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Applications of multirotor drone technologies in construction management

Yan Li and Chunlu Liu

School of Architecture and Built Environment, Deakin University, Geelong, Australia

ABSTRACT
Multirotor drones are considered a new and innovative technology. Therefore, many fields are showing increasing interest in utilizing multirotor drones, such as mapping in mining and surveillance in transportation. The construction industry has been a slow adopter of novel technologies. However, multirotor drones have potential to facilitate construction in many aspects. There is, therefore, a need to extensively research their applications and analyze their roles in construction engineering and management. This paper aims to comprehensively investigate the current applications of multirotor drones, analyze their benefits and explore their potential in the future of the construction industry. Several main aspects are reviewed and discussed, namely land surveying, logistics, on-site construction, maintenance and demolition. The results reveal that the main contributions are work safety, cost-effectiveness and carbon emission reduction, while there are possible adverse impacts on the basis of current limitations of multirotor drones. However, it can be predicted that the usefulness of drones will continue to increase in the future of the construction industry. Thus, this study will benefit construction managers in raising awareness of the use of these emerging technologies and researchers in further exploring applications of multirotor drones in construction projects.

KEYWORDS
Multirotor drones; construction technologies; unmanned aerial vehicles; life cycle; construction management

Introduction

Drones are widely known under various names, such as unmanned aerial vehicles (UAVs), unmanned aerial system (UAS) and remotely piloted vehicles (RPVs) (Siebert and Teizer 2014), and are currently being implemented in the construction industry (Dupont et al. 2017). Drones were initially applied to military uses. They occupy an important position in the military arsenal (Holton et al. 2015). Yet, expensive military drones are often not cost-effective alternative for many users in civil application such as entertainment and transportation. Nowadays non-military drones have allowed 3D high-quality mapping data to become much more accessible. Thus drone technologies enable better management and faster and more informed decision-making, and provide accurate high-resolution archival records for various sites.

Drones can be categorized as multirotor, fixed-wing, single-rotor and fixed-wing hybrid (Australian UAV 2017), as shown in Figure 1. Among these, multirotor drones like quadcopters have distinct advantages compared to other UAV systems, such as robustness, high manoeuvrability, and low purchase and maintenance costs. Multirotor drones have more than two rotors and use fixed-pitch blades. Control of vehicle motion is achieved by varying the relative speed of each rotor to change the thrust and torque produced by each. Multirotor drones can be manoeuvred in small spaces when hovering and can be controlled by various devices such as tablets, laptops and desktop computers. They can also be easily equipped with light detection and ranging (LIDAR) instruments, cameras and communication devices (Harvey et al. 2016). Therefore, many fields are showing increasing interest in utilizing multirotor drones for various non-military purposes (Irizarry and Costa 2016).

For example, in forestry and agriculture, to achieve site-specific weed management, the ultra-high spatial and high spectral resolution imagery provided by multirotor drones was used for weed mapping at very early phenological stages of crop and weed plants (Mesas-Carrascosa et al. 2017). In emergency and disaster management, multirotor drones were applied to search for and rescue people trapped by debris or injured during disasters (Erdelj et al. 2017). In traffic surveillance and management, a drone-based vehicle detection system was developed by Wang et al. (2016) to collect traffic information, track vehicles and monitor driver behaviour. Relevant tests demonstrated high accuracy in vehicle detection and recognition. In addition, previous studies also extensively explored and developed UAV

CONTACT Chunlu Liu chunlu@deakin.edu.au

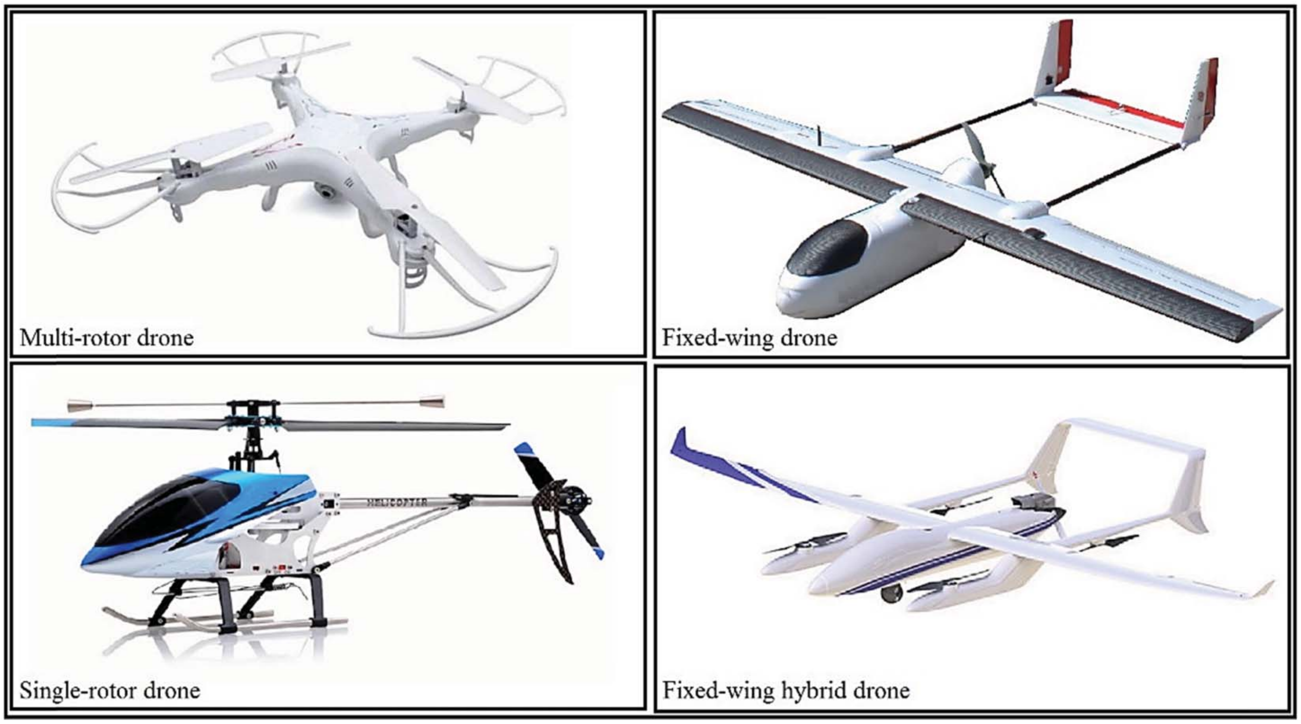


Figure 1. Types of drones.

photogrammetry for 3D mapping and modelling (Nex and Remondino 2014; Martin et al. 2016; Trujillo et al. 2016). The corresponding application for aerial surveying has also become a rapidly developing field in natural resource management and mining (Szentpeteri et al. 2016).

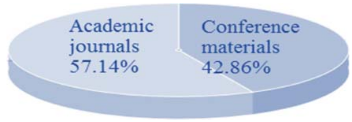
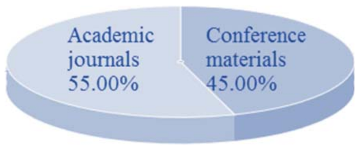
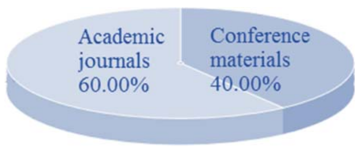
In the contemporary construction industry, multirotor drones as an innovative technology have potential to facilitate construction activities from observation and inspection to monitoring of safe practices, leading to savings in time, cost and injuries, along with quality work (Herrmann 2016). However, multirotor drones have not yet been widely used in the construction industry, as this field has been a slow adopter of emerging technologies (Holt et al. 2015). Consequently, relatively little research has paid attention to the potential applications of multirotor drones in construction engineering and management, compared to some other fields. It is worthwhile to raise awareness of the use of multirotor drones by analyzing the benefits that they can bring to the current and future construction industry. Therefore, this paper aims to comprehensively investigate the applications of multirotor drones, discuss their roles and explore their potential in construction engineering and management.

Research design

There are three main procedures that have been carried out in this research project. First, existing uses of multirotor drones are classified and reviewed to comprehensively investigate their current applications in construction. Second, their merits and limitations are analyzed and discussed, which brings benefits in raising awareness of appropriate uses in construction. Third, future drone technologies are overviewed to contribute to more rapid adoption of new technologies in the construction industry.

The research procedures are specifically implemented as follows. The study has conducted a systematic review of drone-related research in the construction industry by identifying cases that have employed multirotor drones in construction. Previous research reviewed is limited to the last five years (2014–2018) and to non-military purposes of multirotor drones. Since drone technology is still considered a new and innovative technology, there are relatively few research papers in relation to its application in the construction field. Therefore, in addition to scholarly publications retrieved from major databases, namely ASCE Library, ScienceDirect, SpringerLink, SAGE Journals, SPIE Digital Library, IEEE Xplore and Wiley Online Library Journals, a few non-scholarly publications are also addressed in the research project to provide more comprehensive insight into the technology of commercial drones. As listed in Table 1, reviewed scholarly publications can be roughly categorized into three thematic groupings, namely site preparation, such as surveying, on-site construction, such as monitoring, and post-construction, such as inspection. In this

Table 1. Thematic literature analysis of drone technology applications.

Phases	Proportions of source types	Scholarly publications
Site preparation		Liu et al. (2014); Siebert and Teizer (2014); Hubbard et al. (2015); El Meouche et al. (2016); Fang et al. (2016); Fleming et al. (2016); Dupont et al. (2017)
On-site construction		Gheisari et al. (2014); Liu et al. (2014); Wen and Kang (2014); Kim and Irizarry (2015); Lin et al. (2015); Tuttas et al. (2015); Vacanas et al. (2015); Wang et al. (2015); Ham et al. (2016); Irizarry and Costa (2016); Mat Yasin et al. (2016); Vacanas et al. (2016); Bang et al. (2017); Dupont et al. (2017); Hamledari et al. (2017); McCabe et al. (2017); Moeini et al. (2017); Tatum and Liu (2017); Tezel and Aziz (2017); Howard et al. (2018)
Post-construction		Liu et al. (2014); Morgenthal and Hallermann (2014); Santano and Esmaeili (2014); Fernandez-Galarreta et al. (2015); Oskouie et al. (2015); Liu et al. (2016); Mat Yasin et al. (2016); Dupont et al. (2017); Ge et al. (2017); Howard et al. (2018)

research, more detailed construction phases will be considered for analyzing applications of multirotor drones.

Furthermore, the benefits of using multirotor drones in construction are discussed in terms of three aspects, namely social, economic and environmental perspectives, to show that drones work well in the right conditions. Yet some challenges in their use should also be noted during construction processes. Thus, the discussion section indicates that current drone technologies are limited by some internal and external factors which construction firms need to be aware of.

With the constant evolution and improvement of drone technologies and other technologies, this research also explores future uses of multirotor drones in the construction industry through developing drone technologies, updating various systems, carrying new devices and collaborating with future construction equipment.

Drone-based construction management

Reviewing current applications of multirotor drones is a crucial step in comprehensively investigating their merits. In this section, the various applications of multirotor drones in construction are analyzed in terms of the different phases of construction work over the whole construction process, namely land surveying, logistics, on-site construction, maintenance and demolition.

Construction land surveying

First, land surveying is a fundamental part of all land development projects and a key procedure at the beginning of the construction process. Traditional land surveying techniques require bulky tools, such as tripods, total stations and GSP equipment. Multirotor drones equipped with cameras, autopilots and image-processing software can be applied to land surveying and mapping in construction projects for providing faster and less costly land surveys. The research of Siebert and Teizer (2014) compared two types of measurements, a manual, ground-based, real-time kinematic GPS survey and a drone-based photogrammetric survey near the city of Magdeburg, Germany. Figure 2 sketches a photogrammetric survey procedure for a construction site. The left-bottom picture shows a plan view of a construction site and indicates a flight path over the site. The right picture demonstrates that a camera mounted on the drone is pointed down towards the ground to measure 3D dimensional coordinates. 3D models can be then created by aerial photogrammetry. Compared with a traditional GPS survey that consists of 1800 individual points in the area of 60,000 m^2, the drone-based photogrammetric survey approach is capable of autonomously collecting 5,500,000 colour-coded points and producing a result in the format of an orthophoto (Siebert and Teizer 2014). The test demonstrated that the drone-based survey reduced the time to one-third and increased the point density by more than 3000 times.

In addition, Fleming et al. (2016) selected the Transbay Transit Centre construction site with dimensions of 457 m × 56 m × 20 m in downtown San Francisco as a case study. The deep excavation adopted a stiff excavation support system with a wall of mixed cement and

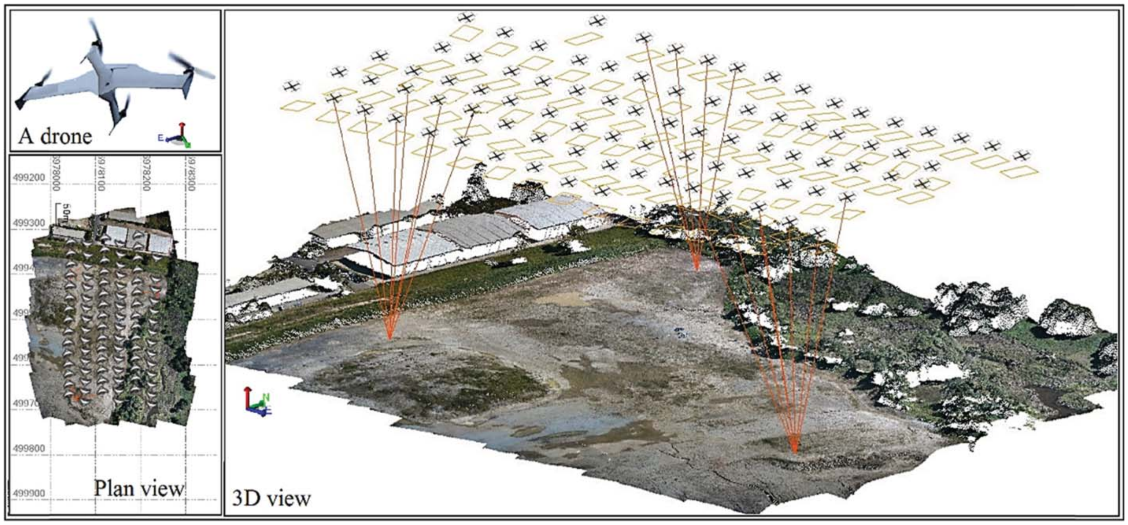


Figure 2. A drone-based photogrammetric survey procedure.

deep soil internally braced with four levels of steel-pipe struts. A multirotor drone controlled by a smartphone was used to capture the support-system geometry during the excavation stage. 2D imaging data was then converted into 3D construction staging models to achieve a detailed record of construction activities, such as the site geometry change, geotechnical engineering evaluation and responses of adjacent structures, so that construction activities can be adjusted in time.

Construction logistics management

Logistics addresses the movement of materials and equipment from where they originate to where the workforce needs them. Most gross work done in construction involves the buying-in of materials and services from suppliers and subcontractors (Ekeskär and Rudberg 2016). To benefit construction logistics managers in improving supply chain management, multirotor drones were applied to transport goods from suppliers and move materials on construction sites (Construction Global 2014). For example, drone-based technologies were used to detect, identify and track locations of tagged materials through a real-time location system, such as GPS, ultra-wide band (UB) radio or radio frequency identification (RFI) (Hubbard et al. 2015).

In 2016, Fang et al. (2016) developed a point cloud–vision hybrid approach to track 3D location information for mobile construction assets. A series of 2D aerial images were captured by drone-based technologies and processed by a structure-from-motion algorithm. As an emerging technique, structure-from-motion photogrammetry is capable of automatically computing camera orientations and scene geometries, and providing results using a dense point cloud with many 3D coordination points and coloured data. In the research of Fang et al. (2016), a case study was then proposed to track two vehicles, namely a concrete mixer truck and a minivan. Depth buffers were created to track 3D geometry objectives based on the data. A mirrorless digital camera mounted on a multirotor drone produced 169 images with a resolution of 4912 × 3264. A 3D point cloud was then generated and further processed. The study revealed that drone-based technologies are capable of dynamically tracking the 3D movement of construction assets in supply management.

On-site construction management

Safety management

Construction safety management has been a popular issue in research and practice, as workers are frequently exposed to fatal accidents in the construction industry (Chen et al. 2016; Enshassi et al. 2016; Park et al. 2017). Irizarry et al. (2012) initially investigated the potential benefits of drone-related technologies for safety managers in the construction industry. As multirotor drones are able to collect and deliver real-time videos of the current situations at construction job sites, Gheisari et al. (2014) explored their applications in safety inspection on construction job sites. An experiment was designed by the researchers to simulate a construction job site. The inspection task of detecting whether or not workers were wearing their hard hats was performed and visualized via different observation conditions, namely a plain view, an iPad and an iPhone. The results revealed the practicability of multirotor drones in safety management, showing that both plain view and iPad visualization conditions could provide satisfactory accuracy in hard hat detection.

Quality management

Quality management during the construction process has also been receiving considerable attention (Rumane 2016). In particular, construction defects are the primary cause of low project productivity, delays, additional costs, and the need for extra materials and workers for defect rectification (Aichouni et al. 2014; Lee et al. 2016). Consequently, effectively identifying defects early in the construction process is critical for quality control.

Building Information Modelling (BIM) can also provide smart solutions for effective project execution (Hardin and McCool 2015). Drone technologies are capable of reducing the human interference and improving the efficiencies in project monitoring and quality control for BIM-related construction projects (Tezel and Aziz 2017). Wang et al. (2015) considered that previous approaches to quality control on construction sites did not assist quality managers to easily identify and manage defects. Their work presented an integrated system of BIM and LIDAR to achieve construction quality control. The BIM–LIDAR approach relies on a LIDAR-based real-time tracking system, a BIM-based real-time checking system, a quality control system, a point cloud coordinate transformation system and a data processing system. To benefit quality managers in quality assessment and quality control, a transformation module for drone flight was used to transform predefined flight path parameters into a drone flight path control system, as illustrated in Figure 3. Consequently, the multirotor drone in the real scene achieved a flight path the same as a predefined flight path in the virtual environment. BIM was also shown to be a successful visualization platform and benchmarking model in the quality management test. The case study demonstrated an improvement to time-consuming quality inspections.

Time management

In addition to safety management and quality inspections, time management can also been improved by drone-BIM technologies in construction projects (Vacanas et al. 2016). 3D BIM models can be enhanced if linked with schedule (4D), costs (5D) and project life-cycle information (6D) (Park and Cai 2017). *n*D BIM models have been applied in the field of construction progress monitoring by presenting multi-dimensional data (Chen and Luo 2014). Multirotor drones aim to efficiently collect records and as-built information, even in indoor construction sites (Hamledari et al. 2017; McCabe et al. 2017). BIM can be then updated to estimate whether the investigated events will cause any delays and whether there could be other effects on normal progress.

Irizarry and Costa (2016) presented four cases to identify more potential applications of multirotor drones during the construction process. The first project included demolition and reconstruction work for an academic office building in the city of Atlanta, Georgia in the USA. The other two projects were construction of an academic research building and a high school building in Georgia. The last project was related to the construction of eight apartment buildings in the city of Salvador, Bahia in Brazil. A total of 200 visual assets including 98 photos and 102 videos were collected within a seven-month period through drone flights at the job sites. After interviewing construction project personnel, the researchers and construction staff considered that multirotor drones had potential applications in progress monitoring and planning for construction management tasks, in addition to safety management and quality inspections.

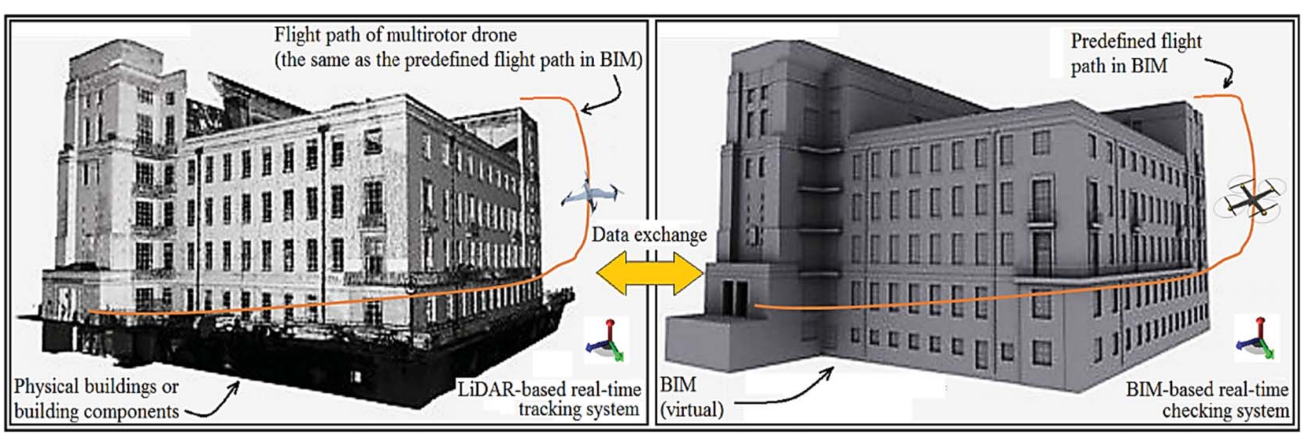


Figure 3. The BIM-LIDAR construction quality control system.

The project progress monitoring and detection of temporary objects can also be achieved by the photogrammetric point clouds from the drone-captured data (Tuttas et al. 2015). Unlike manual procedures, the integrated technology of BIM, UAS and real-time cloud data enables the rapid real-time project control, monitoring and inspection by comparing as-planned information and as-built states of the construction projects (Ham et al. 2016). Lin et al. (2015) proposed a model-driven approach for acquisition and analysis progress images. Drone-based progress monitoring and temporal information in 4D BIM for autonomous data acquisition were discussed. Moeini et al. (2017) provided an example in 2017, namely the rocky ridge facility. The construction project is a recreation facility of 26,000 m^2 located within the inner city of Calgary in Canada. The drone operation was the first official and legal UAV flight with the city boundary. A monthly frequency of site monitoring was implemented throughout the 2-year duration of the project. Metric Photogrammetry and Structure from Motion as cost-effective manners aim to determine object characteristics from rectified stereo-photographs (Vacanas et al. 2015). Figure 4 illustrates the procedures for progress monitoring using cloud points and *n*D BIM models.

The captured visual data, such as photos and videos, could be imported into the photogrammetry software, like Pix4D, for generating 3D point cloud models with the calibration of camera positions, orientations and specifications. The as-built point cloud models can be then manually overlaid over BIM models on an *n*D BIM platform for comparing as-planned and as-built models. The system is capable of detecting progress deviations and providing performance analysis. Finally, the schedule can be updated and critical schedule information can be produced, such as current situations, expected completion data and critical activities.

Site management

To improve construction site management, augmented views of construction sites were provided for construction engineers in terms of high viewpoints and a combination of real and virtual scenes (Wen and Kang 2014). 3D representations using augmented reality (AR) technologies were developed from images that drones captured at specific altitudes and locations. The proposed method combining AR and drone-related technologies can aid practitioners in visualizing both actual field and virtual construction environments in site organization. It would enable managers to plan aspects of the construction site such as material and worker flow and to identify potential issues.

Constructed facilities management

With the increasing number of ageing buildings and infrastructure, effective inspection and monitoring of existing civil structures are becoming critically important. Assessing their structural states and triggering rehabilitation can extend their lifetimes (Cha and Buyukozturk 2015). Traditional inspection methods often involve high costs because of the need for special equipment and specially trained staff. However, a drone only requires an operator on the ground for controlling its flight and camera. So far, drone-based techniques have also been explored for visual inspection and

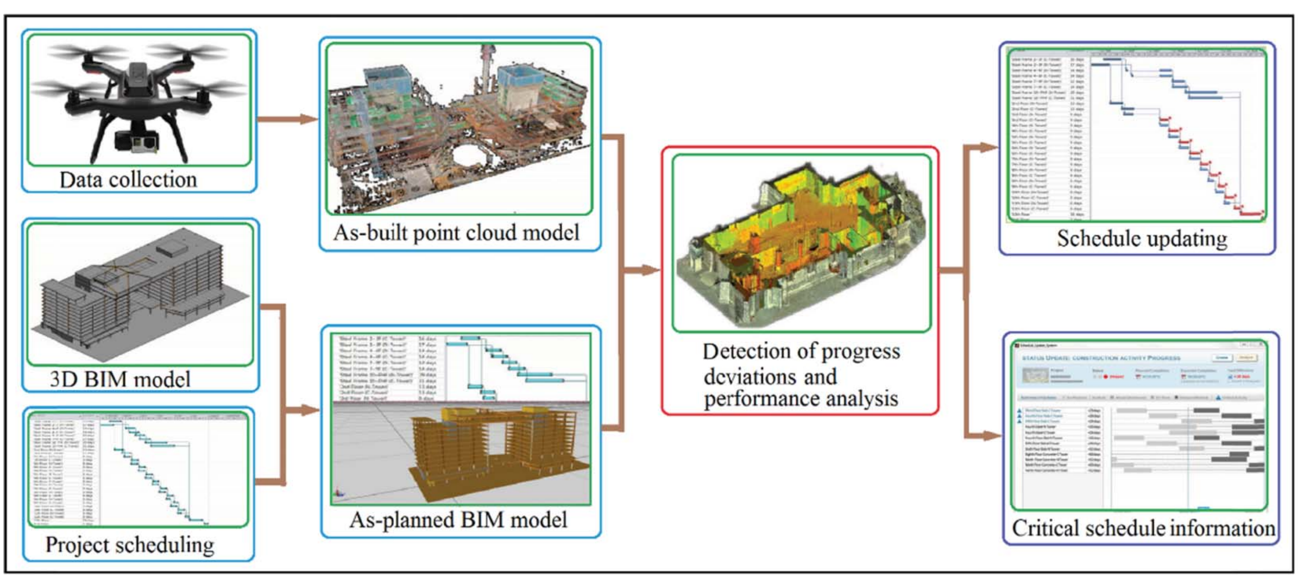


Figure 4. A flowchart of progress monitoring using cloud points and BIM.

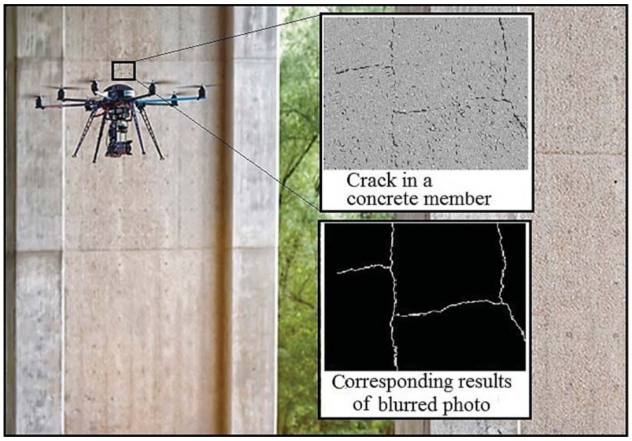


Figure 5. Drone-based crack detection.

damage detection of structures and infrastructure such as hurricane-induced building damage (Ezequiel et al. 2014) and earthquake-induced building damage (Michael et al. 2012). These techniques have also raised this field to new levels of quality and economy (Morgenthal and Hallermann 2014). Specifically, optical remote-sensing mounted on drones can provide high-resolution images ranging from the decimetre to the centimetre scale, as shown in Figure 5.

This allows for performing comprehensive damage assessment through identifying different levels of damage evidence, ranging from complete collapse to cracks on buildings and bridges, by choosing images at appropriate scales. In particular, oblique airborne images based on drone technologies are recognized as a suitable source, since they can facilitate damage assessment on both roofs and lateral elements (Fernandez-Galarreta et al. 2015). The drone technologies also demonstrated the effectiveness of inspecting a glass curtain wall (Liu et al. 2016) and marking regions of concrete degradation resulting from water seepage and leakage issues (Santano and Esmaeili 2014).

Demolition management

At present, multirotor drones could be used for waste management (Ge et al. 2017) and to take footages to view the progress of the demolition (Parramatta Advertiser 2017; Taylor 2017) during the phase of end-of-life building deconstruction. For example, O'Neill (2016) provided impressive footage of a controlled hospital demolition, the 11-storey Millard Fillmore Gates Hospital in New York, from the point of view of an aerial drone: the building was knocked to the ground within 30 seconds. In addition, the Parramatta Stadium is currently being razed for the $300 million Western Sydney Stadium due to open in 2019.

Overall, the application in construction management by processing data from mounted sensors on drones is summarized in Table 2. The extant literature indicates the video data collected by drones is often used for construction and post-construction phases. The combination of drone and point cloud technologies is being widely exploited by researchers in the construction field, such as land surveying, progress monitoring and structural inspection. Moreover, the data is often exported into BIM models to achieve the quality, progress and waste management. Thus, the integration of drone, laser and BIM technologies is relatively popular and suggested to solve more construction problems.

Table 2. Data collection via drones and processing for construction management.

			Application in construction management								
					On-site construction						
Data	Sensors	Data processing	Surveying	Logistics	Safety	Quality	Time	Site	Inspection	Demolition	Relevant work
Image	Digital camera	123D Catch	√			√	√		√		Morgenthal and Hallermann (2014); Fleming et al. (2016)
Video	Digital camera, infrared camera, range finder	D4R, BIM			√	√	√		√	√	Morgenthal and Hallermann (2014); Irizarry and Costa (2016); Dupont et al. (2017)
3D point cloud	Camera 3D scanner, RGB-D sensor, LiDAR laser scanner	123D Catch, PhotoScan eCognition, D4R, BIM, Pix4D	√	√		√	√		√	√	Siebert and Teizer (2014); Fernandez-Galarreta et al. (2015); Wang et al. (2015); Fang et al. (2016); Dupont et al. (2017); Ge et al. (2017)
Tag location	RFID reader	GPS, UB, RFI, BIM		√							Hubbard et al. (2015); Dupont et al. (2017)
Bird view	Digital camera	Nil			√			√			Gheisari et al. (2014); Wen and Kang (2014)
Voice	Voice transmitter	Nil			√						Gheisari et al. (2014)

Opportunities and challenges for drones in the construction industry

The construction industry continues to explore the applications of multirotor drones, since construction companies and engineering researchers have observed the valuable benefits of use of the drones in their work, as described in the previous section. It is necessary to recognize both the advantages and disadvantages of drones in the construction industry.

Social perspective

From the social perspective, the main contribution of multirotor drones in construction is to resolve work safety issues. For example, land surveyors usually work in a dangerous environment due to highly sloped surfaces or being close to heavy equipment. Their work is always outdoors, regardless of weather conditions (El Meouche et al. 2016). Having a drone-mapping solution allows for autonomous flights to eliminate several risks associated with land surveying, such as heavy equipment and injury from hazards.

Drone-based technologies can also resolve the problems of difficult and dangerous structural inspections, such as those of steep-sloped roofs, exterior facades and walls, towers and bridges, damage due to fires and explosions, vehicle accidents and catastrophic events (Mat Yasin et al. 2016). Furthermore, over time buildings change, which makes demolition work hazardous and unpredictable. Predicting how buildings may fall can ensure a safe demolition environment via simulation, in which 3D building models can be created through building thermal inspections from drones. Overall, injury and fatality can be greatly reduced or avoided through the effective use of multirotor drones.

Economic perspective

As discussed in Section 3.1, drone-based surveying approaches are relatively cost-effective. Multirotor drones can achieve the rapid collection and automatic analysis of terrain data. Drones can also be used to automate other simple tasks and significantly reduce project costs. Instead of using human resources, heavy machinery and expensive surveying tools, drone-based technologies are capable of producing complex data with less expense and greater accuracy (Siebert and Teizer 2014). Structural inspections often require typical inspection units, such as truck cranes, elevating platforms and underbridge units (Morgenthal and Hallermann 2014). Drone-based inspection approaches can also avoid the high logistical and personnel costs that large trucks, special elevating platforms and scaffolding require.

Furthermore, drone mapping is also unbeatable in terms of speed, compared with traditional approaches to land surveying. Traditional land surveying may require long hours and carrying of heavy equipment from one location to another. However, drone mapping may take only minutes to complete a site survey with higher accuracy, instead of days or weeks. Similarly, timely gathering of as-built status for construction sites also requires frequent and intensive surveying resources (El Meouche et al. 2016). Drone-based progress monitoring can avoid delays in construction projects. A delay to completion and delivery can result in extra costs and reduce profitability due to consequential losses and expenses.

Environmental perspective

As mentioned above, multirotor drones have many positive applications in construction and offer wide benefits to construction companies. Multirotor drones also greatly contribute to environmental fields, although previous research has mainly focused on the social and economic benefits for construction.

Multirotor drones are electric motor-driven (Gatti 2017), instead of using fossil fuels, which means that they do not produce high levels of carbon dioxide emissions relative to some fixed-wing drones and other construction equipment. This makes them a more environmentally friendly alternative for aerial work such as land mapping, aerial photography and aerial surveying.

The introduction of multirotor drones in built environments also plays an important role in improving environmental conditions. For example, tracking and photographing flora and fauna species using drones can help conservationists better understand the impact of land-use changes (Tang and Shao 2015). The ease and affordability of using drones to monitor energy projects, such as pipelines, wind turbines and solar farms, can significantly contribute to sustainable development and construction.

Current challenges for drones

There is no doubt that the usefulness of drones will continue to increase in the construction industry, with drone technologies constantly improving. However, some challenges in the use of the multirotor drones should be addressed in construction processes (Liu et al. 2014; Siebert and Teizer 2014; Kardasz et al. 2016; McCabe et al. 2017).

First, the greatest limitation of drones is centred on the local regulations surrounding their usage, which may vary from one region to another. Second, professional operators are indispensable for the use of drones in construction, as navigating these devices can be tricky. Third, flight reliability is a critical issue to be addressed on construction sites, as flight paths can be significantly affected by weather conditions such as strong winds and heavy rains. A reliable algorithm that can deal with many conditions needs to be developed to ensure fight reliability and so enhance applicability. Fourth, construction workers can be distracted by a flying drone during construction processes, which may cause safety issues. Fifth, a common issue with drones is still a lack of electricity capacity, which often limits their flight time to 20 minutes and their charging time to an hour. The sixth limitation is the payload problem: mounting more devices on drones requires a better power-generation module.

Development of drones in the construction industry

Drone technology is constantly evolving and currently undergoing ground-breaking progressive improvement for resolving possible adverse impacts on the basis of current limitations (Joshi 2017). In the future of the construction industry, automating tasks as much as possible by using a drone or a drone fleet could be a significant step forward in project efficiency and ensuring the safety of the workforce. Developing existing drone technologies and combining these with other emerging technologies will enable multirotor drones to play more important roles in the future (Liu et al. 2014).

Improvement in existing drone technologies

The future trend in drones is towards designs that are miniaturized, light and efficient (Floreano and Wood 2015). Engineering researchers are dedicating themselves to improving battery capacity and innovating drone aviation technologies, such as the transforming Tesla drone concept (Mortimer 2015). An advanced lithium-ion battery allows the Tesla drone to prolong flight so as to last up to an hour on a single charge. The new drone adopts dual propellers, which can be positioned either vertically or horizontally according to the need for a slow, steady shot or fast-paced action videos by the operator (Mueller 2015).

It can be imagined that new drones with innovative battery and aviation technologies will monitor construction sites better and collect terrain data faster. Attaching methane-sniffing sensors to drones can help detect gas leaks for hundreds of oil pipelines, register locations and measure the volumes of leaks. In addition, improving payload capacity will mean that an autonomous fleet of drones can do bricklaying in the construction process (Burgess 2014).

Combination with new systems

Engineering researchers have also been exploring new navigation systems for innovating drone technologies, which means that future drones will be able to disengage from navigation dependence on GPS satellites (Stark 2017). It will be possible for drones to navigate autonomously inside the structures and infrastructure under construction, such as buildings in deep canyons, underground and in other places where GPS signals are unavailable or unreliable. Thus, the new technology will achieve more comprehensive construction quality inspections and time management.

Furthermore, fatigue is a primary accident risk factor for construction workers and requires better recognition by construction safety managers (Jarkas et al. 2015). Fatigue monitoring systems have been recently explored and developed in the construction industry (Caterpillar 2017). It can be predicted that drones equipped with fatigue-detection systems will be able to simultaneously monitor many vehicle and equipment operators' facial movements to determine whether they are at risk of falling asleep on a construction site.

Equipment with latest devices

Some emerging devices have received significant attention, such as virtual reality (VR) and wearable devices, although they are still in the early stages of development. Unlike AR technologies that utilize mobile devices, such as smartphones and tablets, VR headsets completely enclose users inside a fictional world, with no reference to the actual world (Fuchs 2017). Drones and equipped cameras can be controlled by tracking head movements (Indiegogo 2017). The combination could fully visualize simulated construction from any views of construction sites and building components, test a number of factors without the time and cost of building structures, and reduce the number of errors during construction processes.

Work with autonomous equipment and vehicles

Researchers and engineers have made significant progress in autonomous vehicles over the last decade (Chan 2017). In 2016, a Waymo driverless car was displayed at a Google event in San Francisco (Ohnsman 2017). It is based on a Google self-driving car project and stands for a new way forward in mobility. In the construction field, driverless construction equipment, robotics and electric vehicles can be recognized as ideal solutions to construction environmental problems and labour shortages. However, the central challenge of driverless equipment and vehicles is to teach the machines to deal with the complexity of construction sites (Marshall 2017). In the future of the construction industry, drones could be used to navigate and guide autonomous equipment and vehicles in safe, efficient patterns (Team 2017). Consequently, drones collaborating with autonomous equipment and vehicles on construction sites will be able to achieve lower fuel usage, shorter schedules, safer construction processes and more efficient supply logistics.

Conclusions

Overall, drones are an increasingly popular technology developing in society today. Multirotor drones have many advantages over other drones, such as high manoeuvrability and low cost. Multirotor drones can be equipped with various sensors, such as video or still cameras, far- and near-infrared, radar- or laser-based rangefinders and specialized communication devices, and can be piloted remotely using smartphones, tablets or computers. So far, they have been applied to various fields such as agriculture and mining. Multirotor drones also have potential to facilitate construction, such as site observations and structural inspections, but they are still in an exploratory stage and have not yet been widely used in the construction industry.

Previous researchers initially explored uses of multirotor drones in many aspects of construction engineering and management during the last five years. This paper comprehensively investigates the applications of multirotor drones, discusses their roles and analyzes their potential in construction. Several aspects are reviewed and analyzed, namely land surveying, logistics, on-site construction, maintenance and demolition. The results reveal that the main contributions are work safety from the social perspective, cost-effectiveness from the economic perspective and lower carbon dioxide emissions from the environmental perspective. Construction managers can benefit from the main functions of drones, such as flight and information collection. There is no doubt that the usefulness of drones will continue to increase in the future of the construction industry through developing drone technologies, updating various systems, carrying new devices and collaborating with future construction equipment. It should be noted that relatively little research is, so far, involved in multirotor drones in the construction field. Insufficient relevant research means that the current research has to address a few non-scholarly publications. To be more complete, the future research should be further extended to a review and discussion on the drone technology in any one specific aspect of construction. Nevertheless, the current research is expected to raise awareness of the uses of multirotor drones and their potential in the construction industry.

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