Pervasive sensing technologies for facility management: A critical review

Abstract

Purpose: The practice of Facility management (FM) has been evolving with the rapid development of pervasive sensing technologies (PSTs) such as sensors, Auto-ID, laser scanning, and photogrammetry. Despite the proliferation of research on the use of PSTs for FM, a comprehensive review of such research is missing from the literature. This research aims to cover the knowledge void by examining the status quo and challenges of the selected PSTs with a focus on FM.

Design/methodology/approach: This paper reviewed 204 journal papers recounting cases of using PSTs for FM. The reviewed papers were extracted from Elsevier Scopus database using the advanced search.

Findings: Findings of this study revealed that PSTs and FM applications form a many-to-many mapping, i.e., one PST could facilitate many FM applications, and one application can also be supported by various PSTs. It is also found that energy modeling and management is the most referred purpose for FM to adopt PSTs, while space management, albeit important, received the least attention. Three challenges are identified, which include high investment on PSTs, data storage problem, absence of proper data exchange protocols for data interoperability, a lack of mature data processing methods for data utilization, and privacy of users.

Originality/Value: This paper paints a full picture of PSTs adoption for FM. It pinpoints the promising explorations for tackling the key challenges to future development.

Keywords: facility management; laser scanning; photogrammetry, videogrammetry; sensor; Auto-ID

Paper type: Literature review

1 Introduction

A ‘facility’ refers to an asset that is built, installed or established to serve social and economic activities (Kaplan et al., 2004). Facility management (FM) is the “organizational function which integrates people, place, and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business” (ISO, 2016). In a building or infrastructure’s ‘lifecycle’, which spans from inception, design, construction, operation through to demolition (Xu and Lu, 2018), FM mainly transpires during the operation stage and normally lasts thirty to fifty years if not longer (Atkin and Brooks, 2015). With facilities accounting for nearly forty percent of global energy consumption (Bilgen, 2014), the effectiveness and efficiency of FM have become a pressing issue. Moreover, in the era of automation and intelligence, FM is the key scene of many smart and humanized services for users. Data collection of facilities and users becomes increasingly important for facility owners and managers to enhance smart services concerning individual comfort, quick response to requirements, cost-effectiveness of physical assets, as well as sustainable and environmental performance of facilities (Peng et al., 2017).

Over the last three decades, the rapid development of pervasive sensing technologies (PSTs) has brought new opportunities for the longstanding FM profession. This paper uses the term ‘PST’ as a common nomenclature for advanced data collection technologies, such as Auto-ID (Automatic identification), sensor, photogrammetry/videogrammetry, and laser scanning, which can collect data concerning the condition, operation, and users of a constructed facility. Photogrammetry and videogrammetry are the same processing on different data sources, i.e., images versus video clips (Rashidi et al., 2017). Data is the key to understanding users’ requirements and their behaviors, which can be incorporated by designers in a facility’s design, construction and renovation stages. Data is also the key to understand the ongoing conditions and users’ behavior during the FM stage. In comparison with manual methods, data collection by using PSTs are generally more precise, more cost effective, and less tedious. In short, PSTs can make major contributions to FM because they can help designers, engineers, and facility managers understand what users need, prefer, and what is best for them.

Several reviews have been conducted by focusing on specific types of PSTs in the existing literature. For example, Taneja et al. (2011) reviewed sensing and field data capture technologies, such as radio frequency identification (RFID) and Global Positioning System (GPS), for construction and facility operations. However, the operations were different for FM, which in theory features incremental changes over a relatively long period of time in contrast with construction's moderately short lifespan. Wong et al. (2018) conducted one of the most comprehensive reviews on digital technologies, e.g., BIM (Building Information Modeling) and IoTs (Internet of Things), in FM research. Insightful though these studies were, the adoption of PSTs for FM applications has yet to be satisfactorily reviewed or discussed for the capture of data, the foundation of any smart FM applications and services. Moreover, a guidance for facility managers to choose appropriate PSTs to capture desired data for facility upgrade and smarter services is still missing.

This study seeks to conduct a critical review of PSTs for FM in order to understand the status quo, provide guidance for stakeholders, and point out the challenges ahead for researchers. It should be noted that the review here only focuses on data sensing technologies rather than other technologies which may also be applied to FM. More importantly, it aims to yield a formalization of engineering knowledge to support future studies and applications. The paper is organized as follows. Section 2 elaborates on the research methods and general statistical analysis. Sections 3 provides brief descriptions and comparisons of the four types of PSTs, i.e., Auto-ID, sensor, photogrammetry/videogrammetry, and laser scanning. Section 4 analyzes data extracted from the collected literature by mapping the PSTs and FM applications. Challenges in implementing PSTs for FM in actual practices are summarized in Section 5. Section 6 concludes this study.

2 Research methods

This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), a standard methodology for systematic review, to collect the literature data (Moher et al., 2009). First, various FM applications are grouped into eight categories based on authors' experience and relevant studies, e.g., Wong et al., 2018. Category A1 refers to conservation of historical buildings and maintenance of facilities; A2 investigates the analysis and management of facilities' energy consumption; A3, the health and safety of users and security of facilities; A4, the quality and ambient comfort of indoor environment, e.g., air quality; A5, the assessment of infrastructures like pavements, highways, bridges, and property assets like furniture; A6, the access and visualization of facilities' information through 2D or 3D models; A7, the utilization of interior space; and A8, the monitoring of structural health. The scope of PSTs in this review include sensors, laser scanning, photogrammetry and videogrammetry, and Auto-ID, as they are the most representative PSTs for FM (Fathi et al., 2015; Wong et al., 2018).

A systematic literature search was then conducted on 6 August 2018 using Elsevier Scopus, one of the biggest and most comprehensive research publication databases with access to over 12,000 journals that cover the majority of high-profile scientific publications (Falagas et al., 2008). The literature search used titles and keywords as matching conditions in order to focus on the exact research topics. Only journal articles were considered as they tend to be more original, mature, and precise as compared to other types of literature (Jesson et al., 2011). Each search query consisted of one type of PST, i.e., Auto-ID, sensor, photogrammetry and videogrammetry, or laser scanning, and keywords closely related to FM (Wong et al., 2018). For example, the query for searching literature that used laser scanning for FM is _(TITLE (("laser scan*") AND ("facilit* manag*" OR "building service*" OR "HVAC" OR "maintenance" OR "post-occupancy" OR "refurbish*" OR "building assess*" OR "building energy" OR "built infrastructure")) OR KEY (("laser scan*") AND ("facilit* manag*" OR "building service*" OR "HVAC" OR "maintenance" OR "post-occupancy" OR "refurbish*" OR_ *"building assess*" OR "building energy" OR "built infrastructure")) AND (LIMIT-TO (DOCTYPE , "ar"))*, where " * " denoted a fuzzy search. In addition, the date range of the search was set to before 2018 and the language restricted to English.

The search initially returned 639 total hits. The authors then screened the abstracts of all the returned papers to ensure their applications fit within the eight categories. After screening, 204 articles were selected for further analysis. Table 1 shows the distribution of these articles according to their source journals and publication years. Chronologically, the overall publication number notably climbed, despite some fluctuation in between, before peaking in 2016 with thirty-two articles. Vertically, the 204 articles came from ninety-two journals. The top five journals were *Automation in Construction*, *Advanced Engineering Informatics*, *Building and Environment*, *Energy and Buildings*, and *Facilities*. Nineteen journals featured between two to ten such articles. Grouped into "Others" are the remaining journals, which published only one relevant article each after screening.

Afterward, the authors thoroughly read each of the 204 articles to extract information concerning the adopted PST(s) and target FM application(s). The results are summarized in Table 2. The footer row in Table 2 indicates that Auto-ID and laser scanning are less utilized and somewhat equally so, while sensors and photogrammetry/videogrammetry prove relatively more popular. However, no PST appears to dominate, i.e., no one technique meets all the requirements in any FM category. Auto-ID was especially popular for "infrastructure and property asset management" (13) and the only mentioned option for space management. Sensors are more adopted in "energy modeling and management" (39). Photogrammetry/videogrammetry mostly pertains to "health, safety and security" (20), while laser scanning is largely used in "structural health monitoring" (12). The last column in Table 2 shows the numbers of applications in the categories. It should be noted that the total number of applications may not be equal to the sum of all four PSTs, because one application may involve two or more PSTs. In addition, the total number of the application in the last column is slightly greater than 204, as two or more applications sometimes occur in a single article. More than one-fourth of the research (54) goes after energy modeling and management. Information access and visualization (40) comes second followed by infrastructure and property asset management (34). Among all the applications, space management (3) receives the least attention. The reason why energy modelling and management receives most attention can be twofold: on the one hand energy related study is more direct to benefit the owners/users; on the other hand, it is easier to collect energy-related data with existing devices and PSTs.

Table 1 Chronological distribution of the selected articles

Journal	pre-2004	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Automation in Construction							1		1	4	2	4	4	3	2	21
Advanced Engineering Informatics					1			2	3		3		3	2		14
Building and Environment			1			1					3	1		2	5	13
Energy and Buildings								1			1	1	4	2	2	11
Facilities	3				1		2					1	1	1	2	11
Journal of Computing in Civil Engineering					1		1			1	1	1	2	3	1	11
Journal of Performance of Constructed Facilities	1											1	2	2	4	10
Sensors							1		1			1	1	1		5
Computer-Aided Civil and Infrastructure Engineering					1						1	2				4
Construction and Building Materials							1							1	1	3
Earthquake Spectra				1										1	1	3
IEEE Transactions on Geoscience and Remote Sensing								2					1			3
Journal of Facility Management					1	1	1									3
Remote Sensing									1				1	1		3
Advances in Engineering Software		1		1												2
Disaster Advances										1	1					2
Electronic Journal of Structural Engineering							1	1								2
IEEE Sensors Journal							1								1	2
International Journal of Distributed Sensor Networks											1				1	2
International Journal of Remote Sensing					1						1					2
Journal of Building Performance Simulation									2							2
Journal of Information Technology in Construction				1			1									2
Journal of Infrastructure Systems						1								1		2
Structure and Infrastructure Engineering									1					1		2
Tsinghua Science and Technology						2										2
Others	0	0	1	2	2	1	4	2	3	4	9	10	11	11	7	67
Total	**4**	**1**	**2**	**5**	**8**	**6**	**14**	**8**	**12**	**10**	**23**	**22**	**30**	**32**	**27**	**204**

Table 2 Mapping PSTs and FM applications

Applications \ PSTs	Auto-ID	Sensor	Photo-/Video-grammetry	Laser scanning	Total *
A1 Conservation and maintenance	7	5	3	6	**18**
A2 Energy modeling and management	2	39	11	6	**54**
A3 Health, safety and security	1	10	20	1	**32**
A4 Indoor environment management	-	13	-	1	**14**
A5 Infrastructure and property asset management	13	14	12	1	**34**
A6 Information access and visualization	10	7	15	11	**40**
A7 Space management	3	-	-	-	**3**
A8 Structural health monitoring	1	3	10	12	**24**
Total	**34**	**83**	**63**	**36**	

*: Inequality due to possibly multiple PSTs in one application

3 Pervasive sensing technologies

3.1 Auto-ID

Auto-ID describes a group of data identification technologies, including but not limited to RFID, barcode, and QR code. Auto-ID generally has three parts, i.e., tag, reader, and backend systems (Lu et al., 2011). The tag stores a unique identification number and other relevant data concerning its attached objects. The reader can read the tag and collect data from multiple signals. Back systems consist of a database for data storage and a communication system for data exchange. Among the reviewed literature, twenty-nine papers adopted RFID and four adopted barcode. RFID allows non-optical proximity communication, higher capacity, better security, long-distance reading, multiple readings at one time, durability and usability in harsh conditions (Xue et al., 2018), which help explain RFID’s dominant use.

3.2 Sensor

A sensor is a physical device, which receives an external signal, transforms that signal into an analog or digital voltage, and then sends the voltage to electronic processors (Maser, 1988). There are various types of sensors in line with the signals they receive. The signal, to which a sensor is sensitive, can come from light, motion, temperature, humidity, moisture, sound, chemicals, as well as magnetic and electrical fields. Sensors can be wired or wireless. The latter is increasingly adopted due to its flexibility and convenience. A group of wireless sensors can form into networks, i.e., wireless sensor networks (WSNs), to detect multiple signals in complex conditions. WSNs have been widely employed in buildings, utilities, transportation systems to enable in-time collection of sensory data, fundamental to developing a smart environment for FM.

3.3 Photogrammetry/videogrammetry

Photogrammetry and videogrammetry share the same working mechanism, obtaining reliable measurements of target objects via images and video clips respectively (Klein et al., 2012). The fundamental mechanism of photogrammetry is Collinearity Equations that effectively and analytically transforms the image coordinate system (x, y) in the camera into an object coordinate system (x, y, and z) in the global space (Dai and Lu, 2010).

Based on interior orientation, i.e., the principle point and principle distance of the camera in the image coordinate system, and exterior orientation, i.e., the location coordinates and Euler orientation angles of the camera in the global space, the coordinates of a point in the image coordinate system and in the object coordinate system in the global space can be determined (Dai and Lu, 2010). Embedded with scale and location information, photogrammetry/videogrammetry offers a non-invasive and cost-effective means of reconstructing complex 3D scenarios for FM (Rodriguez-Gonzalvez et al., 2014).

3.4 Laser scanning

A laser scanning system generally comprises a laser ranging unit, an opto-mechanical scanner, a GPS receiver, and an inertial measurement unit (IMU). The operating principle of laser scanning is based on the reflection of laser pulses on the surface of objects (Yang et al., 2014). There are three major types of laser scanner, namely, airborne laser scanner (ALS), terrestrial laser scanner (TLS), and mobile laser scanner (MLS). They capture large surface areas of earth, local fine levels of structures, and mobile mapping respectively. The laser scanner can generate computable point cloud data, which is widely used in applications measuring 3D surfaces and reconstructing 3D models.

3.5 Comparison of the four pervasive sensing technologies

Table 3 shows the comparison of characteristics of the four PSTs. Auto-ID, as its name suggests, provides automatic identification of target objects. The identification contains the name, location, and several other entities preserved. It is easy and relatively cheap to use in object tracking. With a contactless scan of the tag or code, rapid information access and feedback is achieved. However, when encountering disturbance and damage, Auto-ID can prove vulnerable and undependable, especially for barcodes and QR codes. Furthermore, their stored information is easy to access and thus susceptible to changes made by unauthorized parties, e.g., information can be rewritten for multiple read-write RFID tags, causing reliability and privacy difficulties. Sensor is generally unique to one type of signal, but a network of sensors can collect a series of indicators from complex scenarios such as the various and dispersed environmental conditions and activity data in a shopping mall. However, given the relatively high price of a single sensor today, the customization of a WSN can cost a substantial amount of money. Photogrammetry/videogrammetry and laser scanning share a similar function, the remote sensing of objects' shape. They can both be applied to 3D model reconstruction. Compared to photogrammetry/videogrammetry, laser scanning generally enjoys higher accuracy and fidelity, as it directly acquires a larger number of point clouds, but requires more time for data processing and its associated equipment is far more expensive.

Table 3 Comparison between the four PSTs (Piramuthu, 2008; Prasad, 2015)

PST	FM-related functions	Strengths	Weaknesses
Auto-ID	Detection; Identification; Tracking	Easy to use; Cheap; Fast; Wireless; Timely feedback	Vulnerability; Reliability; Privacy
Sensor	Sensing measured properties; Supporting IoT	Small in size; Feasible for complex system	Cost; Customization
Photogrammetry/ videogrammetry	Position recovery; Measurement; 3D model reconstruction; Quality control	Cheap; High positional accessibility	Indirect data acquisition

Laser scanning	Material processing; Measurement; 3D model reconstruction; Quality control	Direct data acquisition; Accuracy; Fidelity	Cost; Low positional accessibility; Time consuming

4 Pervasive sensing technologies for FM applications

Table 4 highlights typical cases of FM applications reported in the reviewed papers. Notably, while some cases rely on different PSTs for separate functions, there are cases demonstrating the deployment of an integration of PSTs. How these PSTs are selected and used to support these FM applications and cases will be further elaborated and discussed in the following subsections.

4.1 Conservation and maintenance

Conservation concerns the preservation of historical buildings or facilities of special cultural or heritage value. The purpose of maintenance is to fix functionally or structurally damaged facilities or equipment. These objects require careful treatment and repair. PSTs can provide help by generating a digital model, monitoring performance, documentation, and so on. In the reviewed literature, a number of studies looked at detecting the state of conservation pertaining to heritage buildings with photogrammetry (e.g., Gonçalves et al., 2009) or laser scanning (e.g., Quagliarini et al., 2017). These two remote sensing technologies can capture the shape of the historical buildings and facilities, generate a 3D model, and report conditions. In some conservation cases, laser scanning and photogrammetry are preferred when identifying the materials (Fortes et al., 2007) and evaluating the performance of critical components (Gul et al., 2013) are necessary, but direct contact and sampling are restricted. Sensors are preferred for awareness of the situation. For instance, the WSN was employed for ambient and pest monitoring of wooden masterpieces and structures in heritage buildings (Capella et al., 2011), phasor measurement sensors were utilized to enhance real-time situation awareness of smart grids maintenance for large geographical area measurement system (Ghosh et al., 2017). RFID can also support conservation and maintenance by storing maintenance records in a database

Table 4 A summary table of PSTs for FM application cases

Applications	Objects	Cases	PST	Reference
A1 Conservation and maintenance	Heritage/historical buildings or sites, facilities or equipment need maintenance	State of conservation	Laser scanning	Quagliarini et al., 2017
			Photogrammetry	Gonçalves et al., 2009
		Chemical characteristics of materials	Laser scanning	Fortes et al., 2007
		Performance of critical components	Photogrammetry	Gul et al., 2013
		Detection of pests	Sensors	Capella et al., 2011
		Situation awareness	Sensors	Ghosh et al., 2017
		Usage and maintenance data/record	RFID	Ko et al., 2013
		Data transfer between workers and system	RFID	Ergen et al., 2007
		Indoor localization	RFID, WSN, IMU	Taneja et al., 2011
A2 Energy modeling and management	Buildings	Post-occupancy evaluation	Sensors	Azar and Menassa, 2016
		Real-time occupancy	Sensors	Pedersen et al., 2017
			Sensors, image	Petersen et al., 2016
			Passive RFID and IR sensor	Manzoor et al., 2012
		Occupant behavior pattern detection	Sensors	Dong and Lam, 2011
		Geometry modelling	Photogrammetry	Cao et al., 2017
		3D spatio-thermal model	Photogrammetry	Ham and Golparvar-Fard, 2013
			Laser scanning	Demisse et al., 2015
		Energy consumption	Sensors	Ploennigs et al., 2011
		Building monitoring	WSN	Wang et al. 2016
		Device control	WSN	Gao et al., 2013
		Cooling effect	Sensors, laser scanning	Yin et al., 2017
		Solar potential analysis	Laser scanning	Jochem et al., 2011
A3 Health, safety and security	Buildings, urban facilities	Post-disaster damage assessment	Photogrammetry, laser scanning	Zhou et al., 2016
		Disaster prevention	RFID	Aziz et al., 2009
			Sensor network	Cheng et al., 2017
		Health performance of buildings	Sensors	Tolman and Parkkila, 2009

			Photogrammetry	Wu et al., 2014
		Air protection	Sensor network	Caron et al., 2016
A4 Indoor environment management	Building	Thermal comfort	WSN	Marzouk and Abdelaty, 2014
		Visual comfort	Sensors	Shen et al., 2014
		Hygiene	Sensor	Jones et al., 2016
A5 Infrastructure and property asset management	Bridge, road, highway, parking facility, pipelines, airport, equipment	Localization and tracking	RFID	Motamedi et al., 2013
			Wireless sensors	Gikas et al., 2016
		Proactive monitoring and inspection	RFID	Kim et al., 2015
			Sensor	Kwon et al., 2014
		Performance assessment	Laser scanning	González-Jorge et al., 2016
			Photogrammetry	Gul et al., 2013
			Sensors	Ryu et al., 2017
		Effective management	Sensors	Aziz et al., 2017
A6 Information access and visualization	Infrastructure, buildings, structures, components, environment	Information storage and access	RFID	Motamedi et al., 2016
			QR code	Lavikka, 2017
		Information visualization	Photogrammetry	Fathi et al., 2015
			Laser scanning	Jung et al., 2014
			Videogrammetry	Brilakis et al., 2010
A7 Space management	Indoor space	Space usage	RFID	Lindkvist and Elmualim, 2009
A8 Structural health monitoring	Bridges, tunnels, (high-rise) buildings, beams	Structural condition assessment	RFID	Zhang and Bai, 2015
			Laser scanning	Riveiro et al., 2016
			Photogrammetry	Koch et al., 2014
		Structural faults detection	Laser scanning	Cabaleiro et al., 2017
			Photogrammetry	Liu et al., 2014
			WSN	Mascareñas et al., 2009

(Ko et al., 2013) and transferring the stored records between maintenance workers and a web-based FM system (Ergen et al., 2007). Although different PSTs have overcome the constraints of data availability, the accuracy of PST-enabled conservation assessments still needs improvement, possibly through the integration of different types of data.

4.2 Energy modeling and management

The target of energy modeling and management in FM is mostly at the building-level. Accurate measurement of the built environment and its energy consumption is the premise (Sait, 2013). The former relies on the precise assembly of 3D model, reconstructed from images or point cloud data (Demisse et al., 2015; Cao et al., 2017), while the latter requires accurate utility meters or sensors (Ploennigs et al., 2011).

To optimize energy management, unnecessary energy consumption must be eliminated. It is believed that appliances running while a facility is unoccupied constitutes a chief cause of energy waste (Masoso and Grobler, 2010), thus a plethora of research, i.e., one-third of the reviewed energy-related studies, starts from detecting occupancy. The most commonly used sensor for occupancy detection is the passive infrared (PIR) sensor, which captures occupant noise and motion. Other types of sensors detect occupancy by measuring the concentration of CO_2, CO, and PM2.5, temperature, and relative humidity. Occupancy information not only helps control heating, ventilation, and air conditioning (HVAC) and lighting systems for energy efficiency (Gao et al., 2013), but also enhances wellbeing in the indoor environment (Ploennigs et al., 2011; Marzouk and Abdelaty, 2014). However, current occupancy detection methods via sensors can only fully detect presence (Zikos et al., 2016) and duration (Dong and Lam, 2011). They remain limited in providing comprehensive occupancy information including location, activity, identity, and track (Labeodan et al., 2015).

Apart from the use of different sensors, some studies have explored the applications of RFID to control lighting (Manzoor, et al., 2012). Additionally, by enabling the assessment of energy performance, 3D spatio-thermal models generated by thermographic images and point clouds have proved popular in energy modeling and simulation (Ham and Golparvar-Fard, 2013; Demisse et al., 2015). Laser scanning was also used to assess solar potential based on roof plane detection (Jochem et al., 2009) and vertical walls extraction (Jochem et al., 2011), as well as cooling effect of direct green façade (Yin et al., 2017). Further studies are expected to fuse the data obtained from both indoor and outdoor environments in order to achieve more comprehensive energy modeling and management.

4.3 Health, safety and security

Several PSTs can support health, safety and security in FM by preventing disaster, evaluating disaster damage, and assessing the health performance of infrastructure and buildings. To prevent disaster damage, Aziz et al. (2009) developed an emergency response and recovery management system that used RFID to record the preliminary damage assessment of buildings. Similarly, Cheng et al. (2017) invented a smart monitoring system to prevent fire. Their system used WSN to perceive a building's indoor environment information and occupants' locations. The collected data were integrated and visualized into a BIM model. In addition, photogrammetry is widely employed in the post-damage assessment of buildings and infrastructure, and has proved effective at estimating damage after disasters (Zhou et al., 2016). To ensure health, safety and security of the building and its occupants, monitoring and evaluating the health status of buildings is inevitable. Tolman and Parkkila (2009) adopted sensors to collect humidity and temperature data, critical for the healthy performance of buildings, to improve the occupants' wellbeing. Similarly, Caron et al. (2016) evaluated the performance of electronic gas sensors in investigating air pollutant. Meanwhile, Wu et al. (2014) evaluated the seismic vulnerability of buildings for formulating pre-disaster mitigation strategies based on a compendium of high-resolution images of building exteriors. More exploration is expected to develop proactive mechanisms for health, safety and security management.

4.4 Indoor environment management

Personalized thermal comfort, where personal preferences are taken into consideration, is emerging as popular topic in indoor environment management. Personalized thermal comfort requires data related to indoor thermal indicators and personal preference data, which can be suitably obtained by WSN. For example, Marzouk and Abdelaty (2014) employed WSN to measure air temperature and humidity at different spaces within the subway to enhance its thermal comfort for passengers.

A few other studies investigate the visual comfort of an indoor environment based on lighting system controls. Some also applied sensors to gauge the luminosity of indoor spaces and then control the lighting and shading systems accordingly. For instance, in Shen et al. (2014), occupancy sensors and photosensors were adopted to detect occupancy and light level respectively. Apart from thermal and visual comfort, hygiene of the indoor environment is another key aspect to consider. Indoor air quality can greatly impact people's health, especially that of the elderly and infirmed, and sensors have been adopted to measure the indicators of indoor air quality (Sumanasekara and Jayasinghe, 2018). An example can be found in Jones et al. (2016), which developed an aerosol sensor to assess the dust concentration in a building.

However, sensors seem to be the only PST utilized in indoor environment management studies. Given their inability to proactively detect the real-time condition of an environment, using Auto-ID, photogrammetry/videogrammetry, or laser scanning alone is difficult to support the application of indoor environment management (Petersen et al., 2016).

4.5 Infrastructure and property asset management

The target objects of infrastructure and property asset management include bridges, roads, highways, parking facilities, airports, and property equipment. To manage these facilities, proactive monitoring and inspection, performance assessment, and enhancement of management efficiency are three major research topics. Some of the equipment and properties also need tracking. RFID has been widely adopted in automatic equipment localization (Motamedi et al., 2013) and real-time resource localization (Costin and Teizer, 2015). Sensors are deployed in elevators (Kwon et al., 2014), parking facilities (Gikas et al., 2016), joint concrete pavements (Ryu et al., 2017), and highways (Aziz et al., 2017) by abetting the collection of a diverse set of data for various functions. The spatial and geometric data measured from images or videos is also a major source for reconstructing digital models of in-use facilities to assess their performance. Therefore, photogrammetry/videogrammetry has been commonly adopted for inspection of building façades (Paulo et al, 2013), automatic reconstruction of infrastructure (Fathi et al., 2015), and automatic analysis and classification of roof surfaces (López-Fernández et al., 2015). The captured as-built data, in the form of point clouds, has also been used to generate 3D models of exterior facilities (Brilakis et al., 2010) and indoor environments (Nguyen et al., 2016). However, most of the available data processing methods require more or less manual operation or can only be applied to specific FM objects. Therefore, the automatic reconstruction of 3D models for FM remains to be addressed.

4.6 Information access and visualization

Many PSTs have been employed to improve information access and visualization for FM. Among them, Auto-ID was mainly used to help users gain access to FM-related information via tag scanning. Once a tag is scanned, the corresponding information, either recorded in the tag or the backend system, can be presented to the users, who can make informed decision and take action (Motamedi et al., 2016). In addition, photogrammetry/videogrammetry and laser scanning are mainly applied for information visualization. With the availability of image/video and point cloud data, 3D digital model of the facilities can be generated based on manual modeling or different automatic or semi-automatic methods (Brilakis et al., 2010; Fathi et al., 2015). The 3D digital model provides a vivid visualization of the facilities. However, visualization alone will fail to achieve the value of the models if there is no further application referring to the effectiveness and efficiency of FM.

4.7 Space management

Surprisingly, PSTs showed to be less studied in connection with space management, supposedly one of the more important aspects of FM. Only RFID was adopted to assist in space management. Specifically, an RFID tracking system was developed to collect occupancy data from each room of a household in order to study how each space was used (Gillott et al., 2006). Another example is the use of RFID to track customers in stores for retailing space management (Uotila and Skogster, 2007). For flexible workspace management in Lindkvist and Elmualim (2009), active RFID tags were placed into the ID cards of a large financial institution's workers, visitors, and contractors. Readers at value-adding points, e.g., entrances and secure areas, can then pinpoint the direction where individuals are going and identify the areas being used. In this case, with the help of RFID-tracked data, facility managers can manage the space in a more effective manner, hereafter providing spare space for newcomers and supplying services.

4.8 Structural health monitoring

The structural health of bridges, tunnels, (high-rise) buildings, and other load bearing structures is of great significance to FM. Existing research focuses on two major aspects of structure health, i.e., structural condition assessment and structural faults detection. Though they are very similar to one another, the former is more a routine inspection while the latter aims to detect deformation and then repair. A passive wireless breakage-triggered strain sensor was developed for rapid identification of spots surpassing pre-set strain thresholds. When the brittle component of the sensor fractures, an RFID tag turns active and the stored data can be inquired by a reader with antenna (Zhang and Bai, 2015). A WSN has also been explored for rapid structural health monitoring wirelessly in the absence of electrical power and applied to the under-structure of a bridge (Mascareñas et al., 2009). Additionally, photogrammetry/videogrammetry have been used to automate crack detection in structures such as pavements (Radopoulou and Brilakis, 2016) and bridges (Gul et al., 2013). This was generally performed by identifying abnormalities or deteriorations found in images or videos of these property and infrastructure assets or by comparing pictures or videos taken over time. Laser scanning is also suitable for structural health monitoring, including the detection of structural faults and damage (Cabaleiro et al., 2017; Jung and Jeong, 2019) and concrete cracks (Liu et al., 2014). However, fewer studies were found to explore the use of PSTs to achieve automatic, predictive maintenance.

4.9 Implications and guidance

After discussing and analyzing PSTs for different FM applications, some implications and guidance for facility owners, managers, and researchers can be made: conservation and maintenance is mainly targeted at historical buildings, photogrammetry and laser scanning are the two major PSTs commonly adopted; energy modelling and management pays more attention to buildings currently by relying on sensors and in some cases supported by photogrammetry and point clouds; health, safety and security looks at the health of infrastructure and buildings mainly powered by photogrammetry, as well as safety and security for users with sensors; indoor environment management of residential and commercial buildings is fueled by sensors and even WSN; asset management of infrastructure and properties usually adopts Auto-ID to locate assets, and also photogrammetry/videogrammetry recently to reconstruct digital models for infrastructures; photogrammetry/videogrammetry and emerging laser scanning are most utilized for information access and visualization by reconstructing digital models for buildings and infrastructure, meanwhile, Auto-ID and lately sensors are also adopted to access non-geometric information; space management of buildings only takes use of Auto-ID as found in the research cases, though videogrammetry and sensors also have the potential for this purpose, which requires further exploration; structural health monitoring of infrastructure and buildings is mostly driven by sensors, some cases also found laser scanning applicable to detect structural faults, cracks, and damages; Auto-ID is a cheap data source of object location; various sensors and WSN are promising in collecting physical attributes of devices, components, and users; photogrammetry/videogrammetry are relatively cheap and accurate data source of geometric information, while laser scanning provides accurate and computable geometric data; one PST can be utilized to multiple applications for different facilities, an FM application can make use of several PSTs.

5 Challenges

Although Auto-ID, sensors, photogrammetry and videogrammetry, and laser scanning are promising PSTs for FM, their applications encounter many challenges requiring examination from different perspectives. Five major challenges stand out given the analysis of existing research on PST for FM, and deserve future research attention.

A primary challenge is the high investment adopting PSTs for FM demands. Although some PSTs for FM have gradually become more affordable in recent years, higher-performance PSTs generally still come with higher price. For example, 3D laser scanning can capture more accurate geometric data than photogrammetry (Klein et al., 2012), while its device, i.e., the laser scanner, is generally more expensive than the camera and involves additional operational costs (Xiao et al., 2017). Likewise, when choosing RFID or barcode for tracking objects in FM (Lu et al., 2011), the price of RFID readers and RFID tags are considerably higher than that of the actual barcode. Such high investments might not be significant for small-scale FM scenarios, but will become a serious issue when scaled up for real-life FM applications. It is expected that continuous technology advancement can help reduce the cost of PSTs for FM. Explorations to investigate cheaper technologies for higher-performance are also largely needed and welcomed. It should also be noted that the high-invest is just a short-term pay, but the benefits of adopting PSTs for FM, such as helping saving energy and operation and maintenance cost, providing smart and humanized services, easier access to data, and better visualization of information, will come in a long-run. The investments will surely be paid off.

Even PSTs are invested to collect data, the storage of data, which requires safety, reliability and expandability, is still a second tricky challenge. To avoid loss, attack, leakage and ensure safe, updated, cost-effective data storage and maintenance remains an area requires improvement and research. Currently, there are two major data storage strategy, distributed and centric, one put eggs in different baskets while the other put them together. The former is more independent and reliable with the cost from complexity, security, and maintenance difficulty, vice versa for centric data storage. Facility owners and managers can establish the combined data base according to the nature and importance of different data, for general operation and maintenance data updated from time to time, to keep them in distributed database is fine, for the important information and sensitive data, a secured centric database is better. For data maintenance, with enough funding from owners, required data structure from managers, operators should keep the data up-to-date. For data ownership problem, leaving it to contracts can be a feasible method.

The format, structure, unit, update frequency of captured data from different PSTs and even different devices of the same PST kind can be very different, how to integrate data with different protocols remain a third tough challenge. Without a unified data exchange protocol, value of the precious data collected by PSTs cannot be exploited. A typical example is the fusion of sensor data and BIM models: data collected by various types of PSTs ordinarily exists in dissimilar formats, which have not been comprehensively wrapped in open standards like IFC (Industry Foundation Classes) and COBie (Construction Operation Building Information Exchange), where manual input is necessary to supplement the missing information in BIM models. Therefore, When fusing various types of data from different sensing sources (Aziz et al., 2017), stakeholders (Motamedi et al., 2016; Pärn and Edwards, 2017), as well as stages and standards on a single platform, it is essential to first ensure the information interoperability by determining the proper protocols for information exchange (Aziz et al., 2017). Although the standardization of protocol can be extremely troublesome, but without which, considerable information could be lost during the exchange. Research and industry efforts for unified international standard of data interoperability is largely required.

Having data is one thing, how to make use of the golden mine is another. However, the lack of mature data processing methods to support more advanced FM applications is a fourth challenge. Practical applications require professional tools for processing various types of captured data, such as a commercial device for automatically processing point clouds into semantically-rich as-built models (Dimitrov and Golparvar-Fard, 2015). Indoor environment management, thermal comfort, visual comfort, and indoor air quality were studied separately by using different sensors respectively. These different types of indoor environment data could be better visualized if fused with 3D thermal digital model generated by thermal photographs for an integrated simulation. However, existing data processing methods are limited. The lack of a suitable data processing technique, capable of extracting the decision-support information from the raw captured data, may explain why some FM applications, e.g., space management, have not been sufficiently studied in the reviewed literature. For instance, surveillance videos are suitable sources for studying space usage rates, function division rationality, and activity patterns in a large facility like a shopping mall, but the reviewed studies did not offer any operable solutions since extracting space utilization features from videos remains challenging.

It should be emphasized that the collecting and utilizing of data must consider the privacy concern of users, a fifth but also crucial challenge to be concerned. The collection of data from users must be subject to the privacy policies of the facility location. With permission choice and clearly stated terms in contracts, pop-up choice at APPs and websites, portal to notify possible personal data leakage, the separation of personal data and usage preference, privacy issue can be largely mitigated. When necessary, such as the facility owner or manager changes, users will be notified and have the right to delete their personal data. In a word, it should be guaranteed that for any FM application, the collection of data must strictly respect the privacy of users with authorized permission.

6 Conclusion

Efficient and effective facility management (FM) demands real-time, accurate data, and seamless coordination of people, assets, and spaces. New opportunities for FM have become possible as pervasive sensing technologies (PSTs) have advanced. However, it is hard to find appropriate technologies to capture desired data for targeted purpose, especially for facility owners, managers, and some researchers who lacked the expertise or paid scant attention to technologies. This study contributes to the body of knowledge by articulating the status quo and challenges in PSTs for FM applications. Several key conclusions can be drawn from this review: energy modeling and management, together with information access and visualization via PSTs received more attention than others, while space management is the least referred; one PST could facilitate many FM application categories and each PST has its own advantages for specific applications; one single application sometimes can be achieved by different PSTs using different data processing methods. These findings can both act as guidance for practitioners to choose appropriate PST to captured desired data and add a new angle for FM researchers who aims to update the theory for facility information management.

Five challenges associated with PSTs for FM were identified, which include high investment on PSTs, data storage problem, absence of proper data exchange protocols for data interoperability, a lack of mature data processing methods for data utilization, and privacy of users. To address these challenges, future studies are recommended: to develop technologies with higher cost-effectiveness for data sensing, to develop a unified protocol as a standard to ensure compatibility of heterogeneous data for further fusion, to develop automatic data processing algorithms, to develop better way to collect and store different types of data in a secured, reliable, and sustainable way.

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