Barriers to adoption of RPAs on construction projects: a task–technology fit perspective

Hamed Golizadeh
DesignandBuiltEnvironmentSchool,UniversityofCanberra, Canberra, Australia

M.RezaHosseini
SchoolofArchitectureandBuiltEnvironment,DeakinUniversity,Geelong, Victoria, Australia

David John Edwards
FacultyofComputing,EngineeringandtheBuiltEnvironment(CEBE), Birmingham City University, Birmingham, UK

Sepehr Abrishami
SchoolofCivilEngineeringandSurveying, UniversityofPortsmouth,Portsmouth, UK

Nasrin Taghavi
University of Tabriz, Tabriz, Iran, and

Saeed Banihashemi
DesignandBuiltEnvironmentSchool,UniversityofCanberra, Canberra, Australia

Abstract

Purpose – Extant literature extensively articulates the advantages of using remotely piloted aircrafts (RPAs) in a myriad of construction activities. Yet, the barriers that hinder their wider adoption on construction projects have received scant academic attention. This study aims at addressing this gap in the literature.

Design/methodology/approach – This study reviews 59 papers published on the use of RPAs for construction activities and offers an evaluation of barriers to widespread adoption throughout the sector.

Findings – Barriers are identified, collated and categorized into five thematic groups, namely, technical difficulties, restrictive regulatory environment, site-related problems, weather and organizational barriers.

Practical implications – The paper contributes to knowledge by: signposting a need for reordering priorities when defining future research on RPAs, suggesting measures to address the barriers identified and providing pragmatic guidance for construction companies intending to use RPAs on their projects.

Originality/value – Using the task–technology fit theory, the study uncovers that current RPA technology is an under-fit match for construction activities and represents a prominent barrier to adoption. This is a dissenting finding, given that past studies on RPAs have primarily focused upon addressing public acceptance, concerns and societal consequences. Enablers of the identified barriers are also collated from extant literature and contemporary practice and encapsulated in a conceptual model.

Keywords: Adoption, Drone, Construction industry, Civil engineering, UAV, Barrier

Introduction

Remotely piloted aircrafts (RPA) are unmanned aerial vehicles (UAVs) that are used for commercial purposes (CASA, 2016). UAVs, popularly known as drones, can be simply defined as: “any aerial vehicle that does not rely on an on-board human operator for flight, either autonomously or remotely operated” (Rao *et al.*, 2016, p. 84). Given the technological advancements on miniaturization of components; the availability of smaller, lighter and cheaper aircrafts; and increased capabilities, RPAs will secure a significant share in various industrial market sectors (Pádua *et al.*, 2017; Li and Liu, 2018). For example, industry reports indicate that global markets will reach US$2.8bn by 2018 and to US$4.8bn in 2021, thanks to the availability of devices, with less cost and more versatility (Market Research Store, 2012; Anastasios *et al.*, 2018). Furthermore, RPAs are predicted to become the most dynamic sector of growth for the global aerospace industry (Zaloga, 2011; Canis, 2015). Top applications of RPAs include their widespread usage as military weapons, aerial photography, shipping and delivery and disaster management (Clarke, 2014a). RPAs have been also successfully utilized in the construction sector for facilitating site layout planning, remote observation of construction progress, site inspection and safety monitoring (Ham *etal.*, 2016; Melo *etal.*, 2017). Moreover, using building information modeling (BIM) on projects has reached an acceptable level of maturity, opening a new avenue for integrating BIM with visual data collected through RPAs (Han and Golparvar-Fard, 2017). The physical size or value of a construction project is not a delimiting factor, as even small-scale construction projects are capable of benefiting from RPAs in various forms – such as creating high-resolution 3D models to be shared online with clients and owners (McPartland, 2017; John *et al.*, 2018).

Despite their broad potential and strong promotion within academic discourse, RPAs have not been widely adopted across the construction industry due to a plethora of barriers (Dupont *et al.*, 2017; McCabe *et al.*, 2017). For example, recent studies suggest that the key barriers include stringent aviation regulations exacerbated by public concerns that RPAs are being used ostensibly as surveillance equipment (Karpowicz, 2017a; McMinn, 2017). Similarly, their commercial use has been criticized by both individuals and activist organizations around issues relating to informational integrity and privacy (Luppicini and So, 2016; Rao *et al.*, 2016). However, literature also reveals that the barriers to widespread use of RPAs remain an under-researched area within a construction context (Lidynia *et al.*, 2017), and that existing studies have too narrow a focus: Gevaert *et al.* (2018) targeted societal barriers, Clarke (2014a) examined regulation-related aspects, Pärn and Edwards (2017) referenced applications in laser scanning, Li and Liu (2018) discussed various applications of multirotor-type RPAs and Zhou and Gheisari (2018) discussed various types of sensors and RPAs for construction activities; recently, Greenwood *et al.* (2019) conducted a review on applications of RPA on infrastructure projects.

With the above in mind, the barriers to adoption of RPAs in the construction context

represent a real problem. According to Müller-Bloch and Kranz (2015), the term research problem – and the ensuing call for action/resolution – can also be applied interchangeably with the term research gap. This research problem – gap – acts as an input for defining review studies; it triggers further research, with the aim of characterization, verification and presentation of the gap through synthesizing the literature (Müller-Bloch and Kranz, 2015).

Consequently, this paper seeks to stimulate a wider academic discourse by:

- identifying the barriers that hinder widespread adoption of RPAs in contemporary practice; and
- defining and delineating the current state (and possible future) of RPAs deployment within the construction industry.

Applications and innovations

Nearly one-and-a-half centuries after Montgolfier brothers designed the first widely known manned flight (a hot air balloon), the Hewitt–Sperry Automatic Airplane in 1916 was demonstrated as the first modern UAV (Zaloga, 2011). UAVs were initially developed for carrying weapons and explosives as early as 1915 in the USA and as targets around 1930 in the UK (Clarke, 2014b). However, these decommissioned military devices have found alternative uses and applications within civilian society. According to the Civil Aviation Safety Authority of Australia (CASA, 2016), UAVs can be categorized into two types:

1. RPAs which are used for government, commercial or research purposes; and
2. model aircrafts used only for entertainment, in sport and recreation activities.

The distinction between the two is that, for a model aircraft, no fee is paid for the service (Clarke, 2014b). Consequently, RPAs represents terminology applicable to the commercial purposes on construction sites and is used within this study. For a further and more exhaustive treatment of terminologies and the various methods of UAVs classification, interested readers should consult with Clarke (2014b).

The fastest commercial growth opportunity for RPAs comes from business with an expected value of US$13bn sales expenditure between 2016 and 2020 (Goldman Sachs, 2016). Of this, the largest market share of up to US$11bn resides within the construction industry (Goldman Sachs, 2016; McPartland, 2017). RPAs have been extensively used in construction projects (Alsafouri and Ayer, 2018) for activities such as: creating 3D models of sites, measurements, monitoring of progress and surveying of earthworks inspections (Cole and Creech, 2016; Ham *et al.*, 2016; Irizarry and Costa, 2016). RPAs have also been used to enhance safety on construction sites (Seo *et al.*, 2015; Irizarry and Costa, 2016; Melo *et al.*, 2017; Alsafouri and Ayer, 2018) and have been integrated with BIM to create a new innovative application of the technology (Teizer, 2015; Hamledari *et al.*, 2017b; Han and Golparvar-Fard, 2017). RPAs have also been used for the quality inspection of buildings, facades, bridges and culverts (Serrano, 2011; Landes *et al.*, 2012; Roca *et al.*, 2013; Morgenthal and Hallermann, 2014; Ellenberg *et al.*, 2016b; Rakha *et al.*, 2018). Inspection tasks are extensive and range from damage quantification of bridge structures (Ellenberg *et al.*, 2016b; Omar and Nehdi, 2017) to use of heat mapping technology for accurate energy audits that seek to maximize energy savings and improvements in building envelopes (Rakha *et al.*, 2018). RPAs are increasingly utilized for monitoring and inspection of buildings that are remarkable in terms of size and architecture – this is because of an increased focus on sustainability and resource efficiency in the building and infrastructure sector that necessitates extending the operational lifetime of constructed facilities (Vacca *et al.*, 2017; John *et al.*, 2018). In summary, the applications of RPAs within academic literature are considerable, but the practical applications within industry would grow further if the barriers hindering their widespread use are addressed (Luppicini and So, 2016).

The theoretical lens: task–technology fit

Technological innovations *per se* are of little value unless accepted and utilized within industry and society (Hosseini *et al.*, 2015; Gledson, 2016). Identifying the reasons preventing the acceptance of technological innovation paves the way forward for promoting its usage and tackling the barriers that hinder its widespread application among the target population (Samaradiwakara and Gunawardena, 2014; Mollaoglu *et al.*, 2016). According to innovation diffusion theory, adoption of any technological innovation is stifled by some barriers like resistance from consumers, among others (Rogers, 2010). A fine-grained approach is essential when exploring the barriers to adoption of technological innovations (Antioco and Kleijnen, 2010).

The technology acceptance model (TAM) and the task–technology fit model (TTF) represent two significant models for explaining user acceptability of technological innovations (Dishaw and Strong, 1999; Imoudu Enegbuma *et al.*, 2014). TAM has been criticized for weakness in terms of its lack of task focus – that is, robustly evaluating the technological innovation acceptance, use and performance, as argued by Dishaw and Strong (1999). Conversely, TTF developed by Goodhue (1995) has been widely used to successfully explain the factors that affect the adoption of technological innovations (Junglas *et al.*, 2008):

- investigate software maintenance systems (Dishaw and Strong, 1998);
- investigate group support systems (Zigurs and Buckland, 1998; Dishaw and Strong, 1999); and
- evaluate performance factors of an integrated information center on end-users (Goodhue, 1997; Goodhue *et al.*, 1997).

Specifically, TTF is not reliant upon historical information on the use of the technological innovations (Schlauderer *et al.*, 2016) and is therefore, more suitable for RPAs that do not have a long history of use.

TTF can be assessed as a trichotomous variable, namely: “ideal-fit”, “under-fit” and “over-fit” (Junglas *et al.*, 2008). *Ideal*-fit indicates an exact match between task requirements and the functionality of a technological innovation. *Over*-fit occurs when more functionality is provided than is required, and *under*-fit reflects situations in which technological innovation is not capable of: “facilitating solving the problem at hand in an ideal manner” (Junglas *et al.*, 2008, p. 1050).

Research methods

Data for systematic reviews are available from databases such as the Web of Science (WoS), PubMed, Google Scholar and Scopus. Of these, Scopus was selected because it has a wider range of coverage, faster indexing process and lists more recent publications (Hosseini *et al.*, 2018). To identify pertinent keywords, it should be acknowledged that various terms are commonly used in referring to RPAs across the construction industry. For example, the Federal Aviation Administration of the USA uses remotely piloted vehicles (RPVs) and RPA. In the UK, the term remotely piloted air system (RPAS), UAV and drone are preferred (Fishpool, 2010; Herlik, 2010; Marchant *et al.*, 2015). The Civil Aviation Safety Authority in Australia shifted from using the terms UAV and drone to RPAs, and unmanned aircraft systems (UASs) (CASA, 2016). Together, these homogeneous terminologies were used as keywords for identifying relevant research studies associated with RPAs within Scopus. The search had no time limitation, with the date range set to “all years to present”. The document type was refined to filter only articles published in journals; the rationale being that journal articles represent the most influential research studies. Conference papers are published in large numbers, and little is gained by including them, given the extra level of complexity added to the analyses (Butler and Visser, 2006). Keywords were searched on abstract/title/keywords. The preliminary outcome comprised of 11,672 studies related to RPAs published from February 2005 to October 5, 2017. The search was further narrowed to publications relevant to the construction industry. The findings were limited to those studies having the term “construction” in the abstract/title/keywords, whereas terms such as chemistry, bio-chemistry, agriculture, medicine and nursing were excluded from the search. This filtering reduced the pool of studies down to 299. However, because the term "construction" carries an ambiguous quality (being used to describe the manufacture of aircraft, as well as the industry more broadly), further refining was needed. Thus, the abstracts of all 299 studies were reviewed manually and those dealing with the manufacture or design of aircraft/components were omitted from the list. The outcome of this three-tiered filtering process produced a final list of 59 journal articles that clearly discuss RPAs in the construction industry. These articles provided multiple sources of information and were utilized to determine the barriers to the use of RPAs within construction practice. Once the existing barriers are mapped, this study will look at fitness criteria required for RPAs usage in the context of construction projects. This allows to determine whether RPAs are ideal-fit, under-fit and over-fit based on the definitions provided by Goodhue and Thompson (1995). It is noted that a technological innovation will have a constructive influence on performance if, and only if, it is applied and the functions granted by the technology fit the task. The last step of the analysis is to provide solutions for the identified barriers that make the RPAs under-fit or over-fit for the current practice requirement of the industry. These solutions are provided based on the collected 59 articles, as well as existing research studies on RPAs in other industries, specifically research from the aviation industry. Figure 1 illustrates the research design and the sequence of activities.

Barriers to adoption of RPAs

The major barriers and various dimensions associated with each dimension are tabulated in Table 1; these barriers are thematically grouped into five categories by: technical difficulties, restrictive regulatory environment, site-related problems, weather and organizational barriers. The technical difficulty category deals with the shortcomings associated with the operating system of RPAs, as well as the technical flaws RPAs in performing specific tasks. Restrictive regulatory environment points to the regulations that restrict using and applying RPAs for various tasks. Site-related barriers present problems that are specific to the operation of RPAs on construction sites, while weather category describes the weather conditions that affect or prevent the operation of RPAs. Lastly, organizational barriers present difficulties that affect the adoption of RPAs, stemmed from business considerations within constructioncompanies.

Technical difficulties

Land surveying and inspection tasks conducted by RPAs produce large-sized images/videos and, consequently, require a reliable and efficient transferring platform and storageprocess (Irizarry and Costa, 2016; Han and Golparvar-Fard, 2017). Typical methods are wireless platforms such as MICA, MICA2, MICAz or Imote2 for sending real-time data to a host base station (Kurata *et al.*, 2005; Lynch and Loh, 2006; Maqbool and Sabeel, 2013). Loss of such a large volume of data is a major concern in wireless transferring platforms where the range of data loss may vary between 30 and 50 per cent (Yang and Nagarajaiah, 2017). Data loss can also occur due to failure in the documentation process (Kim *et al.*, 2016). Storing large data can be problematic for construction companies, as this requires a "systematic" storage process approach, where practitioners struggle to avoid "drowning in drone data" (Karpowicz, 2017b). External hard drives are relatively low-cost, provide an affordable data storage and exchange solution within construction offices. However, exchanging bulk volumes of data among offices in different locations is still prone to various problems such as security concerns (Karpowicz, 2017b). Current data compression methods provide an unconvincing solution for such problems, because a high compression rate can create data reconstruction errors (Yang and Nagarajaiah, 2017).

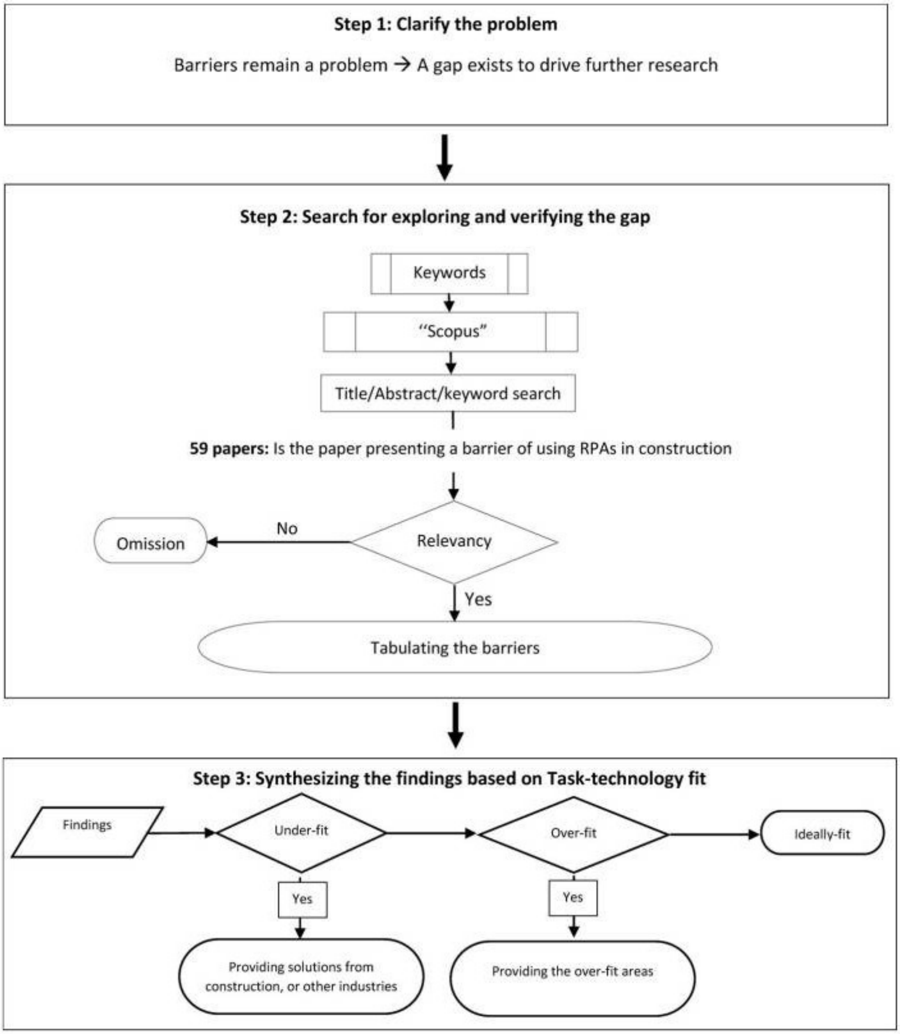


Figure 1. Research design

Loss or interference of GPS signals of RPAs within a building's interior or within the vicinity of densely populated buildings and/or high-rise buildings can lead to losing control of RPAs (Ham *et al.*, 2016). Due to the ensuing erroneous positioning, RPAs can travel in any direction or location outside the predefined path and step outside the scope of the radio link, resulting in the consequent loss of the aircraft. Indeed, controlled flight via GPS signals is deemed to be a high-risk activity in public areas or spaces. Moreover, Morgenthal and Hallermann (2014) indicated that a GPS-driven RPA can experience loss of calibration on magnetometer sensors when entering close proximity to steel components – rendering the technology unsafe for an industry that is heavily reliant upon steel components within structures. Because of these aforementioned difficulties, Kim *et al.* (2016) argue that RPA

Table 1. Barriers to adoption of RPAs in the construction industry

Category	Barrier	Reference
Technical difficulties	Large volume of the generated data and data loss	Irizarry and Costa (2016), Kim *etal.* (2016), Hamledari *et al.* (2017a), Han and Golparvar-Fard (2017), Karpowicz (2017b), Yang and Nagarajaiah (2017)
	Failure of GPS signals	Morgenthal and Hallermann (2014), Ham *et al.* (2016)
	Inefficient flight paths	Irizarry and Costa (2016), Kim *etal.* (2016), Torres *etal.* (2016)
	Lack of accuracy in detectingon site dynamics	Ham *etal.* (2016), Wang *etal.* (2016)
	Lack of communication with human objects	Irizarry *et al.* (2012)
	Limited flight duration	Irizarry *et al.* (2012), Morgenthal and Hallermann (2014), Opfer and Shields (2014), Munoz-Morera *etal.* (2015), Ellenberg *etal.* (2016b), Fang *etal.* (2016), Kim *et al.* (2016), Leahy *et al.* (2016), Moud and Gheisari (2016), Torres *etal.* (2016), Hassanalian and Abdelkefi (2017), Yang and Nagarajaiah(2017)
	Limited payload	Eschmann *et al.* (2012), Liu *etal.* (2014), Morgenthal and Hallermann (2014), Siebert and Teizer (2014), Ellenberg *et al.* (2016a), Leahy *et al.* (2016)
	Low resolution of the captured images	Li *et al.* (2016), Wang *et al.* (2016)
	Positioning system inaccuracies	Siebertand Teizer(2014), Li *etal.* (2016), Reagan *etal.* (2016)
	User-friendliness	Kim *et al.* (2016), Luppicini and So (2016)
	Vibrations of the mounted camera	Ellenberg *et al.* (2016a), Reagan *et al.* (2016)
Restrictive regulatory environment	Aircraft traffic restrictions	Irizarry and Costa (2016), Kim *etal.* (2016), Stöcker *etal.* (2017)
	Restrictive national regulations	Morgenthal and Hallermann (2014), Blinn and Issa (2016), Herrmann (2016), Ka,cuni,c *et al.* (2016), Kim *et al.* (2016), Stöcker *et al.* (2017), Anastasios *et al.* (2018), CASA (2018)
	Certifications for pilot and flight	Irizarry *et al.* (2012), Opfer and Shields (2014), Blinn andIssa (2016),Boudreau (2016),Kim *etal.* (2016), CASA (2018)
	Insurance issues	Boudreau (2016), Herrmann (2016), Thelander (2017)
	Privacy issues	Jordan (2015), Boudreau (2016), Costa *etal.* (2016), Herrmann (2016), Kim *etal.* (2016), Luppiciniand So (2016), Lidynia *et al.*(2017)
	Public safety	Opfer and Shields (2014), Siebert and Teizer (2014), Clothier *et al.* (2015), Boudreau (2016), Ka,cuni,c *et al.* (2016), Kim *et al.* (2016), Luppicini and So (2016), Anastasios *et al.* (2018), John *et al.* (2018)
	Accidents	Morgenthal and Hallermann (2014), Clothier *etal.* (2015), Jordan (2015), Costa *et al.* (2016), ATSB (2017), Lidynia *et al.* (2017), John *et al.* (2018)
Site-related problems	Interferences with project activities	Costa *et al.* (2016), Anastasios *et al.* (2018)
	Obstacles on construction sites	Boudreau (2016), Irizarry and Costa (2016), Kim *etal.* (2016), John *et al.* (2018)
Weather	The RPAs’ behavior is sensitive to weather	Roca *etal.* (2013), Morgenthal and Hallermann (2014), Siebertand Teizer(2014), Bulgakov *etal.* (2015), Jordan (2015), Ka,cuni,c *et al.* (2016), Wang *et al.* (2016)
Organizational barriers	Acquisition, setup, operating, and maintenance costs	Liu *etal.* (2014), Opfer and Shields (2014), Siebertand Teizer (2014), Ka,cuni,c *et al.* (2016), Kim *et al.* (2016), Kumar *et al.* (2016)
	Management and owner support	Kim *et al.* (2016)

operations should have an emergency fail-safe plan. The GPS-based flight positioning system of the RPAs can also engender flight inaccuracy when operating within confined and/or indoor areas (Siebert and Teizer, 2014; Reagan *et al.*, 2016). Similarly, height and speed variations of the flights can also cause inaccuracy within the RPAs positioning system (Li *et al.*, 2016).

Surveying a vast area requires a logical way of capturing a sufficient number of images

and, therefore, efficient flight path planning is essential (Irizarry and Costa, 2016). Flight path planning represents a major concern in large terrain mappings and 3D terrain reconstruction (Torres *et al.*, 2016) and requires careful consideration prior to RPA flights. Using RPAs for site safety inspections and modeling the as-is condition of sites also faces challenges due to the inability of RPAs to track the location of onsite dynamic objects like mobile off-highway plant and machinery (such as: rough terrain telescopic handlers, crawler cranes and dump trucks) (Kim *et al.*, 2016). This inability limits safety inspection features of RPAs to static equipment such as generators. A potential solution is flying several RPAs simultaneously to cover the entire site, though it still requires a carefully planned path, to avoid clashes between RPAs.

As illustrated in Table 1, images taken by RPAs can have low resolutions that provide insufficient details for modeling and analyses purposes; this represents a significant barrier to the adoption of RPAs for these activities. This largely occurs due to the erroneous selection of flight altitude and speed (Li *et al.*, 2016) or mounted camera's resolution rate (Wang *et al.*, 2016). Surveying procedures by laser scanner devices mounted on RPAs also experience a mixed pixel phenomenon, thus reducing the usefulness of the data collected (Hamledari *et al.*, 2017a). The problem occurs when the scanner faces reflective materials which are prevalent in construction sites like reflexive glass or galvanized steel components, leading to difficulties in the use of collected data with extra effort needed for the subsequent modeling process (Hamledari *et al.*, 2017a). RPAs flying system can also cause vibrations that can adversely affect image qualities (Reagan *et al.*, 2016). The rotation of RPAs propellers causes some turbulence as a result of the air movement across the propellers which is known as wake interaction (Kim *et al.*, 2017). Ellenberg *et al.* (2016a) suggest that placing the camera upon a vibration dampening system at the bottom of RPA, instead of placing it on a gimbal, will reduce the vibration levels (m/s^2). Kim *et al.* (2017) propose optimizing the aerodynamics of RPAs through modifying the affecting forces (thrust, drag, lift and weight) alongside the RPAs center of gravity.

The load carriage capacity of RPAs is significantly lower than manned aircrafts and helicopters. This limits the aerial capabilities of the RPAs and their capacity in carrying various types of cameras for aerial photography (Eschmann *et al.*, 2012; Liu *et al.*, 2014; Morgenthal and Hallermann, 2014; Siebert and Teizer, 2014; Ellenberg *et al.*, 2016a; Leahy *et al.*, 2016). Most RPAs also have limited storage capacity in terms of power. Battery types commonly used include lithium polymer (LiPo), nickel metal hydride (NiMH) and nickel cadmium (NiCd) batteries that provide circa 30-min flight duration (Drone Omega, 2017). This restriction is significant where long-time flights are required (Hassanalian and Abdelkefi, 2017). Several studies have argued that short battery capacity is an obstacle to further use of remote aerial vehicles' potentials in the industry (Irizarry *et al.*, 2012; Morgenthal and Hallermann, 2014; Opfer and Shields, 2014; Munoz-Morera *et al.*, 2015; Ellenberg *et al.*, 2016b; Fang *et al.*, 2016; Kim *et al.*, 2016; Leahy *et al.*, 2016). Power shortage is also a reason for loss of data during transferring of images or videos (Moud and Gheisari, 2016; Torres *et al.*, 2016; Yang and Nagarajaiah, 2017). LiPo batteries, the most common battery type in the RPA industry, are very easily damaged and their electrolyte is volatile and extremely flammable. LiPo batteries, therefore, are described as one of the most dangerous batteries, and their incorrect use can lead to fire or even explosion (Droneblog Editor, 2016).

From an operator's perspective, the ease of RPA use is an imperative factor. Kim *et al.* (2016) found that the user-friendliness of the RPAs operating interface is a significantly important factor for inspection tasks, as well as having interactive functions to hover around the focused area to provide real-time videos/photos. This is, however, a lesser problem for surveying tasks and current interfaces are highly user friendly.

Restrictive regulatory environment

Given the rapid growth of RPAs usage throughout the aviation industry, there is a need for an aviation traffic settlement to avoid in-flight collisions. For example, Clothier *et al.* (2015) and Jordan (2015) note the significantly elevated risk of collision between high-altitude flying RPAs and conventionally piloted aircraft – such could be catastrophic for passenger safety. According to the Australian Transport Safety Bureau (ATSB), 48 per cent of RPA unsafe flight reports from January 2012 to June 2017 included close encounters with manned aircrafts, and 23 per cent were collisions with terrain, where remaining ones were related to the loss of control issues (ATSB, 2017). Post-analysis studies have shown that a majority of RPAs accidents occurs due to system failures, due to equipment problems (Wild *et al.*, 2017). These problems, hence, can be attributed to the lack of a proper collision avoidance system in commercial RPAs (Morgenthal and Hallermann, 2014). With this issue in mind and with public safety as the top priority, RPA operations internationally have been subject to restrictive regulatory frameworks (Morgenthal and Hallermann, 2014; Blinn and Issa, 2016; Herrmann, 2016; Kaçunić *et al.*, 2016; Kim *et al.*, 2016). Amendments to Part 101 of the Civil Aviation Safety Regulations 1998 of Australia commenced on September 29, 2016, and restricts commercial flights with no need for licensed pilots to RPAs under 2 kg. Also, anyone operating RPAs under this category must notify the Civil Aviation Safety Authority (CASA) at least five working days before the first flight and follow the standard operating conditions (CASA, 2018), which arequite restrictive for typical construction activities.

The CASA requires the RPA remote pilot license (RePL) and also remote operator certificate (ReOC) for any operation that does not fall within the above conditions, namely, those termed as "excluded RPA" (CASA, 2018). Therefore, construction tasks, typically beyond the "excluded RPA" conditions, require licensed operators on construction sites. Blinn and Issa (2016) importantly highlight the need for highly skilled personnel to operate RPAs due to construction site complexities and layout. This incurs additional cost on projects and creates concerns related to the cost of employing a certified operator (Irizarry *et al.*, 2012; Boudreau, 2016; Kim *et al.*, 2016). Opfer and Shields (2014) suggest subcontracting the task to an external firm specialized in RPAs, although this can reduce the agility of the main contractor to perform this task when needed.

Ownership, maintenance and use of RPAs in construction create legal liability for the contractor. Property owners and contractors will require an insurance provider to cover the risks associated with RPAs operations (Herrmann, 2016). In Australia, RPAs insurances are available as: hull cover that covers loss and damages occurred to the RPA itself and liability that covers damage to third parties/properties caused by RPA operation (Thelander, 2017). However, Boudreau (2016) states that contractors should not assume that insurance will fully recover the suffered damage. Pilots of RPAs are usually unknown to many, and identifying who is liable for the flight can be problematic. According to Lidynia *et al.* (2017), the public is extremely concerned about pilot anonymity breaches of privacy without their permission. Similarly, on-site construction workers feel uncomfortable about being monitored by an unknown person (Boudreau, 2016; Costa *et al.*, 2016; Herrmann, 2016;

Kim *et al.*, 2016). The perception of using RPAs for commercial purposes is quite recent and many people are unfamiliar with the technology and concomitant safety issues (Clothier *et al.*, 2015). Although flying RPAs in populated areas is restricted by the aviation safety regulations in different countries, palpable concerns still remain (Opfer and Shields, 2014; Siebert and Teizer, 2014; Boudreau, 2016; Ka,cuni,c *et al.*, 2016; Kim *et al.*, 2016). The reasons for the public's disquiet are myriad, but a notable lack of emergency plans further exacerbates matters considerably (Kim *et al.*, 2016). These issues could be solved through a well-established communication protocol to advertise stringent measures implemented to protect the public (Anastasios *et al.*, 2018).

Site-related problems

RPAs are proven efficient in detection and measurement of structural health of building elements (Ellenberg *et al.*, 2016b, 2016a, Moud and Gheisari, 2016; Reagan *et al.*, 2016). However, RPAs operating on construction projects elevate safety risks for on-site workers, particularly when a close-up view for structural health monitoring is required (Costa *et al.*, 2016). Indeed, Phua (2016) illustrated that construction workers have a significant propensity for risk-taking. Therefore, to avoid collisions between workers and RPAs, a tiered system of safety control measures must be implemented. This could include: operating in areas where workers have restricted or no access, using "engineered-out" solutions such as alarming systems and/or deploying safe systems of working such as using an aircraft information map and a traffic controlling system on site (Irizarry and Costa, 2016; Kim *et al.*, 2016). In fact, construction site safety monitoring and management through use of RPAs have received significant academic attention (Golizadeh *et al.*, 2018; Li and Liu, 2018); however, safety concerns must be properly addressed in the risk management of actual projects – taking into consideration the fact that operating RPAs would unexpectedly interfere with project activities. For example, Costa *et al.* (2016) highlight possible workers' distraction while RPAs are flying in close proximity and the implications this has upon reduced concentration, safety and productivity.

Weather

Commercial RPAs are significantly low weight and can be affected by extreme weather conditions (Bulgakov *et al.*, 2015; Ka,cuni,c *et al.*, 2016). High winds (>30 km/h) limit control and reduce flight time due to overuse of battery power to maintain position. Stronger winds can blow the RPA off course into objects and/or push the aircraft beyond areas of recovery (Jordan, 2015). The quality of images is also reduced as wind causes RPAs to vibrate, thus affecting performance of the attached camera (Siebert and Teizer, 2014). Reduced quality of images is a major concern in structural health monitoring where the accurate measurement of the displacements is required (Morgenthal and Hallermann, 2014). Operation of RPAs in foggy and snowy weather is also difficult as operator visibility reduces from the standing point, as well as the first-person view (Wang *et al.*, 2016). In addition, Roca *et al.* (2013) describe how lighting direction can adversely affect images taken. Typical commercial RPAs are also not waterproof, and the desired photo quality would not be affordable in such weather (Jordan, 2015).

Cold temperatures make batteries lose charge faster, while heat is also problematic to engines and propellers, because RPAs typically produce quite a bit of heat on their own; hence, heat can put unnecessary wear and tear on batteries, computers and engines.

Organizational barriers

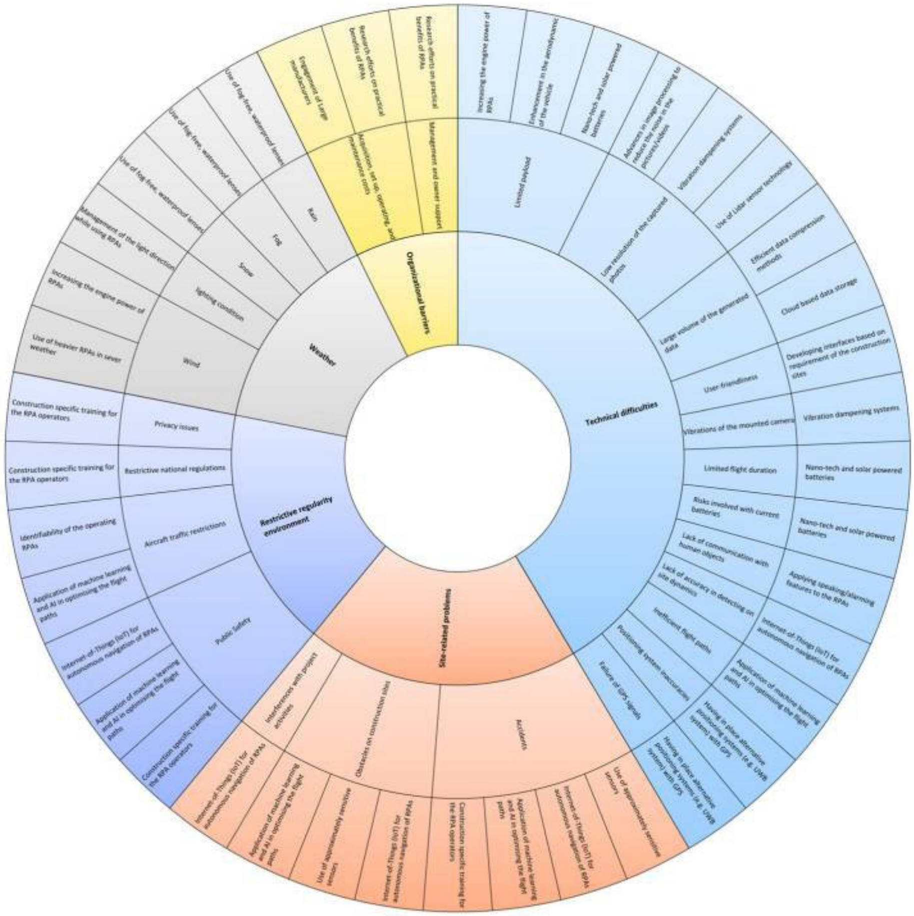
Acquisition, setup, operating and maintenance costs of RPAs at the current state are relatively high (Opfer and Shields, 2014; Kim *et al.*, 2016; Kumar *et al.*, 2016). There are also major risks in using RPAs such as a loss of asset in case of breakdown or crash of aircraft (Ka,cuni,c *et al.*, 2016). A study by Siebert and Teizer (2014) shows that the running costs of flying systems (such as airships, fixed-winged aircrafts and helicopters) for surveying tasks in earthwork projects are relatively higher than RPAs. RPAs at their current state are still evolving beyond their military origin to become powerful business tools (Goldman Sachs, 2016) and require further customizations for civil engineering tasks – where the costs of customizations can be high (Liu *et al.* (2014). Considering the growing number of RPAs throughout the industry, there is an opportunity in the future for the mass production of specific/bespoke RPAs for construction usage that would reduce their costs. Kim *et al.* (2016) argue that lack of support from owners and project managers is a major barrier for using RPAs in the construction sites, one explanation being the fear of additional liabilities incurred. This barrier would require a comprehensive understanding of the benefits and risks that RPAs bring to site operations.

Discussion

Research and industry reports have acknowledged the existence of barriers that hamper the wider adoption of RPAs in the construction context (Dupont *et al.*, 2017; McCabe *et al.*, 2017; McMinn, 2017; Zhou and Gheisari, 2018). With this in mind, this study provides original insight by taking the argument about the barriers to the next level. Raising awareness of the nature of these barriers, exploring and providing a typology of them are among the major contributions of this study. Moreover, addressing the identified barriers from a broader perspective through proposing remedial solutions based on the TTF lens and lessons learned in other industries make the study the first of its kind on the topic.

RPAs: an under-fit match for construction activities

The main purpose of using the TTF lens is to identify areas in need of change in terms of the technology or its environment (Samaradiwakara and Gunawardena, 2014). Figure 2 conceptualizes the nature of barriers identified within extant literature. A major part of barriers to RPA adoption on construction projects have roots in technical difficulties – the incapability of RPAs technology to deal with the requirements of the tasks. Indeed, inefficient flight paths, lack of accuracy, lack of functionality in consuming information from other devices and actors, limited flight duration, etc. can all be attributed to the immature technology of RPAs. This insight is in line with industry reports that call for more technologically capable aircrafts to make RPAs a viable solution for businesses (Morrison, 2016). The restrictive regulatory environments enforced, problems with inclement weather and the site-related problems facing construction companies in using RPAs also have roots in the immature technology of RPAs (Anastasios *et al.*, 2018). That is, the restrictive regulatory environment and problems on construction sites largely stem from the intention to avoid collision risks with manned aircrafts, objects on sites and workers (John *et al.*, 2018). These concerns mostly stem from the fact that RPAs technology in automatically sensing, detecting and avoiding fixed and moving objects and obstacle can be described as immature when compared to manned aerial vehicle (Zhahir *et al.*, 2016). In fact, safety issues and collision problems with RPAs on construction projects are predominantly rooted in the deficiency of their collision avoidance technology (John *et al.*, 2018).



Note: The inner layer shows the typology of barriers, the layer in the middle describes the barriers and the outer layer contains the description of enablers

Figure 2. Model of identified barriers and proposed enablers

The primary challenge, therefore, is to improve the collision avoidance technology in RPAs. Given the limitations of payloads, an effective collision avoidance technology is still missing. That is, under current circumstances, viable collision avoidance technology must be lightweight, small in size and consume low power, hence limited in efficiency (Zhahir *et al.*, 2016).

From the perspective of TTF, the technology utilized in RPAs can be described as *under*- fit against the background of construction project requirements, according to the definition by Junglas *et al.* (2008). This is a dissenting viewpoint, given that previous studies have largely focused upon public acceptance, privacy concerns and negative perceptions as being the key barriers to the widespread use of RPAs (Clothier *et al.*, 2015; Rao *et al.*, 2016; McPartland, 2017). This study, nevertheless, points to another source of problem, namely, immature technology as the driving barrier to presenting RPAs as an *under*-fit match for construction activities.

Barriers and proposed enablers

With the above in mind, Figure 2 presents the identified barriers along with the potential enablers proposed to tackle these. While these solutions are not validated on real-life cases, they are adapted from the literature and recommendations by industry experts and RPA operators reflected – as widely reported via industry discussion forums, weblogs and websites devoted to RPAs.

As illustrated in Figure 2, storage of big data collected by RPAs could be shifted to cloud storage which provides sufficient space with live accessibility for on-site and off-site users (Jiao *et al.*, 2013). Alternatively, data can be compressed to lower capacities; hence, the main challenge with this approach is the development of an appropriate compression method that does not hemorrhage data (Yang and Nagarajaiah, 2017).

RPAs are expected to work in GPS-denied environments such as tunnels or close to heavy steel structures such as bridges. To avoid adverse consequences related to the loss of RPAs position requires the utilization of alternative local positioning systems like ultra- wideband (UWB) in tandem with GPS (Tiemann *et al.*, 2015). Installation of a UWB module on RPAs enables the aircraft to actively send location tracking data to fixed UWB receivers at certain positions (anchors), thus overcoming the limitations of utilizing GPS: blocked line- of-sights, failure in indoor, forest or urban environments (Guo *et al.*, 2016).

Having an alarming/speaking function integral within an RPA design also allows it to communicate with out-reach people, who are in close distance to the RPAs. As argued by Irizarry *et al.* (2012), such a system improves the productivity of the RPAs on construction sites and allows the safer use of RPAs for real-time site inspections during the times the site is populated withworkers.

RPAs are expected to be operational full time on construction sites, and that requires a fundamental solution to low battery capacities. Recent advancements in nanotechnology have found new battery types such as those produced by A123 Systems LLC, M-Phase Technologies and HE3DA that have greater power storage capacities and are already being used in other products (Wong and Dia, 2017). Besides, advances in nanotechnology batteries can be a solution to many drawbacks with batteries currently used in the RPA industry (Wong and Dia, 2017). Photovoltaics could also be used to tackle the issues with current batteries, as well as their data management systems (Rojas *et al.*, 2015). Having more power on-board enables longer-duration operations and makes RPAs capable of carrying heavier equipment with more accuracy and efficiency (Corrigan, 2018a). This, however, relies also on parallel development of lightweight equipment for RPAs that can endure the flying condition.

As illustrated in Figure 2, use of machine learning and AI are proposed as remedial solutions that can resolve the current deficiencies of RPAs through a variety of scenarios. These can facilitate reducing the flight durations by designing and optimizing the flight paths (Torres *et al.*, 2016). AI can also be implemented for faster and effective image processing and model development (Ofli *et al.*, 2016; Cha *et al.*, 2017). AI can also assist in making RPAs safer and reduce risks to the public through trying various trajectories, experiencing crashes into objects and creation of a data set to capture the various modes and ways in which RPAs crash or collide. This self-supervised mechanism is proven effective in navigating RPAs in extremely cluttered environments with dynamic objects and even humans (Gandhi *et al.*, 2017) – conditions similar to that of construction sites. Another approach to reduce the risk of unsafe proximity of RPAs with construction equipment and workers can be using proximity sensors and Internet of Things (IoT) for autonomous navigation of RPAs around construction sites (Palossi *et al.*, 2018). As practiced by Teizer and Cheng (2015), real-time location tracking systems (RTLS) can spot the location of workers, off- highway plant and equipment and produce warnings in unsafe proximity cases.

Construction-related operations require an understanding of the nature of construction activities, and hence, particular training courses can enhance the effectiveness and safety of flights (McMinn, 2017; Ayemba, 2018). Further, proximity detecting sensors can be helpful in this regard, as they can prevent unpleasant clashes between RPAs and human or site objects (Teizer and Cheng, 2015; Corrigan, 2018b).

Conclusion

RPAs represent an emerging technological innovation that will revolutionize the construction industry, given its potential in improving productivity, enhancing site logistics, accelerating project progress and increasing site safety. Construction companies, however, face a wide range of barriers to adopt RPAs on site. This research represents the first attempt to provide a succinct and clear picture of these barriers and, consequently, breaks new grounds in identifying and conceptualizing them from extant literature. The study also provides insight into the major source of barriers that hinder the widespread use of RPAs in construction projects, in dialogue with the TTF theory. There is need for a paradigm shift in focus from societal impacts and RPAs acceptance (by the public) toward addressing the technological deficiencies of RPAs, particularly those pertaining safety matters like collision avoidance systems. It is noted that RPAs at the current stage are under-fit for the construction sector, and majority of the technical barriers root in the operational systems of the RPAs. This can be addressed as a cross-disciplinary issue of the construction and aviation industries, requiring R&D activities to address the problems. The paper is also the first attempt in identifying potential enablers to barriers identified in the existing literature on RPAs, visualized in the form of a graphical model. The model demonstrates that looking toward future advances, RPAs are not considered as separate data providers and disconnected from the rest of construction activities. Future RPAs are expected to be: intelligent and programmed to predict risks (AI), in constant connection to all equipment and resources around them (IoT), empowered by nanotechnology batteries, prepared to operate in severe environmental conditions and operated under more accurate positioning systems. Despite the focus of the study on the construction context, the findings carry implications for RPA manufacturers and technology companies. That is, the model of barriers can be regarded as collected feedback to provide insight into the requirements of construction companies in terms of the capabilities and functions of ideal RPAs to perform construction activities.

Despite the contributions above, the research undertaken has three limitations noteworthy of mentioning. First, given that the findings come from a literature review, they remain theoretical and require validation through exposure to empirical data and tested on real-life projects. Second, the regulatory environment is analyzed from a predominantly Australian perspective and, hence, discussions on this area might not be directly transferrable to other regulatory contexts. Third, the study intends to provide a picture of barriers and their corresponding enablers in abstract concepts, and as such, might lack precision for direct application on construction projects. Certainly, the barriers, enablers and suggestions presented in this study are subject to further review from RPA operators, aviation authorities and manufacturers to complete any missing items that the authors have not identified. That said, it is envisaged that the work presented here is the starting point to move toward a widely accepted framework to overcome the barriers, to make the RPA market sustainable. These limitations, hence, provide fertile grounds for future research and much-needed wider academic debate. Future studies can also delve into the nature of each identified barrier and attempt to provide remedial solutions for each item. The findings of the study also warrant further research into improving the collision avoidance technology used in RPAs, given the conditions of their application on construction sites. In addition, given the large market size for RPAs in the construction industry, research into the design of customized RPAs for construction purposes might be another area of investigation offered through the findings presented here.

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