Structures 28 (2020) 2404–2414

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Emerging RFID technology in structural engineering – A review

Kang-Kang Duan, Shuang-Yin Cao *

School of Civil Engineering, Southeast University, Nanjing 211189, Jiangsu, PR China

ARTICLE INFO

Keywords:
Radio frequency identification (RFID)
Intelligent construction
Structural health monitoring (SHM)
Intelligent management and operation
Internet of things

ABSTRACT

Radio frequency identification (RFID) has become a hot topic in structural engineering. It has an immense potential in promoting the intelligence of construction, changing the traditional way of detection, optimizing the usage of building. Especially during the last ten years, the number of publications focus on this technology has increased dramatically. In this paper, we presented a literature review of articles which focus on the applications of RFID in structural engineering. According to the different effects of RFID in different stages of the lifecycle of a building, we organized these applications into three main categories: intelligent construction, structural health monitoring (SHM) and intelligent management and operation. The basic theory of RFID technology, the tendency and status of current researches were discussed in this paper. Finally, the gap and latent improvement of existing applications in each category were proposed. It is hoped that our analysis of these researches will provide meaningful information on the comprehension of the applications of RFID in structural engineering.

1. Introduction

Radio frequency identification is a form of non-contact data communication technology in which users can send radio-frequency signals to the tag through a reader and receive response information from the tag. It is a ramification of radar technology. Between 1940 and 1950, the theory of RFID technology was initially shaped. However, it took 50 years to become a mainstream application and the rapid development of RFID was due in large part to mandatory RFID tagging decrees by Wal-Mart, the US Defense Department, and European companies such as Metro and Tesco [1]. The main reason for its past long-time dormancy is its cost, but the price of RFID had fallen so much that it could enable a large-scale adoption [2]. Now RFID is one of the most representative technologies in wireless sensors. RFID can make work efficient in many industries and it has been widely used in many fields such as medicine, automation technology, food industry and environmental erosion measurement. In 2000, the worldwide market for RFID system was only worth $900 million, however, it was worth $2.65 billion in 2005. RFID is one of the fastest growing fields (e.g. radio industry, smart phone) in the world [3]. Besides, RFID technology has a tremendous potential in structural engineering (e.g. intelligent construction, SHM and intelligent building management and operation).

In fact, RFID has attracted increasing attention in structural engineering. Essentially, RFID is a kind of information transfer technology. It stores information in a tag, then, civil engineers can receive the information from wireless receiver, and the form of information is various, i.e., any status information of structures (e.g. location, strain, temperature and corrosion status) is available in theory. The first conception of the application of RFID in building construction was proposed in 1995 [4], and the first attempt was done in 2003 [5]. Therefore, studies focus on this topic have been continuing for nearly twenty years, and the real prosperity came after 2010 (Fig. 1). However, it is noted that the number of papers declined in 2015–2020 in both Figs. 1 and 2, a possible reason is the influence of COVID-19 pandemic. Fig. 2 also shows that, comparing with other fields, the application of RFID in structural engineering still has a large potential. Besides, there are many articles focus on the application of RFID in promoting the informatization and automation of structural engineering, but only few literature reviews are completed [6,7]. And these review articles [6,7] only focus on the usage of RFID in building construction, but the fact is that RFID technology brings breakthroughs to all aspects of structural engineering. Especially with the integration of RFID and sensors, the detection of structures is going through an innovation [8].

Therefore, this literature review aims to present a comprehensive introduction to the application of RFID technology in structural engineering. The latest studies in different aspects of structural engineering were reviewed. This review also discussed the gap in current studies and suggested the future development direction of research. The review paper is structured as follows. In the section 2, this paper will introduce the research methodology of this review, the detailed information (e.g.

* Corresponding author.
E-mail addresses: 220191037@seu.edu.cn (K.-K. Duan), 101000873@seu.edu.cn (S.-Y. Cao).

https://doi.org/10.1016/j.istruc.2020.10.036
Received 23 July 2020; Received in revised form 10 October 2020; Accepted 15 October 2020

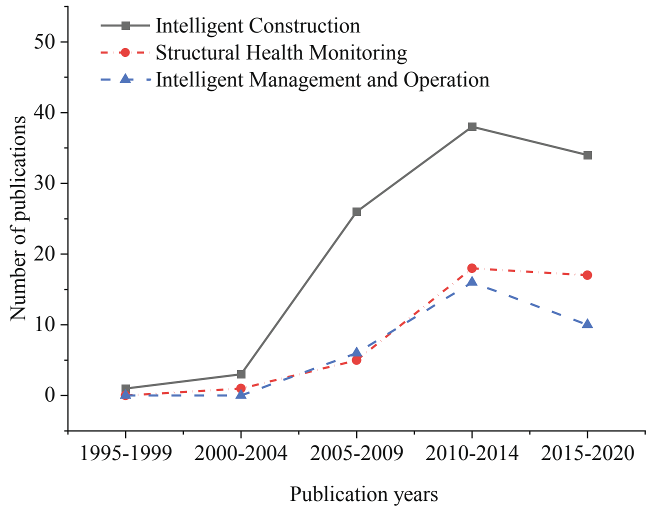

Fig. 1. Research publications on the use of RFID in different aspects of structural engineering, 1995–2020 (left).

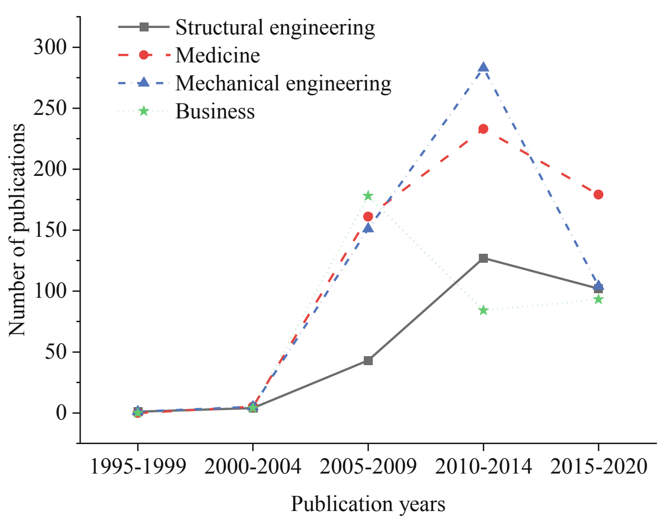

Fig. 2. Research publications on the use of RFID in different subjects, 1995–2020 (right).

words searched, selection criteria for papers etc.) is discussed. Composition and basic theory of RFID system, and a comparison between RFID technology and other similar technologies is drawn in Section 3. Section 4 reviews application researches of RFID in structural engineering. The reviewed articles in Section 4 are classified into three main aspect, and a further classification of content is made according to the uses of RFID in each main aspect. Finally, a discussion on current research gaps and some concise conclusions are drawn in Section 5.

2. Method

In order to make a comprehensive and scientific review on the usage of RFID in structural engineering, content analysis method was adopted to conduct the review process. Content analysis, proposed by Bernard Berelson, is a class of methods that can be applied both in a quantitative and a qualitative way in the analysis of literatures [9]. The retrieve process is conducted as follows.

These research papers [4,5,10–110] we referenced all come from *Web of Science Core Collection*. In order to obtain more results, we retrieved papers with only one topic "RFID". Thus, all papers refer to RFID were selected. Afterwards, we refined the results by web of science categories "Engineering Civil" and "Construction Building Technology". Papers selected after this step include articles, conference papers, etc., and not all the papers are precisely about structural engineering. However, we believe that these papers are enough for just evaluating the approximate tendency and plot Figs. 1 and 2. Then, we further refined the results by document types and retained all "Article" type papers. This is because we believe that journals are the resources that are most commonly used to acquire information and release new findings. Then, we browsed these 161 articles and excluded 58 irrelevant articles (e.g. some articles are about traffic and transportation). Finally, we reviewed the rest of articles. We put no limitation on the publication years, because only a small number of articles are published before 2010. The detailed information of retrieve and selection is shown in Table 1.

This paper finally selected 103 research papers from academic databases *Web of Science* and organized these studies into three research directions according to the different effects of RFID in different stages of the lifecycle of a building. Qualitative and quantitative analyses were performed in this review.

3. RFID technology

Common RFID system includes a tag, a reader and a data management system [8]. Tags are designed to acquire energy from a battery (active tag) or electro-magnetic induction (passive tag), and send encoded signals to the readers. Compared with active tags, passive tags are normally smaller, more inexpensive and more convenient packaging. Readers are used to decode the signals from tags, and data management systems store and manage the information. According to the processes of information transmission, RFID systems can be classified into half duplex (HDX) system, full duplex (FDX) system and sequential (SEQ) system. According to the valid communication scope, RFID technology can be classified into near-field RFID and far-field RFID. This classification also refers to different correspondence theory of RFID system.

3.1. Near-field RFID

The correspondence of near-field RFID system is based on magnetic induction [9]. The reader contains a coil; when the alternating current passes the coil, an alternating magnetic field will be sparked. The alternating magnetic field could result in an alternating voltage within a tag which contains a coil. The alternating voltage could be used to power the tag chip with the help of capacitors. Based on the current across the coil in the tag, the reader could perceive a small increase in current flowing through it. According to this character, engineers use load modulation to realize the correspondence between readers and tags. The process is shown in Fig. 3. Load modulation refers to controlling the make and break of load resistance according to the data to change the impedance of a tag, and the variation of impedance will cause regular changes of voltage in the coil of a reader. Common modulation methods include amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying(PSK).

The correspondence of near-field RFID adopts low and medium frequency signals (125KHz, 13.56 MHz etc.). The scope of correspondence

Table 1
Detailed information of retrieve and selection.

Database	Web of Science Core Collection
Topic for retrieve	RFID
Publication years	1995–2020
Categories for refinement	"Engineering Civil" and "Construction Building Technology"
Document types for refinement	Article
Criteria during the reading	Relevant papers should refer to construction, detection or operations of a building.

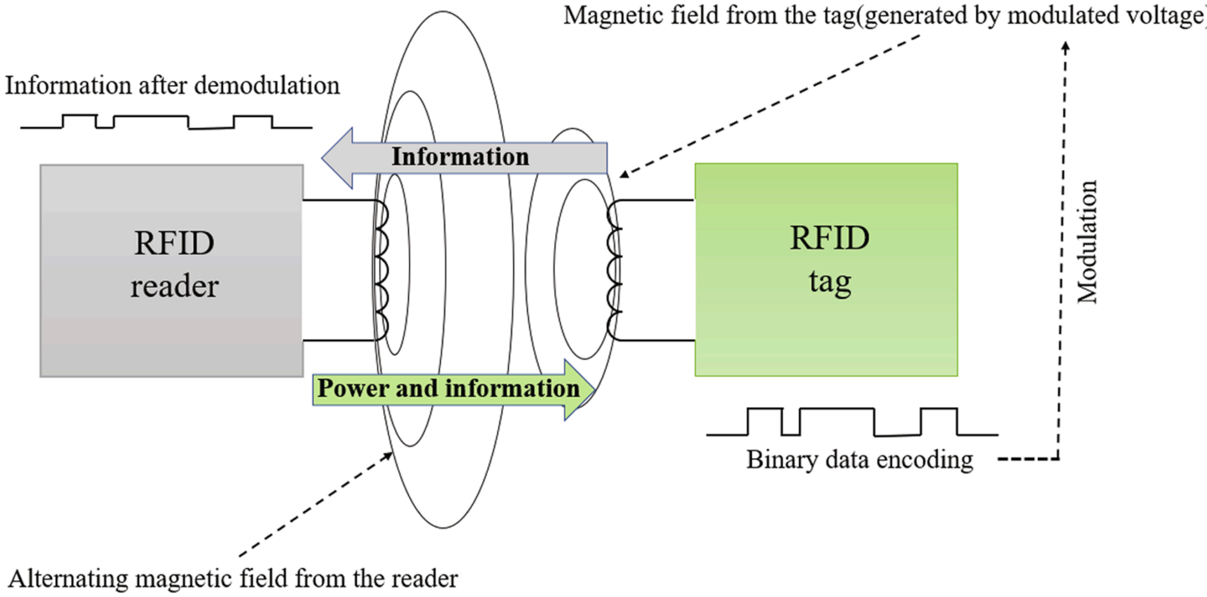

Fig. 3. Mechanism of near-field RFID technology.

could be calculated by $c(2\pi f)^{-1}$, where c is the speed of light and f refers to the frequency. Therefore, when the frequency increases, the valid scope of near-field RFID decreases. Besides, when the distance r between tag and reader increases, the magnetic field drops off at a factor of r^{-3}, i.e. the attenuation of magnetic field limits the valid scope of near-field RFID.

3.2. Far-field RFID

Far-field RFID is based on electromagnetic wave capture. The correspondence between tags and readers is realized by dipole antenna. A reader could send electromagnetic wave with a dipole antenna, and a dipole antenna attached in a tag could capture the wave and form an alternating potential difference in the dipole. Whereupon, with diode and capacitor, the tag could capture the energy from the electromagnetic wave. It is noted that the correspondence distance is outside of the scope of magnetic field generated by readers, so load modulation is no longer suitable here. Instead, far-field RFID uses back scattering for correspondence. The dipole antenna attached in a tag can be designed to absorb fixed frequency electromagnetic wave from the reader. When the antenna's impedance is changed, the tag will scatter electromagnetic wave to the reader. Fig. 4 depicts the mechanism of this pattern. The variety of impedance can carry the information which is stored in tags, reflect the status changes in the component in which the tag is embedded, and be used for determining tags' location.

The correspondence of far-field RFID usually adopts ultra-high (e.g. 860–960 MHz, 2.45 GHz) (UHF) or super-high (e.g. 5.8 GHz) (SHF) frequency signals [8]. If the antenna of the reader uniformly emits electromagnetic waves in all directions at power P. The radiation power density from the tag back to the reader approximates to $P\sigma r^{-4}$, where σ is the radar cross section [111], i.e. if we double the radiation power of tags, we should increase the transmit power 16-fold with other conditions constant. Therefore, the power of tag is an important index in improving the correspondence scope of RFID system. Some companies

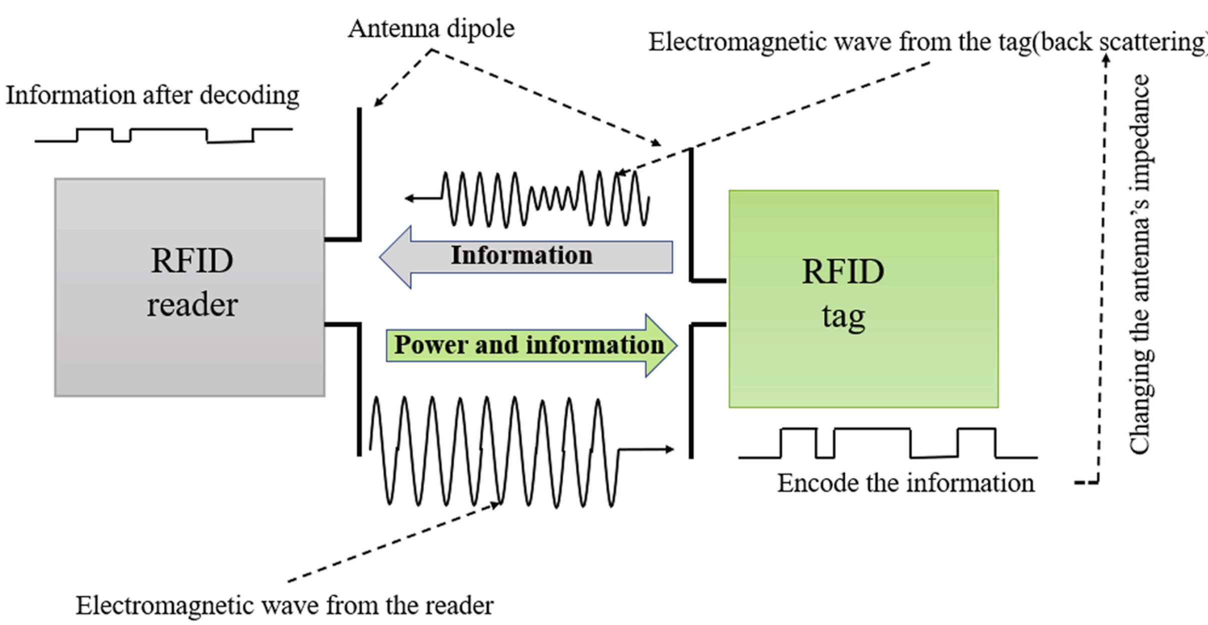

Fig. 4. Mechanism of far-field RFID technology.

declare that their RFID systems' read range can reach more than 10 m.

3.3. Data carrier

According to the data carrier of tags, the RFID systems can be divided into two categories: read-only and read-write. Read-only transponder is low cost. Once the read-only tag comes into the valid scope of the reader, it will send its information to the reader. Generally, the information is fixed in the manufacture of the tag. The structure of read-only tag is very simple, and some tags are even smaller than needle eye. Read-write transponder supports writing and it can load a 64 KB memory [111]. However, it is noted that read-write transponder's writing times is limited, and it is depended on the technology of chip (e.g. for E^2PROM, 1002013500000 times is supported) [112]. Common data recorders include RAM, EPROM, FRAM, E^2PROM, Flash E^2PROM, etc.. For RAM unit, the data stored will vanish if the power supply breaks. For E^2PROM unit, the data can be well saved for 10 years.

3.4. RFID and other technologies

RFID tag has a small size and can work without battery, and RFID system has a low cost and an acceptable read range. Besides, the tag is convenient packaging and corrosion resistant, and it can be used for non-contact structure detection. However, there is no free lunch. For example, passive tag only needs to obtain energy from the reader, however, the energy decrement is large. Therefore, passive tag needs to be ultra-low power (e.g. thanks to Moore's law, now the power of a tag can be <5 μW [113]). Generally, passive tag's communication is weak. Besides, mitigating path loss and multipath effects are two shadows in the applications of RFID system.

There are several approaches such as Zigbee, Bluetooth, etc., can also be used for wireless communication. Fig. 5 shows the tendency of applications of these approaches in structural engineering. RFID is the commonest technology and WLAN is less used. All of applications (RFID, Zigbee, etc..) began during 2000–2004, however, the gap between RFID's applications and other technologies' applications was widen during 2005–2009. Fig. 5 implies that under the present technology level, RFID is the most promising wireless technology in the applications in structural engineering. In order to increase comprehension, we list some features of these wireless technologies in Table 2. It is noted that, compared with other technologies, RFID has the lowest data rate and the least read range, however, if the project requires less on them, RFID will also be a competitive option. Because RFID supports passive tag, and its cost is significantly lower than Zigbee and UWB.

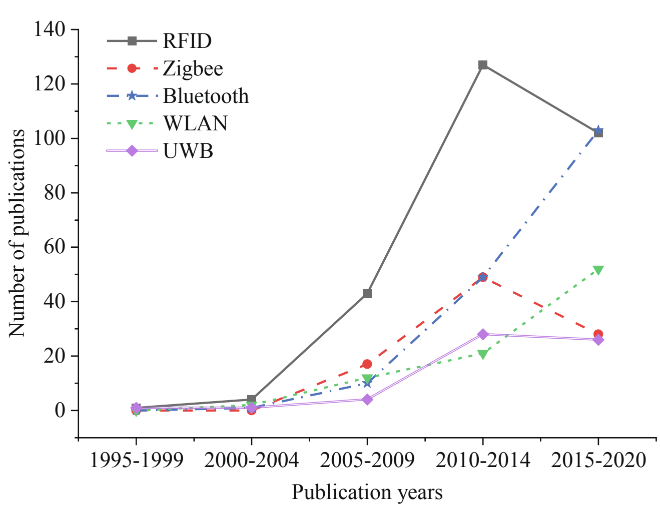

Fig. 5. Research publications on the use of common wireless technologies in structural engineering, 1995–2020.

Table 2
Comparison and features of RFID, Zigbee, Bluetooth, WLAN and UWB commonly used in applications. *LF refers to low frequency; HF refers to high frequency; BLE refers to Bluetooth low energy.

Technology	Transceiver type	Radio band	Data rate	Read range
RFID	Passive or active	LF, HF, UHF and SHF	<100 kbps	<15 m
Zigbee	Active	868 MHz, 915 MHz, 2.4 GHz	<250 kbps	10–100 m
Bluetooth	Active	2.4 GHz	1 Mbps (BLE)	10–100 m
WLAN	Active	2.4 GHz, 5 GHz	<54Mbps	50–100 m
UWB	Active	3.1–10.6 GHz	400–600 Mbps	<60 m

4. Applications of RFID

In order to review these studies better, we classify them into three aspects according to the different effects of RFID in different stages of the lifecycle of a building: intelligent construction, SHM and intelligent management and operation. Intelligent construction focuses on the application of RFID in building process. SHM includes articles with the topic of monitoring or detection. Intelligent management and operation consists papers concentrate on the usage, management and maintaining of a building after completion. Fig. 1 shows that majority of studies started after 2005, and the great majority of the related studies are about intelligent construction, but the researches in SHM increases rapidly. However, there is a limitation on the statistics of intelligent management and operation, because intelligent management and operation class involves electrical engineering, energy and environmental science, biology, mechanical engineering and many papers in this field are outside the scope of the definition structural engineering, so this part is not fully included in the journals of structural engineering. The papers in intelligent management and operation discussed here only consists of papers published in journals of structural engineering.

Beside paying attention to number of papers, the content of studies is also attractive. It is noted that the application of RFID in structural engineering is associated with the development of RFID technology, because different aspect requires different technology. Fig. 6 depicts the referred researches' development in terms of technology. Early researches only concentrated on single RFID technology. Along with the deep development of study, many researchers combined RFID with other technologies such as GPS, GIS, BIM. The results imply that single RFID technology could not meet the complex requirement of a mature management system and the unity of RFID and BIM is a hot research topic these years. Table 3 shows the details of the application of different technologies in the application of RFID in chronological order.

4.1. Intelligent construction

Intelligent construction means applying modern technologies in building projects and making the building process more efficient, wise, safety and saving. Similarly, we can classify these articles [4,5,10–79] into three more sophisticated aspects according to RFID systems' functions in construction: tracing system, safety system and building quality and efficiency control system. Fig. 7 depicts the differences in the number of articles published in the three directions. The study of RFID in the tracing system is the mainstream.

4.1.1. Tracing system

A tracing system can promote the traceability of material, equipment and constructors. Location technology and information storage function is the significant characteristics of it. Fig. 8 shows the pattern of a tracing system. Tag is used to reserve basic information and mark relative position of materials. After receiving signals from the tag, we can calculate

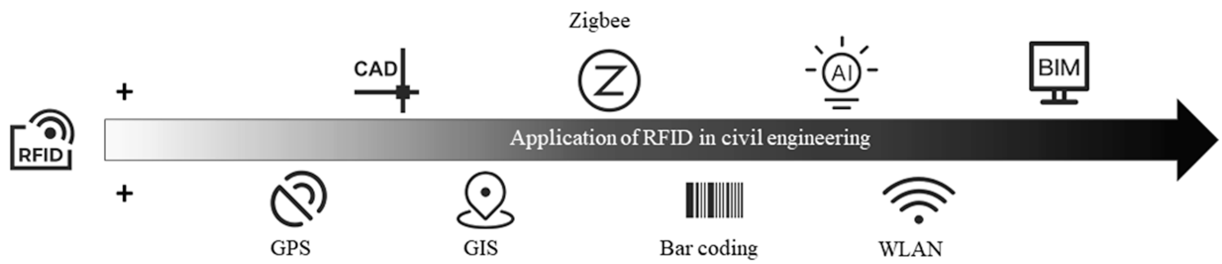

Fig. 6. Tendency of the research of RFID in structural engineering in recent years (in terms of different technologies).

the coordinates of targets according to the values of three readers. This system can also be used for tracing building equipment, construction vehicles or constructors. It just like the way GPS works. We can disintegrate tracing system's framework into three layers: tags (layer1), readers (layer2) and computer (layer3). Generally, tracing system applies far-field RFID and active tags. The majority of studies [4,5,10–64] focus on intelligent construction are about tracing system. Jaselskis et al. [4] discussed the potential applications of RFID in construction industry in 1995. In 2003, Jaselskis et al. [5] researched the applicability of RFID in material procurement process, which can be regarded as the earliest RFID tracing system in architecture region. In this period, studies are about how to build or complete a simple tracing system's framework.

With the further development of the research, there are two main problem in the applications. One is the influence of environment on the information transmission. The obstacles exist between layer 1 and layer 2. Therefore, many researches have been conducted to explore the influence of different obstacles and improve the location algorithm and methods. For example, Goodrum et al. [13] researched the limitation of RFID and found low temperature and stacked substance in the space can influence the reading ability of active tag. Tzeng's [15] study implies a passive tag embedded in the material receives a weak signal and a handheld RFID reader for moving readings can work better. Razavi et al. [26] argued that the precision of the estimated locations can be improved by using active tags as reference tags. Each reference tag can provide a unique offset vector for the ordinary point and the final offset vector can be calculated by sum these products of unique offset vector and range weight. Razavi et al. [41] developed a data fusion method for optimizing location estimation in construction. This method includes a fuzzy inference system and a metafusion algorithm. Fuzzy inference system estimates the reliability of observed results and metafusion algorithm is used to fuse imperfect data according to the reliability of these data. Li et al. [44] adopted offset vector method (OVM) and convergence method (CM) to improve the indoor location accuracy and the result proved that OVM and CM increase the overall accuracy by 5.1 and 2.7% respectively.

Another problem is that only RFID technology could not satisfy the complex requirement of a powerful and multifunctional tracing system. In general, there are two research directions. Some studies combined technologies of similar functions, such as GPS, Bluetooth, with RFID, to make them complement each other's advantages. For example, Song et al. [12] suggested that combine RFID and GPS can reduce cost of tracing system. Torrent et al. [20] adopted GPS to gain the coordinate of readers and used RFID to ascertain the location of construction components. Kim et al. [29] first adopted Zigbee to send information to computer and found this combination was suitable for a wireless communication system in construction site.

Another direction is about the combination of RFID and technologies in different dimensions. The affiliation of different technologies expands the function and improves the performance of system. El-Omari et al. [24] applicated bar coding, RFID 3D laser scanning, photogrammetry, multimedia, and pen-based computers in an automated data acquisition tracing system. A revolutionary progress is the combination of RFID and BIM. Because RFID can create a digital link between the virtual models and the physical components in the construction process to improve the information handling and sharing in construction operation management. Motamedi et al. [48] investigated the usage of RFID and BIM technology for indoor localization of RFID equipped assets during the operation. Ko et al. [50] proposed a cost-effective materials management and tracking system based on a cloud-computing service integrated with RFID for automated tracking with ubiquitous access, which is friendly to small-to-medium businesses. Li et al. [55] applied this combination in prefabricated public housing projects at Hong Kong and achieved a good result. Based on BIM, Motamedi et al. [63] raised a method that tags can be used during the lifecycle by different stakeholders for data storage and handover.

4.1.2. *Safety system*

Safety system is another important application of the RFID technology. It is noted that a safety system often needs the tracing characteristic of RFID, but it also needs a judgement function to determine if it is the time to adopt measures. In general, studies focus on this field is not as many as studies focus on tracing system, but the combination of RFID and other technologies emerged at the beginning. Wu et al. [66] proposed an integrated information management model using a ZigBee-RFID sensor network to promote safety construction. Chae et al. [65] established a support system to prevention of collision accident with heavy equipment. Kelm et al. [68] developed a personal protective equipment detection system. Ding et al. [67] conducted a real-time safety early warning system. RFID was used to detect the dangerous location of constructors in many safety systems, and if constructors enter the danger zone, the system will warn constructors. However, compared with tracing system, there are less studies focus on this aspect. Based on the consideration of requirement of judgement in safety system, RFID technology can make more contribution for constructor if it is associated with computer vision and artificial intelligence.

4.1.3. *Building quality and efficiency control system*

Building quality and efficiency control system is also an attractive application of RFID. The application of RFID in this direction mainly refer to two characteristics: detection and trace. Building quality and efficiency control system needs to detect the status of components in the process of construction and trace the material dispatching in a certain construction process to improve building quality and efficiency. For example, Lee et al. [72] used RFID to provide the crane operator with an enhanced view of the work space, which can improve accuracy and driving efficiency. Because tracing system is discussed in 4.1.1, we ignore papers which mainly use tracing system to improve building quality and efficiency in this part. Kang et al. [73] put an RFID tag integrated with a temperature sensor in concrete to provide information for constructors to make an informed decision for stripping the formworks without having to worry about wiring issues on construction site. Kim et al. [76] developed a real-time pipe tracking system based on RFID and WLAN, which was used to decrease construction errors. Zhuo [78] proposed an intelligent tensioning control and management integrated system and used RFID to identify each beam. Tao et al. [77] adopted RFID technology to identify components "ID" in GHG emission

Table 3
Combination of technologies in the application of RFID (chronological order) *IC refers to intelligent construction; IMO refers to intelligent management and operation.

Refs.	Domain	Technologies	Main content
[17]	IC	RFID, 4D CAD	Logistics and progress control of structural steel works
[80]	SHM	Nanocomposite, RFID	Wireless strain and pH sensors
[16]	IC	RFID, GIS	Information management system
[81]	SHM	RFID, GIS, BBS	Information-technology-based collaboration framework
[98]	IMO	RFID, GPS, NFC	Real-time navigation support and location based information delivery system
[75]	IC	RFID, USN	USN hardware toolkits for hoists
[29]	IC	RFID, ZigBee	Building materials management system
[27]	IC	Wireless sensor, RFID	Search and rescue data access point system
[26]	IC	Infrared, GPS, RFID, REID	Calibrating the location estimates using reference tags
[24]	IC	Bar coding, RFID, etc.	Collecting data from construction sites required for progress measurement
[41]	IC	Data fusion, RFID	Increasing confidence, accuracy and precision of location
[38]	IC	RFID, CCTV	Material delivery monitoring system
[12]	IC	RFID, GPS	Building materials management system
[101]	IMO	RFID, AI, etc.	Improve the efficiency of facility management
[76]	IC	RFID, WLAN	An intelligent management system for piping installation
[69]	IC	RFID, ZigBee	An information management system for struck-by-falling-object accidents
[67]	IC	FBG, RFID	A real-time safety early warning system
[105]	IMO	2D barcode, RFID	A lab equipment and instrument maintenance management system
[104]	IMO	RFID, Sensor	An elevator scheduling system
[45]	IC	RTK GPS, RFID	Improve the accuracy of a locating system
[102]	IMO	Computer vision, RFID	A system to aid the analytical procedures of the study of architectural artifacts
[85]	SHM	RFID, BIM	A technology to enable non-contact scanning of structural deformation
[47]	IC	Machine learning, RFID	A localization system based on RFID which does not need infrastructure
[106]	IMO	FAMOS, RFID, etc.	A solution for the function-space assignment problem
[50]	IC	Cloud computing, RFID	A material tracking system for small-to-medium businesses
[49]	IC	BIM, RFID	Indoor localization of mobile construction resources
[90]	SHM	Machine learning, RFID	Prediction of complex physical phenomena
[53]	IC	BIM, RFID	Real-time visibility and traceability in prefabricated construction
[70]	IC	Ultrasonic, RFID, infrared	An Internet-of-Things-based safety barrier warning system
[55]	IC	RFID, BIM, VR	A platform to provide decision support tools and services to different stakeholders
[78]	IC	RFID, cloud technology, etc.	An intelligent tensioning control and management integrated system
[109]	IMO	Machine learning, RFID	An intelligent HVAC management system
[71]	IC	Infrared, RFID	A non-hard-hat use inspection system
[61]	IC	RFID, BIM	Realize the integration and visualization of prefabricated component information
[92]	SHM	RFID, BIM	Provide a novel approach for corrosion management under insulation
[64]	IC	RFID, BIM, GNSS	A dynamic optimization method for PC component transportation and storage

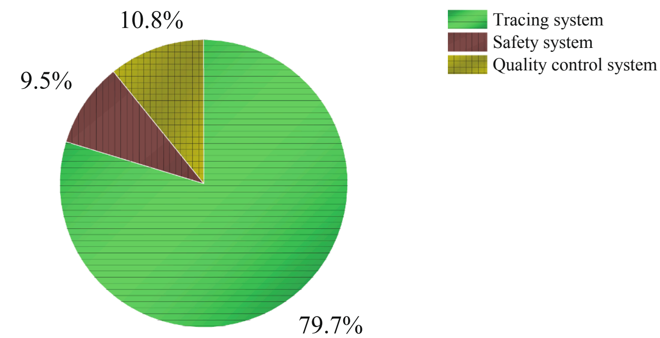

Fig. 7. The number of papers in different directions of intelligent construction.

monitoring system. In generally, among all studies focus on intelligent construction, only few studies focus on this field. But, RFID technology will be an ideal technology to monitor the construction process when the object to be observed is invisible.

4.2. Structural health monitoring

Structural health monitoring (SHM) is a process of identifying and characterizing the structural impairment. SHM become a hot topic in structural engineering recent years. Studies focus on SHM began later, but the number of papers published keep increasing (Fig. 1). In general, there are two forms of the application in SHM. In one situation, RFID as a "ID identifier" of structure and stores essential information of components. Under this circumstance, the application of RFID is only a migration application. This application is still a building information storage system or a tracing system essentially. Another application is the RFID based sensor system for structure detection. This system integrates RFID technology and sensor technology, which involves many subjects such as electronic science, information engineering, computer science, chemistry and civil engineering. The majority of studies [80–93] in this field are focus on the RFID based sensor system. Therefore, this part focuses on the second application.

4.2.1. Working modes of RFID based sensors

According to the position of tags, RFID based sensors can be classified into two classes. The first is to put tags on the surface of components. Under this circumstance, the tags can be used for new structures and existing structures. The second is to embed tags in components. This approach can obtain the real-time status of components. Most of embedded tags are passive tags. However, the valid read range of embedded tags is greatly weakened.

According to the mechanism of detection, common RFID based sensors can be divided into three aspect. The first is to integrate RFID tag and specialized sensor. The chemical sensor is used to inspect the status of target, and the tag is designed to receive the information from the specialized sensor and send signals to the reader. However, limited by the power acquirement of passive system, sensors that require high energy elements, such as metal oxide semiconductor sensors, are not very common [8].

For crack detection of metal, the second approach can be adopted. This kind of RFID based sensor does not need an additional sensor. In fact, the combination of the tag and the metal to be detected forms a sensor. Under this circumstance, the interaction between the crack opening and the signals can be explained as an interference between the tag antenna, and the crack acts as a slot antenna that alters the electromagnetic field.

The third method requires researchers to design the structure of tags, and add environment-sensitive materials so that the activated tags can send signals at different levels according to the external stimulus. According to 3.1 and 3.2, with environment-sensitive material, the

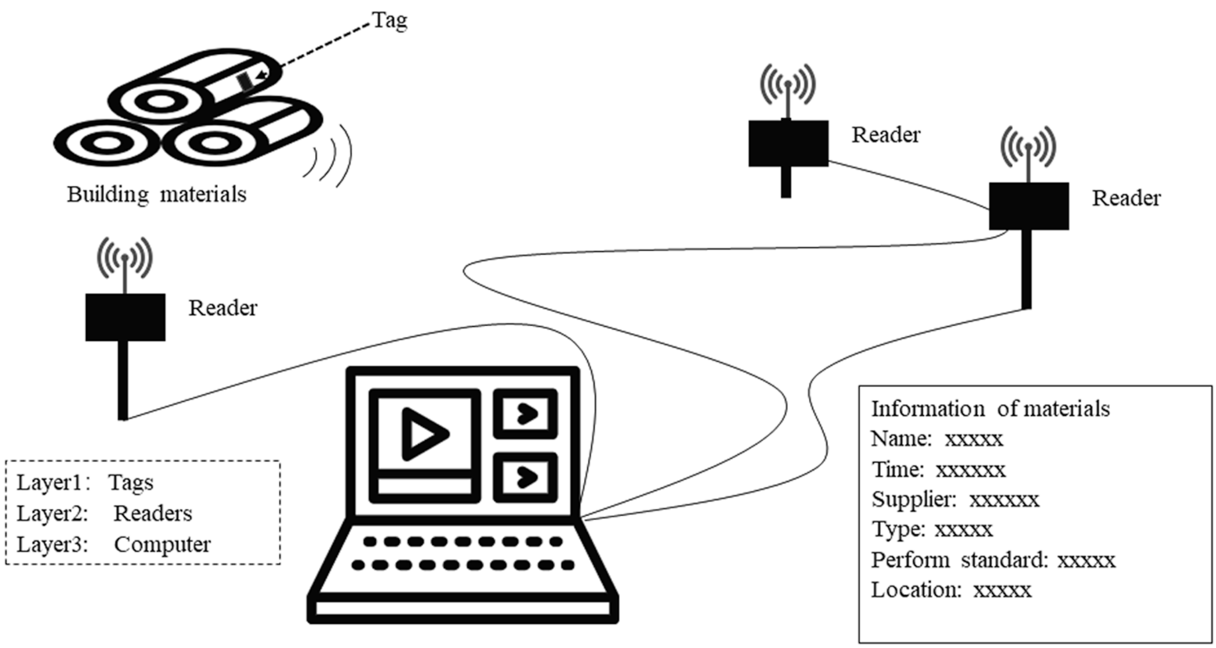

Fig. 8. The application of RFID in construction information management.

impedance of this kind of tag can be changed regularly to encode the data. After receiving the signals, engineers can analyze them and find the abnormality of a component. Therefore, the combination of sensitive material and tags makes the RFID a sensor system. Besides, if no environment-sensitive material is added, the response element is just tag itself. For example, in the damage detection of component, the deformation will affect the antenna and the component simultaneously, so we can detect the abnormality of the structure. Fig. 9 shows the pattern of RFID based sensor system.

4.2.2. Applications

RFID based sensors provide a new solution for the detection of structures. Engineers can acquire the status information (e.g. strain, temperature, pH, etc.) of a component without breaking it, and they even do not need to bury a wire in the component. Battery is not necessary for a passive tag, and tags can have a very small size and a low cost. Researches in this field show a large potential of RFID's application. Loh et al. [80] fabricated a nano-structured multifunctional carbon nanotube-based thin film and films were specifically designed to change electrical properties to strain and pH stimulus. Based on this technology, characteristic frequency and bandwidth changes in tandem with varying strain and pH, respectively. Therefore, this tag can be applied in the neutralized monitoring of concrete. Materer et al. [82] presented an embedded low-cost corrosion sensor based on RFID technology. Pour-

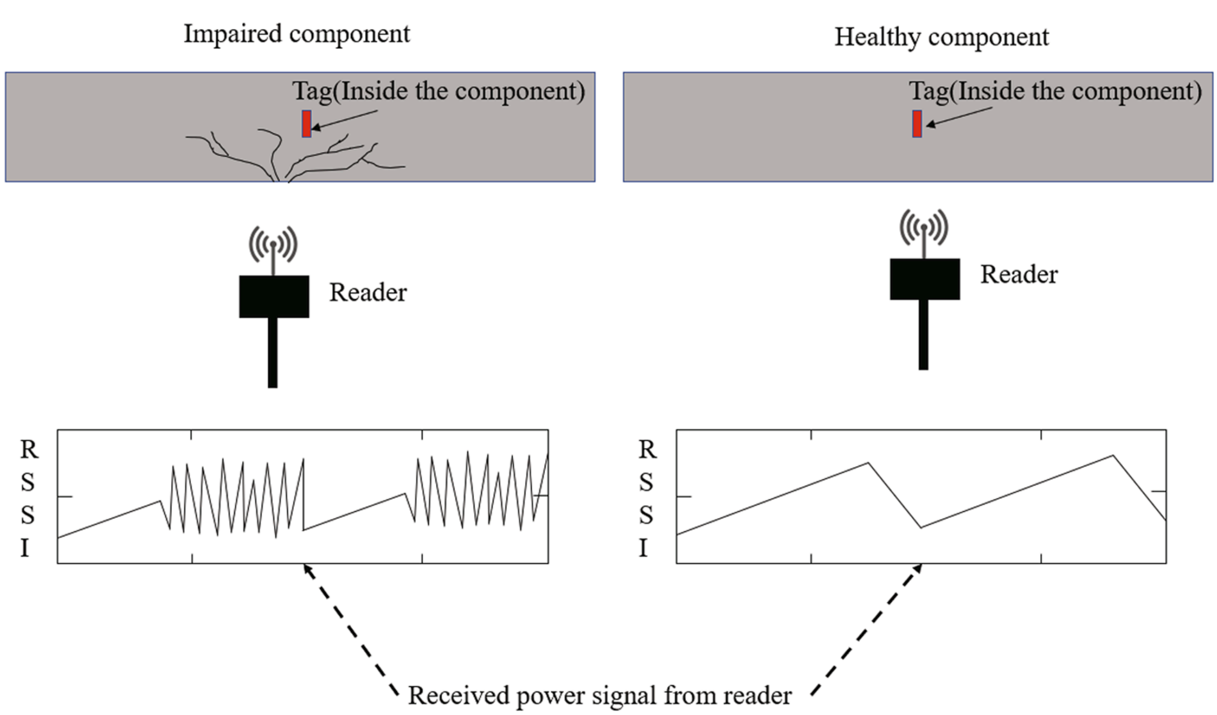

Fig. 9. The application of RFID based sensor in SHM (RSSI means received signal strength indicator).

Ghaz et al. [83] proposed a wireless crack detection sensor. This detection was achieved by a conductive material attached on a component. This conductive material is linked with a tag, when component was strained, the conductive material at the surface is stretched, and its electrical resistance increases. Therefore, we can identify the damage from signals sent by the tag. Ceylan et al. [84] discussed the use of a wireless concrete monitoring system based on RFID and off-the-shelf MEMS-based temperature and humidity sensors. Zhang et al. [85] proposed a non-contact scanning of structural deformation. This system integrated BIM and RFID to realize the visualization. Khalifeh et al. [87] presented two RF corrosion-sensitive resonators that can be easily integrated in RFID device. One is sensitive to a loss of metal and another is sensitive to the corrosion potential of metals. The read distance was also tested, and the results show that these sensors could be used for short distance read (<2 m, in air). Shishir et al. [89] proposed a frequency-selective surface (FSS) array sensor for detecting damage location in laboratory environment. The FSS based wireless sensor adopted was made on a flexible substrate and it could be easily attached to arbitrary component. Chen et al. [91] first used RFID based sensor to monitor the temperature variation in concrete. The results show that the maximum reader-tag communication distance is 7 m at 915 MHz. Tsai et al. [92] utilized temperature and humidity to evaluate the corrosion depth of pipelines. They obtained the environmental data through RFID based sensors, realized visualization in BIM models. The results show that the maximum read range of used passive tags is more than 8 m, and this method can make inspection more efficient. Martínez-Castro et al. [93] used RFID based sensors to characterize gradual metallic plates' crack damage. The results show that single-sensor configurations can detect a crack opening as narrow as 0.0650 mm with the distance between tags and readers reaches 0.91 m . More details of these researches are shown in Table 4. Most applications adopted passive tags, and items which can be detected in current applications include common parameters of structures such as strain, corrosion, crack and temperature.

4.2.3. Communication issues

However, it is noted that researches focus on SHM still have much work to do. The characterization of backscattered signals from tags is fundamental for feature extraction with respect to influences from defects and measurement conditions [114]. A severe problem is that tags used in this situation are usually passive tag and some tags are need to be embodied in the components, so the strength of signals are sensitive to the material. Especially the influence of concrete or metal, metal can severely disturb the signals and concrete can seriously weaken the signal propagation distance. This problem has been superficially discussed in 4.1.1. However, there are large differences between the influence of environment on tracing system and component detection. In generally, tracing system adopts active tags but detection need passive tags, and passive tags have stringent power limitations. Therefore, mitigating path loss and multipath effects are more needed for the passive tags.

Table 4
Detail of papers focus on SHM.

	Sensor	Tag type	Work mode	Time	Refs.
1	pH	Passive	–	2008	[80]
2	Temperature and humidity	Passive	Embedded	2014	[84]
3	Crack	Passive	Surface	2014	[83]
4	Corrosion	Passive	Embedded	2014	[82]
5	Strain	Passive	Surface	2015	[85]
6	Temperature and vibration	Passive	Surface	2016	[88]
7	Corrosion	Passive	Surface	2016	[87]
8	Strain and crack	Passive	Surface	2016	[86]
9	Damage location	Passive	Surface	2017	[89]
10	Scour depth	–	–	2017	[90]
11	Temperature	Passive	Embedded	2018	[91]
12	Crack	Passive	Surface	2019	[93]
13	Temperature and humidity	Passive	Surface	2019	[92]

Moreover, for power-based measurements, we need to exchange the mismatch of the antenna impedance and efficiency for the sensing capability [115]. Before we analyzing the damage of structure, we need to extract features. It is important to mitigate multiple influences of interferences such as: multiple scattering and component surface geometry. Besides, these tags embodied in the structure will force and deform with components, and this stress/tension also has an effect on tags.

4.3. Intelligent management and operation

Intelligent management and operation refers to the work after completion. This field includes the operation and maintenance of a building. According to the difference between objects on which they focus, these articles [94–110] could be organized into two aspects: human behavior and building and equipment status.

4.3.1. Human behavior

The majority of papers focus on intelligent management and operation are about the action of human. In fact, many articles we retrieve from building and construction technology journals out of the scope of traditional structural engineering, and more articles similar with these papers out of scope are published in journals of electronic science and communication engineering. Therefore, the result of retrieve of this aspect is not as sufficient as other aspects. However, the topic of these papers we choose are closer to structural engineering than papers published in journals of other fields, and we also can develop an integrated frame with limited articles.

When a building is completed, an important topic is the occupant's scientific use of this building. Under this situation, RFID technology is used to identify the location of residents. Studying residents' behavior can provide important basis for many other researches. Fig. 10 depicts the pattern of application of RFID in this aspect. Tags are distributed within the building; they perceive the action of people and transfer this into different magnitude and phase of the back-scattering wave. We can attach the tag to the body or only use a non-contact tag. We use the non-contact tags in Fig. 10, and this kind of tag has a fixed location, for example, in Fig. 10, tags are put on the wall, and thus the change of back-scattered wave is due to the residents' behavior in a static environment. When readers receive signals, they will send information to the control system and this system will analyze the information and capture the movement of body. Based on the analysis of residents' behavior, the system can scientifically schedule the devices. For example, some papers [99,104,109] used this behavior research in construction energy conservation. Kwon et al. [104] proposed an efficient elevator scheduling system. According to the information of occupant's movements, this system can generate a reservation call for candidate passengers and control the moving direction and the moving time of elevator cars efficiently. Li et al. [99] presented an RFID based occupancy detection system. This system is designed to support demand-driven heating, ventilation, and air conditioning operations according to the detection of occupants in multiple spaces simultaneously. Besides, based on the analysis of occupants' behavior, researchers [102,103,106] can optimize the space assignment of building.

4.3.2. Building and equipment status

RFID technology is an ideal instrument to record the status of the equipment in the building or the building itself. For example, tags can be used to record the original information and update some maintenance information. Therefore, RFID technology can service the upkeep of construction and equipment in a building. Ko et al. [101] suggested that combine RFID technology with internet technology and artificial intelligence will make facility maintenance more efficiency. Dziadak et al. [97] adopted RFID technology to protect buried infrastructure, and RFID was used to identify the 3D location of underground utilities.

RFID technology is also used to locate building and equipment. For

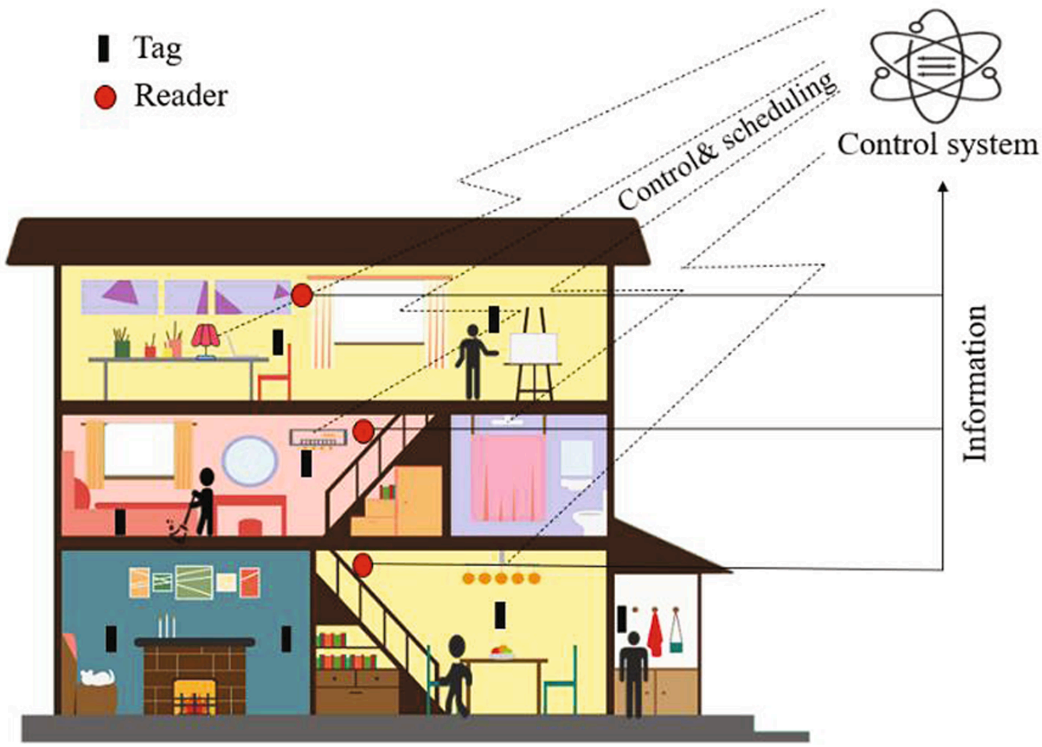

Fig. 10. The application of RFID in intelligent management and operation.

example, Saeed et al. [98] presented a real-time navigation system. In this system, they combined RFID technology with GPS, Dijkstra algorithm, Near Field Communication systems and 2D barcode, and this system was designed to locate the user and inform the user about buildings and other artefacts relating to the site where s/he is currently located and guide the user to a next point of interest efficiently. Won et al. [110] proposed an integrated unmanned aerial vehicle-RFID (UAV-RFID) platform and used deep learning algorithms to localize an RFID tag position, which provided a basis for the establishing of integrated platform for construction resource localization. The orientation of buildings can improve the management of building in an area, and if we locate the objects in a building, we can develop an intelligent management system. For example, Wang et al. [95] proposed a RFID based quality management system. This system can improve the automation of laboratory management. This application of RFID has an enormous potential in warehousing and logistics. The accurate location of the goods in the warehouse RFID provided can make work more efficient.

5. Conclusions

With the development of industry, the low price of RFID declares a termination for its past long-time dormancy, and a beginning for its future large-scale adoption. In order to expound the development of research, point out the gap of current studies and find the tendency of application, 103 articles were referred. These articles were organized into 3 aspects, and analysis is carried out based on this classification; the following conclusions were obtained:

Studies focus on intelligent construction is the mainstream in these years. Many researches have proved that the usage of RFID technology can observably improve the efficiency of construction. RFID largely influences the material supplies, improves the traceability of components and construction safety, and increases the control ability of participants in construction process. The combination of RFID and BIM largely improves the visualization of construction and becomes an increasingly hot topic in relevant studies. However, shortcoming always exists. Generally, the read range of RFID system is usually <10 m. Therefore, for a largescale building site, a lot of readers need to be placed, but, not all building sites have many positions for placing. Besides, if manager arranges workers to read tags with readers, amounts of manpower will be needed. Therefore, improve the valid read scope and accuracy or increase automation of reading (e.g. robots and unmanned aerial vehicle) is advised. Secondly, in the previous sections, we have pointed that many studies are about tracing system, so, there still has a tremendous potential in safety system and quality control. A comprehensive intelligent construction management system should integrate tracing system, safety system and building quality and efficiency control system. Besides, though many studies are finished, the usage of RFID technology in construction site is still not universal. In order to promote a wider application, proposing a general standard of RFID's application in structural engineering is also necessary.

RFID technology also inspires more and more attention in SHM. Common status information of structures such as strain, temperature, corrosion and humidity can be easily acquired with RFID based sensor system in current applications. RFID based sensor system is convenient for inspectors to detect structures which are sheltered or located in a disgusting environment. Compared with other technologies, RFID system's tag is small, cheap, convenient packaging and supports no power source. If well encapsulated, tags can have a long service life even in an inclement environment. However, there are still some problems have to be settled. The first is the read ability. For example, the read ability is influenced by the surface which tags are attached on, the obstacle between tags and readers, and the power of tags. Water will interdict the corresponding between tags and readers, so tags under the water need to put the antennas into the air with buoys. Concrete will also impair the corresponding, if tags are embedded in it. Therefore, great antenna design and low power tags are important for further applications. Besides, quantitative study of the influence of common structure materials on RFID based sensor system is suggested for the design. Besides, compared with surface tags, there are less studies focus on the embedded tags (Table 4), but, we believe that, compared with other technologies, passive tags have more advantages in embedded work mode. Moreover, more researches should consider the real status of structures (component is under pressure/tensile state). In real engineering, tags are likely to force and deform with components, and this may influence the information transmission. Finally, in terms of sensors, the selectivity and durability are also important. Selectivity refers to, for the same target (humidity, pH, etc.) to be detected, the variety of sensors. Durability emphasizes sensors should work steadily for decades with the influence of harsh environment.

For the applications in intelligent management and operation, RFID technology is an important part of current smart home system. Besides, RFID technology has a great performance in recording of building status information, which makes the repair and maintenance of building more convenient, becomes a basic technology of smart city and effectually saves energy for public building's operation. However, compared with other technologies (e.g. UWB), the accuracy of indoor positioning of RFID system needs further improvement.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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