (Siebert and Teizer, 2014). Despite encountering some technical limitations, the authors described this surveying technique as successful by comparing it with alternative earth-volume estimation methods based on tachymetry. Concurrently, Hugenholtz et al. (2015) surveyed a gravel stockpile before and after partial extraction to conduct volume measurements using aerial photogrammetry and real time kinematic GPS. They showed that both approaches yielded similar results and recommended UAV usage for medium-sized earthwork projects, for being more efficient, safe, and cost-effective. Without comparing drones' results with traditional techniques, Kim et al. (2015) acquired images from different aerial platforms and advocated UAV utilization for 3D model generation and earthwork calculations.

Traffic surveillance and monitoring. UAV use for traffic surveillance and monitoring was discussed within 4 of 16 (25%) peer-reviewed manuscripts in the transportation category. Three of these acknowledged weather conditions as a potential limitation that could affect aerial traffic surveillance and monitoring. One study analyzed images and videos captured by a Micro-UAV (MUAV) and compared them to field observations (Hart and Gharaibeh, 2011). Limited by operational issues, the authors showed a high matching percentage (81%) between both observations (on-site and MUAVs), with promising UAV utilization improvements in the evaluation of the level of service (LOS) condition of different road samples. Another research team proposed a monitoring method using UAVs in sparse networks (Xiao-Feng et al., 2013). The authors confirmed the effectiveness of UAVs in such applications, but advanced multiple potential drone improvements to enhance traffic monitoring outcome with higher quantities of deployed UAVs. Recently, Wierzbicki (2018) analyzed the practicality of 5 UAV image datasets for traffic flow and car monitoring by proposing a low altitude vehicle detection method. Despite encountering vegetation interferences such as recognizing trees as vehicles, they obtained a detection efficiency averaging 64% and recommended the use of this proposed method in this context. In collaboration with the Michigan Department of Transportation, a research team successfully used a blimp to monitor traffic flow on highways while aiming of assessing the UAVs applicability in meeting the DOT's needs for data collection (Brooks et al., 2017). The joint study did not discuss, however, any limitation encountered with their UAV deployment process.

In summary, drones have been successfully integrated and applied for landslide monitoring and mapping, earthwork volume calculations, and traffic surveillance. For landslide monitoring and earthwork, UAV techniques were implemented to generate digital terrain models as well as orthomosaics, and were then compared to traditional surveying methods that encompassed terrestrial laser scanners, geodetic GPS receivers, and tachymetry. Other studies did not include any comparative analyses, but were able, through UAV photogrammetry, to obtain high quality and measurable 3D models. Drones image and videos were also an effective method of traffic surveillance. However, one study recommended the use of multiple UAVs for significant improvements in traffic surveillance. Issues affecting the outcomes of the studies included weather and lighting conditions, which affected the UAVs' performance, as well as vegetation interferences that caused the recognition of trees as vehicles. Future research is warranted to evaluate the use of multiple drones for traffic monitoring, to improve the efficiency of the applied algorithms, and to enhance the platforms' software and hardware as to control environmental challenges and vegetation interferences.

4.3 Cultural Heritage Conservation

Many investigations targeted the potential use of drones in historical conservation. More specifically, 16 of 17 (94.1%) articles applied photogrammetric images captured from camera-equipped UAVs to survey, map, and reconstruct historical buildings and monuments. The Landenberg castle was surveyed by terrestrial- and UAV-acquired images (Püschel et al., 2008). Despite requiring longer work time for building detailing and texture mapping, the generated high-resolution 3D model allowed measurements and facade plans obtention. The Milano Cathedral dome was also surveyed for reconstruction of its highest part (Scaioni et al., 2009). Aided by a structure from motion algorithm, the research team created a digital replica of the dome and recommended adding positioning sensors for better modeling output. After comparing their results with LiDAR benchmark datasets, Wefelscheid et al. (2011) proposed an automatic processing chain as an alternative to generate building 3D models. Complex historical buildings, including towers, churches, and other monuments were surveyed by UAVs

(Dominici et al., 2012; Kruijff et al., 2012; Candigliota and Immordino, 2013a; Candigliota and Immordino, 2013b; Carvajal et al., 2013; Hallermann and Morgenthal, 2013; Uysal et al., 2013; Achille et al., 2015). In all instances, this technique proved accurate and efficient for cultural preservation, assessment, and restoration. Additionally, Carvajal et al. (2013) noted that UAVs surpassed classic surveying methods in complex building modeling, despite being limited by the weather conditions. More recent studies revealed that UAV-acquired computer-processed visualizations can be relied upon for automatic damage detection and accurate 3D surface reconstruction (Morgenthal and Hallermann, 2014; Hallermann et al., 2015a). After comparing data obtained from UAV and traditional surveying techniques, a concurrent analysis reconstructed a high-quality 3D digital replica of an Ottoman monument in Greece using structure from motion and dense multi-view algorithms (Koutsoudis et al., 2014). An accurate 3D model of a historic sawmill, generated by experiments combining aerial and ground images while comparing different mapping software, was later successfully utilized by Banaszek et al. in their urban revitalization analysis (Zarnowski et al., 2015; Banaszek et al., 2017).

Aside from building conservation, only 1 of 15 (5.9%) studies explored the feasibility of employing UAV-generated images oriented through automatic algorithms for landscape preservation, reconstruction of views situated next to river banks, in particular (Brumana et al., 2012). This study recommended extracted 3D panoramic and front views for sustainable planning purposes.

In summary, UAVs were deployed to survey, reconstruct, and preserve historical monuments. This was accomplished by using UAV photogrammetric visuals to generate three-dimensional textured digital replicas of the studied structure which, can be used to conduct visual assessments and damage quantification. This technology was also combined with terrestrial surveying to generate 3D models of several monuments. Compared to traditional surveying methods, this accurate and efficient technique was a better alternative in modeling complex monuments. UAVs were also employed and recommended to reconstruct 3D panoramic and front views for landscape heritage analyses and territorial preservation. Weather conditions was a challenge pointed out by some authors. Future studies should focus on improving UAV platforms, their software, and the applied image processing algorithms to solve this limitation.

4.4 City and Urban Planning

Ten of 86 (11.6%) systematically retrieved articles were related to the topic of city and urban planning. Of those, 6 manuscripts (60%) reported 3D city and building modeling tasks. In a four-step algorithm, Bulatov et al. (2011) employed UAV-acquired videos and discussed the promise of generating georeferenced 3D urban models of a German village. Aerial photography testing, using a UAV-mounted 4-combined camera with a special overlapping image design, was performed on two different buildings (Feifei et al., 2012). The study justified this method's feasibility for 3D city and building modeling and visualization purposes. Drone images and a terrestrial mobile mapping system were shown to complement each other in establishing complete and precise 3D point clouds with high resolution (Gruen et al., 2013). Qin et al. (2014) relied on photogrammetry to generate a high-quality textured 3D model that reflected urban buildings, vegetation, and infrastructures. UAV-related limitations included its battery life, GPS accuracy, and poor image quality. Other studies, detailed in previous sections, discussed UAV applications in city street modeling, urban revitalization, and building reconstruction (Wefelscheid et al., 2011; Banaszek et al., 2017).

Cadastral and land policy monitoring with aerial platforms was discussed by 2 (20%) articles. Despite some limitations in terms of image quality and the definition of ground control points, Manyoky et al. (2011) conducted multiple comparative studies between UAVs and traditional tachymetry and global navigation satellite system techniques. As a mapping technique, UAVs were similar to traditional methods, but were capable of generating 3D and elevation models. A more recent study employed UAVs to analyze a set of land plots characterized by different boundary conditions, uses, and shapes (Mesas-Carrascosa et al., 2014). The researchers showed that drone-obtained results fell within the European Union standards, recommending this technique as a supplementary land policy monitoring tool.

Two additional studies (20%) reported UAV applications pertaining to cartography. They were both capable of highlighting the high resolution orthophotos generated by UAVs (Carvajal et al., 2013; Kedzierski et al., 2016). In one of the articles, the authors conducted a comparative analysis with basic maps to evaluate the location of several objects, and noted a significant reduction in processing time with UAV usage (Kedzierski et al., 2016).

In summary, drone uses in city and urban planning were mainly related to cities and buildings modeling, land policies monitoring, cadastral surveying, and cartography upgrade. For cities and buildings modeling, UAV-acquired images and videos were processed through specific algorithms to generate three-dimensional textured point clouds of the studied areas. Examples of applications include building reconstruction, city modeling, and urban revitalization. UAVs were also combined with terrestrial mobile mapping systems to generate high-resolution 3D models. Challenges faced included deficiencies in GPS accuracy, UAV battery life, and image quality. Land policy monitoring and cartography upgrade using UAVs exhibited similar results compared to traditional methods, but with their additional abilities to generate 3D models and orthophotos, and to significantly reduce tasks' processing time. Additional studies should be conducted to enhance the technicalities of the platforms' onboard components in order to improve GPS's performance, the image quality, and the battery life.

4.5 Progress Monitoring

UAV applications for progress monitoring were described in eight of 86 (9.3%) articles. Six studies validated the drones' efficacy in improving progress tracking without being initially designed to specifically address this hypothesis. Integrating augmented reality with UAVs to visualize construction sites has been used to envision actual and virtual site conditions while improving both the simulation and validation of the project progress (Wen and Kang, 2014). Another research team equipped a Radio Frequency Identification (RFID) sensor on a UAV to rapidly monitor materials on complex construction jobsites and increase work productivity (Hubbard et al., 2015). Their supply chain management system analysis provided information that could potentially be used to facilitate project progress monitoring. Irizarry and Costa (2016) utilized UAV-retrieved images for construction management purposes. After acquiring jobsite videos and images, the authors conducted interviews with construction professionals, and recommended UAV generated visuals for progress monitoring. Two different sites were also surveyed to assess UAV-related 3D mapping challenges (Kim et al., 2016). This system's improvement and accuracy correlated with the number of overlapping key-points between images, depended on some inherent software, hardware, and environmental factors, but constituted a powerful tool for project surveying and tracking. A recent report successfully converted UAV-retrieved videos into a high-resolution 2D map to aid managers better understand site conditions (Bang et al., 2017). Combined with ground robot 2D representations, such visualizations were also able to automatically generate comprehensive 3D point clouds, which improved construction progress monitoring effectiveness by reducing human intervention, time, and inspection-associated risks (Park et al., 2018).

Two additional studies specifically aimed at assessing the drone's ability to enhance construction progress monitoring. UAV-mediated construction monitoring of a road and bridge was successful, but needed to be supplemented with ground data to ensure higher result accuracy and validation (Ezequiel et al., 2014). Aerial photogrammetry was also successful in detecting accurate changes within a zero-emission building over a 5-month time interval (Unger et al., 2014).

In summary, enhancing construction progress monitoring through UAVs was an indirect consequence of some studies. These studies included the integration of drones with virtual reality to visualize construction sites, mounting an RFID sensor to monitor material in a jobsite, analyzing UAV visualizations to explore potential UAV applications, as well as mapping 2D and 3D models and assessing their challenges. Other, more specific studies advocated the use of UAVs for progress monitoring, but some authors associated this technology's improvement and accuracy with some software, hardware, and environmental factors. Advantages of this technology included significant reductions in time and safety hazards when compared to conventional inspections. Future work lies in improving UAVs software and hardware to account for environmental and technical difficulties.

4.6 Post-Disaster Assessment

The employment of UAV in the post-disaster setting was described in 10 (11.6%) of 86 retrieved publications. All but one study, detailed in the Construction Safety section, emphasized the impact of UAV and virtual reality in post-disaster safety training (Agung Pratama et al., 2018). The remaining nine (90%) manuscripts focused mainly on structural and damage assessment and quantification. The damage that the Piazza Palazzo and a Mirabello church endured during devastating earthquakes (in 2009 and 2012, respectively) was accurately evaluated using high-quality UAV-retrieved models (Dominici et al., 2012; Vetrivel et al., 2015). Despite the challenging presence of on-site metal components that interfered with the mounted magnetic compass in terms of indoor flight control, drones were combined with ground robots for the safe inspection of historical buildings after the occurrence of an earthquake (Kruijff et al., 2012), findings that were corroborated by a more recent report (Michael et al., 2014). Combining drones with laser scanning showed similar results in the evaluation of the earthquake-hit Santa Barba tower, especially for its restoration, maintenance, and damage quantification (Achille et al., 2015). In their low-altitude photogrammetric assessment of distinct post-earthquake structures in Candigliota and Immordino (2013a) and Candigliota and Immordino (2013b) identified UAV as a high-quality potential supplementary surveying tool with particular ability to access elevated areas after natural disasters. This technique was also shown to yield better ground sample distance measurements compared to conventional imagery, while suggesting possible structural failure mechanisms and improving post-disaster building inspection (Adams et al., 2014). In addition to damage assessment, UAV applications were later extended to include their ability to guide relocation and rehabilitation of areas hit by a typhoon (Ezequiel et al., 2014).

To summarize, in the post-disaster setting, UAVs have been mostly employed for restoration and damage quantification. They were effectively used to generate high-quality 3D models in order to accurately evaluate the structures' conditions, and were combined with other terrestrial robots and traditional surveying techniques in this context. Compared to traditional imagery, this technology yielded better measurements and enhanced post-disaster inspections. Also, drones were effectively utilized to guide relocate and rehabilitate typhoon-hit areas. Advantages include the UAVs' ability to reach elevated, dangerous, or inaccessible areas, reducing thus post-disaster-associated risks. Magnetic interference between the UAV hardware and the presence of on-site metal components caused some difficulties while conducting experiments, which is a limitation that could be mitigated by improving the platform's hardware.

4.7 Construction Safety

UAV use for construction safety has also been reported in the current literature in 6 (7.0%) of 86 articles, 4 of which used drone visuals for construction safety inspection purposes. A heuristic evaluation combined with a user participation survey proposed the use of large-screen devices for higher accuracy, and recommended an ideal drone type to assist managers for safety inspection applications (Irizarry et al., 2012). UAV visualizations, independently analyzed by construction professionals, was validated as a potential asset for safety conditions evaluation (Irizarry and Costa, 2016). These findings were corroborated by a more recent analysis, which relied upon in-depth drone visuals to delimit multi-site items that did not conform to safety standards (de Melo et al., 2017). Cranes were also accurately localized using a UAV-mounted object detector to monitor their safety hazards in real-time (Roberts et al., 2017).

Two additional studies focused mainly on equipment hazards and safety training. Tomita et al. (2017) successfully deployed UAVs for air volume measurement in an attempt to reduce safety hazards related to building equipment works. The authors advanced this innovative technique as a potential replacement of traditional methods that put the inspector's life at risk. UAV photogrammetry and 3D modeling of the interior of a building were utilized to generate a virtual reality real-life scenario for safety training (Agung Pratama et al., 2018). This technique exhibited potential reduction in inspector-associated safety hazards and provided the ability to access hard-to-reach areas.

In summary, drone visuals were often used to conduct safety inspections and training. Several studies relied on UAV visuals to delineate safety hazards in construction jobsites, findings that provide evidence of the technology's efficiency for construction safety inspections. Other studies successfully deployed drones to reduce safety hazards associated with conventional air diffuser volume measurements, and created a virtual reality real-life scenario using UAV photogrammetry for safety training purposes. Results showed that drone deployment tremendously reduced tasks-associated safety risks while offering the ability to access hard-to-reach and dangerous areas. Further studies should discuss the means and methods to improve the integration of UAVs in safety inspection tasks. This could be accomplished by enhancing the UAVs' efficiency in providing faster feedback such as integrating real-time safety risk algorithms or object detectors on the UAVs, expediting thus decision-making and simplifying inspection tasks.

5. UAV TECHNOLOGY IN THE AEC DOMAIN

5.1 UAV Flying Styles

Generally there are three types of UAV flying styles: (1) Autonomous navigation, which is accomplished by either pre-determining UAV flight paths through defining GPS waypoints, or by integrating GPS with computer path planning software; (2) Semi-Autonomous, which can be characterized by a combination of human and computer autonomy involvement; and (3) Manual, where the pilot has full control on the UAV with no computer autonomy. These styles vary based on the deployed UAV type and its application. Table 5 shows this mapping and the number of related publications. Several studies implemented more than one flying style to control their aerial platforms. Thirty-one publications did not report the flying style applied on their platforms (Table 5).

TABLE 5: UAV flying styles and related number of publications

Flying Style	Degree of Autonomy	Number of publications
Autonomous	No Human Intervention/Full Computer Autonomy	30
Semi-Autonomous	Human Intervention and Autonomy	5
Manual	Full Human Intervention/No Autonomy	22

Several researchers relied upon GPS waypoints to pre-define and plan their autonomous flight routes (Unger et al., 2014; Merz and Kendoul, 2011). As an example, waypoint navigation guidance was used to autonomously operate a UAV while mapping a landslide (Carvajal et al., 2011). Similarly, another group of researchers generated a flight path with more than 100 waypoints and showed the UAV's capabilities in following a pre-defined route autonomously (Siebert and Teizer, 2014). Other research teams on the other hand, utilized navigation software tools to assist in generating pre-defined paths that would allow autonomous UAV flight control (Ezequiel et al., 2014; Zhang and Elaksher, 2012). However, GPS use might be associated with some navigational inaccuracies, resulting from the shadowing effect from adjacent buildings and the sparse space between the waypoints (Eschmann et al., 2012; Rathinam et al., 2008). Consequently, researchers integrated other onboard sensing technologies such as UBS (Kang and Cha, 2018), LiDAR (Merz and Kendoul, 2011), and visual sensors (Rathinam et al., 2008) to ensure better navigation in GPS-deficient or deprived locations.

Advantages of autonomous navigation, when compared to manual navigations, were partially presented by Püschel et al. (2008), who noted that the level of practice and expertise required from pilots to manually operate the drone is more challenging than the autonomous ones. Also, the ability of an autonomous system to adapt to changes associated with the flying environment (e.g., inclement weather or wind) during the flight constituted another important benefit over other flying styles.

UAVs were semi-autonomously operated in several papers. However, only 1 article discussed the reasons behind conducting semi-autonomous flights (Qin et al., 2012). In their attempt to generate a digital model of a university campus, Qin et al. (2012) intermittently interrupted their autonomous operation to manually take-off and land. The authors noted that this autonomous-manual transition enabled them to better handle environmental complexity (namely confined spaces) and improved flexibility.

Other researchers used the manual flying styles and presented the pros and cons faced with such deployment. Scaioni et al. (2009) had to manually fly their helicopter to survey and reconstruct a dome, as it did not have any autonomous capabilities. Proximity to buildings or other structures was another factor that forced users to adopt manual flights; Eschmann et al. (2012) and Eschmann et al. (2013) manually flew the UAV near buildings for digital monitoring and crack observation, and highlighted the inevitable need of anti-collision and navigation sensors for an autonomous flight in such contexts. Other factors such as space limitations (Khan et al., 2015), federal regulations that limit autonomous control (Wefelscheid et al., 2011; Hugenholtz et al., 2015), and unstable and gusty environments (Adams et al. 2014) were a few justifications provided for using manual flying styles. Niethammer et al. (2012) favored the manual control over the autonomous one in case of high strength wind conditions, stressing on the abilities that the pilot should have to control UAVs in such situations.

In summary, flying styles of UAVs in the AEC domain included three types: autonomous, semi-autonomous, and manual. Autonomous control does not require human intervention, and is accomplished either by pre-planning the UAV path using GPS waypoints, or by integrating GPS with path planning software. Semi-autonomous navigation involves both humans and computer autonomy, whereas the manual flight depends entirely on humans. Results revealed that manual and autonomous styles were almost equally used in the literature, with only few researchers adopting the semi-autonomous control. Advantages of autonomous navigations include moderate expertise required from pilots when compared to manual operations, and the ability of the systems to adapt to climatic conditions changes. Semi-autonomous flights were only adopted in cases where autonomous operations could be interrupted. Confined space complexities, for instance, forced some authors to semi-autonomously operate their UAVs. Manual control was used either to prevent any risk associated with autonomously flying the drone in specific locations, or as a result of the absence of UAV autonomous capabilities. Proximity to buildings and structures, absence of anti-collision and navigation sensors, space limitations, windy environments, and federal regulation were some justifications for using manual style. Another limiting factor for autonomous navigation was the GPS accuracy which led researchers investigate other onboard sensors (UBS, LiDAR, and visual sensors) to mitigate this issue. Future research is justified to efficiently develop and improve the technicalities (software and hardware) of UAVs, which could ultimately overcome these limitations.

5.2 UAV Types

Three UAV types of rotary-wing, fixed wing, and blimps were reported in the AEC literature. Fixed wing vehicles are aerial platforms that resemble to traditional aircrafts and are known in their ability to perform continuous flight-demanding tasks (Achille et al., 2015), but they require runways to take off or land and cannot hover. Rotary-wing UAVs can hover, take off and land vertically, and can be helicopters or multicopters depending on the number of propellers mounted on the drone (Kim et al., 2015). Blimps, or aerostats, are lighter-than-air vehicles that gain their lift through indoor gas pressure available in the unit, allowing longer flying time when compared to other UAV platforms (Brooks et al., 2017).

Among all the reviewed articles, seven (8.14 %) used fixed-wing, 76 (88.37 %) used rotary-wing, two (2.32 %) used blimps (Feifei et al., 2012; Brooks et al., 2017), and four did not specify their deployed UAV type. In the majority used rotary-wing type, 32 used quadcopters, 20 used octocopters, 13 used helicopters, 7 used hexacopters, and only 1 employed a customized three rotor aerial platform (Adams et al., 2014). It is worth noting that in 9 papers, researchers custom-built their own UAV platforms for their studies.

Carvajal et al. (2013) and Kim et al. (2015) noted that the advantage specific to rotary wing aircrafts lies in their ability to vertically takeoff and land (VTOL), a feature that is not possible with fixed wing vehicles as they need large takeoff and landing runways. Ruggles et al. (2016) associated the improvement of the point cloud resolution with the deployment of multi-rotary platforms instead of fixed-wings. Propellers redundancy is another benefit that rotary platforms offer, allowing controlled return even after multiple engine failure (Eschmann et al., 2013; Hallermann and Morgenthal, 2014). The surface type (rocky or rough) might negatively affect the fixed-wing aircraft in landing operations, favoring thus the usage of multi-rotor platforms (Hugenholtz et al., 2015). Moreover, multiple studies recommended the use of the rotary vehicles in windy environments for stability purposes (Hugenholtz et al., 2015; Wen and Kang, 2014; Siebert and Teizer, 2014). On the other hand, fixed wing vehicles present many advantages, as they are able to: (1) fly at higher altitudes and carry heavier payloads (Carvajal et al., 2013); (2) cover wider photogrammetric areas (Achille et al., 2015); and (3) have longer flight endurance (Kim et al., 2015).

Sixty-seven research teams stated the manufacturers' information of their employed aerial platforms. Our analysis revealed that most popular UAV manufacturers were DJI®, Ascending Technologies (Asctec)®, Parrot®, and Microdrones® each with 20, 13, 5, and 4 drone deployments, respectively. The mostly used models were Asctec Falcon 8 (12 articles), Microdrones MD4-200 (4 articles), DJI Phantom 2 Vision+ (3 articles), DJI Phantom 3 Pro (3 articles), and the Parrot A.R Drone 2.0 (3 articles).

In summary, rotary, fixed wing, and blimps were the three different UAV types reported in the AEC literature. Rotary UAVs, which was the most frequently deployed type, comprised helicopters, quadcopters, hexacopters, and octocopters. Quadcopters were the mostly used platforms, followed by octocopters, and helicopters. Also, several research teams custom-built their drones in their experiments, with only one study employing a customized three rotor aerial platform. Advantages of rotary wing over fixed wing vehicles include the former's abilities to take-off and land, on rough surfaces, and without the need of large runways. Also, rotary wing vehicles are characterized by the redundancy of their engines, ensuring thus a safe and controlled return even after multiple engine failures. It is noteworthy to mention that some authors associated the improvement of the generated point cloud with the deployment of rotary wing vehicles instead of fixed wing. Other studies recommended the use of rotary wing vehicles in gusty environments to ensure better stability. Fixed wing vehicles, on the other hand, are able to fly longer distances, carry heavier payloads, and cover wider photogrammetric areas. Most popular drone manufacturers include DJI®, Ascending Technologies (Asctec)®, Parrot®, and Microdrones®. The mostly used models were Asctec Falcon 8 and Microdrones MD4-200. Future research should focus on refining the technical specifications of the drones' software and hardware to ideally meet the AEC industry requirements. Other potential studies include investigating the performance of a combined VTOL/fixed wing drone that could more effectively operate in AEC applications.

5.3 Onboard Sensor Types

As discussed earlier, aerial platforms are highly affected by their mounted sensor loads. Thus, sensors used should meet different requirements, such as weight restrictions and simplicity of installation, while accomplishing the required tasks (Roca et al., 2013). Besides typical payloads, including global positioning sensor, altimeter, inertial measurement unit (e.g., magnetometer, accelerometers and gyroscopes), barometers, humidity, temperature, and obstacle avoidance that are common on the UAV platforms, there were specific sensors that had vital roles in different UAV applications (see Table 6).

TABLE 6: Onboard sensor types used for UAV applications in the AEC domain

Sensors	Number of Studies
Readily Available Cameras	79
Thermal Cameras	6
LiDAR and Laser Scanning	5
Ultrasonic Beacon System (UBS)	1
Radio Frequency Identification (RFID)	1

Retrieved information showed that cameras were the most predominant devices mounted on aerial units and were applied in 79 studies. These devices were relied upon at first to collect images and videos. Then, UAV visualizations were either processed through image processing algorithms (Ellenberg et al., 2016; Sankarasrinivasan et al., 2015), or used to conduct direct visual observations (Hart and Gharaibeh, 2011; Hallermann and Morgenthal, 2013). Ellenberg et al. (2016) processed UAV images and videos through image calibration, homography, and crack identification algorithms to detect and quantify bridge-related damages on their mock-up bridge. Eschmann et al. (2013) processed UAV acquired images to obtain high resolution 2D and 3D reconstructions of a building, and were able to inspect facades and characterize cracks. Direct observations of UAV images and videos assisted other researchers in their analyses. Irizarry et al. (2012) used only UAV-acquired images to evaluate the use of the captured media as safety inspection tools. UAVs visual assets were used also in determining potential construction applications by conducting interviews with construction professionals (Irizarry and Costa, 2016).

Several authors touched on modifications that can be applied on UAV-mounted readily available cameras to improve their performance. Despite being able of recording 4K videos, Gillins et al. (2016) recommended the use of a high-resolution camera with zooming abilities for better safety operation and degree of image details to conduct visual observation on a bridge and inspect its components. Several other researchers also indicated similar need for higher resolution cameras for their specific UAV applications such as exploring potential construction applications (Irizarry et al., 2012), assessing individual buildings and their surroundings in the post-disaster setting (Adams et al., 2014), generating three-dimensional urban buildings and infrastructures (Qin et al., 2012) and monitoring a landslide using both, conventional and UAV-developed techniques (Ruggles et al., 2016).

Thermal imaging cameras were used in six different studies. Two studies combined the red-green-blue (RGB) and infrared (IR) camera on UAVs for application such as obtaining information about bridge subsurface delamination and cracks location (Khan et al., 2015) as well as bridge decks inspection (Brooks et al., 2017). Four other studies employed thermal imagery sensors for PV cells inspection (Tyutyundzhiev et al., 2015), curtain wall thermal performance assessment (Mutis and Romero, 2018), 3D thermal reconstruction of buildings (Mauriello and Froehlich, 2014), and photogrammetric assessment of earthquake-hit buildings (Candigliota and Immordino, 2013b).

Five other studies employed LiDAR and laser scanners in their analyses. The Microsoft Kinect and the ASUS Xtion Pro were employed in three different studies for applications such as outdoor facades inspection (Roca et al., 2013), and damage assessment of earthquake-hit buildings (Kruijff et al., 2012; Michael et al., 2014). While not stating any problem faced in the ASUS Xtion Pro, the Microsoft Kinect's ability to adapt to changes in lighting conditions was an issue encountered and discussed in two different studies (Roca et al., 2013; Kruijff et al., 2012). Roca et al. (2013) reported that the Microsoft Kinect sensor is highly affected by material and lighting conditions, a factor that forced them to explore different sensors for optimum design configuration. Moreover, Kruijff et al. (2012) mounted the ASUS Xtion Pro on an aerial robot and were able to safely conduct their post-disaster experiment. When deploying their Kinect-mounted ground robot however, the authors were concerned about the ability of that sensor to adapt to lighting condition changes. In another study, Michael et al. (2014) pointed to the degree of robustness that the Hokuyo UTM-30LX laser scanner and the Microsoft Kinect could withstand in environments where dust and airborne obscurants are of primary concern. The same type of laser scanners was also applied by other researchers, who presented an obstacle avoidance and close-range infrastructure assessment guidance system using their aerial platform (Merz and Kendoul, 2011). The 2D LiDAR sensor, in addition to the performed flight modes, proved to be successful for real world applications, exhibiting advantages over heavier and costly 3D LiDAR systems. Another study used the OptiLogic RS-232 laser range finder in combination with a video camera to assess and monitor unpaved roads condition (Zhang, 2008). Single studies included other devices such as Ultrasonic Beacon System for positioning purposes in GPS-deprived locations (Kang and Cha, 2018) and radio frequency identification (RFID) sensor to locate materials on site (Hubbard et al., 2015). RFID limitations included excessive payloads induced by the device's weight, and its reading range which failed to detect tagged materials at farther distances.

Along with typical payloads, UAVs were equipped with special onboard sensors that included cameras, thermal cameras, LiDAR, laser scanners, ultrasonic beacon system, and radio frequency identification. Cameras were the mostly employed type of sensors in the literature, and were used for images and videos acquisition. The obtained visuals were then either processed through image algorithms, or used to conduct direct observations. Recommendations were to utilize high-resolution cameras with zooming abilities to conduct bridge inspections, post-disaster building assessment, city and infrastructure modeling, as well as landslide monitoring. Thermal imaging devices were either used solely, or combined with RGB cameras to conduct inspections on bridge components, buildings, PV cells, and curtain walls. Laser scanners and LiDAR devices were deployed for structure and infrastructures assessment, as well as inspection of earthquake-hit buildings. Limitations included the scanners' ability to withstand environments with limited visibility, and to adapt to material and lighting changes. Other sensors included the UBS for positioning purposes in GPS-deprived locations, and the RFID to locate materials on site. Issues faced with the RFID are the device's heavy weight which affected the UAV's performance, and its reading capabilities at farther distances. Future research will heavily focus on the technical improvement and optimization of these sensors to account for such limitations.

6. ANALYSIS OF TASK AND TECHNOLOGY CHARACTERISTICS

Each of the studies was reviewed to extract information regarding the task and technology characteristics of the application area being evaluated. For each article, the task being performed with the UAV was deconstructed to determine whether or not the task itself was: (1) static, (2) hazardous to human workers, (3) routine, (4) urgent, (5) had low error tolerance and (6) required close human supervision. In addition, the UAV technology used to complete the task was also noted, specifically with respect to the UAV's type, flight style and sensor package. The results of this analysis are summarized in Table 7. For each row, the value represents the percentage of studies within the application area that had a particular task or technology characteristic. Note that for technology characteristics, the sum of the percentages within each application area does not always sum to 100%. This is because some studies either did not report enough detail on the UAV technology or used a combination of multiple UAV technologies. Shaded cells represent those task or technology characteristics that were found in the clear majority, 60% or greater, of articles within each application area.

Across all application areas, we find that UAVs have been most widely implemented in tasks that are static, routine, have a low error tolerance and require close human supervision. With the exception of construction safety, the subject matter of all other AEC applications of UAVs was predominantly static. That is, the object (e.g., bridges, facades and terrain) around which the task was centered was stationary and unchanged for the duration of the task. This suggests that UAV technology is not yet advanced enough for more dynamic applications that involve frequent movement. Three out of the seven application areas contained tasks that were nearly always considered hazardous to human workers. Specifically, structural and infrastructure inspection (85% of articles in the application area) and cultural heritage conservation (94%) involved work performed at considerable height or in difficult to access areas. Post-disaster assessment tasks were also considered hazardous (100%), as recently damaged structures and utilities present a danger to rescue to workers, as well as the general public. Routine tasks, or those performed frequently at regular intervals, were common in most application areas, with the exceptions being city and urban planning (20%) and post-disaster assessment (40%). The articles referencing these applications typically used UAVs to perform a one-time survey, rather than part of a recurring monitoring plan. Task error tolerance varied widely by application area. Some applications had a very low tolerance for errors as they were measuring small cracks and defects (e.g., 100% of structural and infrastructure inspection and 94% of cultural heritage tasks) or surveying post-disaster damages (90%). In other applications, accuracy and precision were less important. For example, for progress monitoring (13%), UAVs were used to monitor the overall flow of work, rather than the specific quantities of work put in place. Few application areas contained tasks that were considered urgent. Only post-disaster assessment (90%) and construction safety (50%) areas reported tasks needing a quick response UAV deployment. Lastly, nearly all application areas needed close human supervision of their tasks. Transportation tasks reported in articles required supervision rarely (25%) and city and urban planning was more mixed (60%).

TABLE 7: Task and technology characteristics by UAV application area in the AEC domain

	Task Characteristics (%)						**Technology Characteristics (%)**										
							Flight Styles			*UAV Types*			*Sensors*				
Application Area	Object is static	Task is hazardous to human	Task is routine	Task has low error tolerance	Task is urgent	Task requires close supervision	Autonomous	Semi-autonomous	Manual	Rotary-wing	Fixed-wing	Blimp	Readily Available Cameras	Thermal Cameras	LiDAR And Laser Scanners	Ultrasonic Beacon System	Radio Frequency Identification
Structural and Infrastructure Inspection	100	85	100	100	3	100	28	10	28	90	3	3	90	13	8	3	0
Transportation	81	25	81	63	6	25	50	0	19	94	13	6	100	13	0	0	0
Cultural Heritage Conservation	100	94	71	94	29	94	24	12	35	100	0	0	100	6	6	0	0
City and Urban Planning	100	30	20	60	0	60	40	10	20	70	30	10	100	0	0	0	0
Progress Monitoring	100	13	88	13	13	88	50	0	25	88	13	0	88	0	0	0	13
Post-Disaster Assessment	100	100	40	90	90	100	30	0	30	80	10	0	80	10	20	0	0
Construction Safety	33	33	67	50	50	83	NS	NS	NS	83	0	0	83	0	0	0	0

Notes: Cells with values greater than or equal to 60% are highlighted to ease interpretation; NS = Not Specified

Across all application areas, we find that both autonomous and manual flight styles are nearly equal in their usage, while rotary wing UAVs with readily available, "off the shelf" cameras are the most common configuration by a wide margin. When considering flight style, semi-autonomous control of UAVs was rarely found in the literature. Conversely, the frequency of manual and autonomous control was nearly equal in structural and infrastructure inspection (28% for both), cultural heritage conservation (35% for manual, 24% for autonomous), and post-disaster assessment (30% for both) application areas. Autonomous control was about twice as common as manual in transportation (50%), city and urban planning (40%), and progress monitoring (50%) applications. No articles discussing construction safety applications of UAVs made any specific reference to flight styles. With respect to the type of UAV used, rotary wing designs were the most common in all application areas. However, fixed wing and blimp UAVs were selectively used for city and urban planning (10% and 30%, respectively) tasks. Similarly, there was not much variation in the sensor packages installed on UAVs across application areas. Readily available cameras, either as an integral part of the UAV or a mounted "off the shelf" model, were the most commonly used sensors for all applications. Thermal cameras were occasionally used for transportation (13% of articles studies), infrastructure and structure inspection (13%) and post-disaster assessment (10%). LiDAR and laser scanners were only used in post-disaster assessments (20%) and RFID systems were only found in progress monitoring (13%) applications. Ultrasonic beacon systems were very rare, appearing in only 3% of articles with infrastructure and structure inspection tasks and no other application areas.

One of the future potential tasks that could justify UAV deployment is to accurately assess and delineate stationary objects behind walls and exterior facades, especially in the post-disaster as well as structural and infrastructure inspection context. In such environments, the inspector would be subject to unknown and potentially hazardous indoor conditions that might put the personnel's life and equipment at risk, a factor that could be mitigated by deploying UAVs with see-through walls capabilities. UAV use can also be well-suited to enhance construction safety inspection tasks. Monitoring of construction workers for instance, could be improved by integrating artificial intelligence and machine learning to collect, analyze, and process data, in order to provide real-time jobsite feedback. Predictive analytics, which combines artificial intelligence, machine learning, modeling and statistics, could be also integrated, or combined with other technologies, to analyze data and provide construction safety insight. Not only would this integration assist managers in anticipating problems, but also helps in reducing the inspection time required by conventional inspecting methods.

7. CONCLUSION

This paper presented a comprehensive systematic literature review of the unmanned aerial vehicles applications in the architecture, engineering, and construction domain while focusing on the technology use. Compared to other reviews, this analysis exhaustively evaluated current literature and grouped UAV uses under categories that adequately reflected their specific applications while further exploring the technology use under each category. The outcome of this study is expected to better assist AEC researchers and professionals in identifying the state-of-the-art research on UAV applications in the AEC domain.

The categories around which the review was organized included infrastructures and structures inspection, transportation, cultural heritage monitoring, city and urban planning, progress monitoring, post-disaster, and construction safety. Authors consistently recommended UAV integration in the AEC domain by providing equal, if not, higher outcomes compared to conventional methods in terms of time, accuracy, safety, and costs. Other advantages included the UAV's flexibility in reaching elevated or inaccessible areas. Issues reported were mainly environmental (weather and lighting conditions, wind speed and direction, sunlight reflectivity), and technical deficiencies in the employed sensors and platforms' components (GPS-deficiency, magnetic interferences, UAV batteries, and image quality). Drone flying styles were almost equally divided between manual and autonomous navigation, with the latter considered as the most commonly used type of flight control. Few authors adopted the semi-autonomous navigation. Rotary, fixed wing, and blimps were the three different types of UAVs reported in the literature. Rotary platforms were the mostly deployed drone type retrieved in our analysis. They comprised helicopters, quadcopters, hexacopters, and octocopters. Those aerial platforms were equipped with typical and special sensors to achieve particular tasks. Of those sensors, commercial cameras were the most predominantly used type in the current literature, serving as the basis for images and videos acquisitions, processing, and 3D modeling. Other sensors included thermal cameras, laser scanners, radio frequency identification, and ultrasonic beacon system. Future research is warranted, and further studies should be conducted to enhance the applied visual algorithms, as well as the platforms' onboard hardware and software components. Also, additional technological alternatives should be investigated to enhance these devices' performances and overcome the presented environmental and technical challenges.

In an industry that is consistently evolving and integrating new emerging technologies, UAVs have proved to be a safe, yet efficient alternative. It is envisioned that UAV technology, associated with the future hardware and software advancements, will be more widely applied in the AEC industry. Further studies are needed to define methodologies and best practices for current and future integration of UAVs in existing AEC processes. Identifying the advantages, as well as implementation challenges, and comparison with common UAV-less processes should be further investigated. The integration of UAVs with other recent technological innovations (e.g., building information modeling, photo/videogrammetry, virtual/augmented/mixed reality, wearable technologies, big data, 5G technology, smart connected solutions, artificial intelligence, and machine learning predictive analytics), in addition to the legal and financial aspects of using them, will also lead future research of UAVs and their integration in the AEC domain.

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