ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

A BIM-BASED LOCATION AWARE AR COLLABORATIVE FRAMEWORK FOR FACILITY MAINTENANCE MANAGEMENT

SUBMITTED: May 2019
REVISED: July 2019
PUBLISHED: July 2019 at https://www.itcon.org/2019/19
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SUMMARY: *Facility maintenance management (FMM) accounts for a large amount of the total cost of facilities' lifecycle, illustrating the importance of improving FMM efficiency. Many mechanical facilities, like ventilation ducts above ceilings, are normally hidden, indicating the necessity of applying certain technology that can enable users to visualize and update the information of hidden facilities. Real-time location information is also needed so that users can be aware of their current location and the surrounding facility can be displayed accordingly. Therefore, this paper aims to develop location aware augmented reality (AR) framework for FMM, with building information modeling (BIM) as the data source, AR for the interaction between users and facilities, and Wi-Fi fingerprinting for providing real-time location information. The developed framework has the following features: (1) a proposed softmax-based weighted K nearest neighbour (S-WKNN) algorithm is used for Wi-Fi fingerprinting to obtain the current location of users; (2) a room identification method, based on BIM, the obtained location, and ray casting algorithm, is proposed to identify which room the user is currently in; (3) according to the obtained location and the identified room, users can visualize and interact with their surrounding facilities through the AR devices; and (4) users in a remote location can visualize site situation and interact with site facilities in real time through video streaming and the shared database. At the end of the paper, an experiment was designed to evaluate the effectiveness of the developed system. As shown by the experiment, the developed AR collaborative system can reduce the completion time of the designed task by around 65% compared with traditional 2D drawing-based method, and can provide a localization accuracy of around 1m.*

KEYWORDS: *Augmented reality, Building information modeling, Facility maintenance management, Remote collaboration, Wi-Fi fingerprinting*

REFERENCE: *Keyu Chen, Weiwei Chen, Chun Ting Li, Jack C. P. Cheng (2019). A BIM-based location aware AR collaborative framework for facility maintenance management. Journal of Information Technology in Construction (ITcon), Vol. 24, pg. 360-380, http://www.itcon.org/2019/19*

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1. INTRODUCTION

Being an integrated approach of managing and maintaining facilities in an organization, facility management (FM) is essential to keep facilities functional (Barrett and Baldry 2009). Among different FM activities, facility maintenance management (FMM), which refers to activities taken to prevent functional failure of facilities, accounts for 65%~85% of the total cost (Lavy and Jawadekar 2014). The larger amount of cost incurred from FMM illustrates the importance of optimizing FMM methods and improving FMM efficiency. However, managing facility maintenance tasks effectively is not easy. A complete workflow of FMM can contain several consequent tasks, such as inspection, reporting, repair, etc. requiring multiple users at different places to collaborate with each other. For example, when there is water leakage in a particular room, people in the room will report this problem to the office in charge (e.g. facility management office). Then the people in charge will instruct technicians to repair or replace the corresponding facility. However, as the mechanics may not know the site fully, they may have to go there to check the problem first, and it is quite likely that they need to go back to their workplace to bring necessary tools for repair and replacement. This kind of traditional FMM method is time-consuming, inefficient and expensive. Therefore, it is necessary to provide a platform for collaboration, information sharing, and real-time communication among different users. There are three prerequisites to developing such an effective collaboration platform: (1) a data source that can provide both geometric information and semantic information of facilities to help users understand the facilities and facilities' condition; (2) a user-friendly user interface (UI) that lets FMM staff read and update facility information conveniently; and (3) a localization method that can provide location information to link site users with their surrounding facilities so that the users can use the proposed UI to directly interact with the facilities.

Building information modeling (BIM) is an intelligent model-based approach that can be used to track, update, and maintain facility management information to support better decision-making in planning, operation and maintenance throughout a building lifecycle (Chen et al. 2018). Defined as a new approach to building design, construction and operation, BIM can facilitate the exchange and interoperability of information in digital format (Eastman et al. 2011). The information database of building assets contained in BIM can support various activities during a building's whole lifecycle, including FMM (Gan et al. 2019; Tan et al. 2019). Among various types of information required for FMM, location information is of vital importance, as location information can aid in obtaining the exact location of certain components, obtaining the location of each FMM staff, and guiding FMM staff to the required location. However, BIM cannot directly provide real-time location information for FMM staff. An efficient localization method is needed to facilitate BIM to obtain required location information. On the other hand, it is difficult for FMM staff to have direct interaction with site facilities in real time using current existing BIM software. With current BIM software, facilities have to be manually located from the whole building models when FM staff need to check or update the facilities' information. A new technique with a friendly UI is needed to enable users to directly read and update facility information so that the rich information of BIM can be better utilized for FMM.

Augmented reality (AR) is an innovative technology that can enable digital information such as 3D models, images and animations to be overlaid on the real world to achieve a natural interaction between users and their surrounding environment (Cheng et al. 2017). AR has been applied to the AECO industry for years (Dunston and Wang 2011; Dunston and Wang 2011). By combining the virtual world with the real world, AR makes the information of users surrounding facilities readable and manipulable. AR applications can be classified into two categories – marker-based AR and markerless AR. Marker-based AR has to use a marker as a trigger, while markerless AR normally uses localization methods to link the virtual world with the real world. For FMM, it is difficult to attach markers to all facilities, as some facilities, like ventilation ducts above ceilings and water pipes under floors, are normally hidden from users. As a result, an appropriate localization method can be used to match the required digital information with the real world to realize a markerless AR, as well as providing accurate location information for FMM.

To provide real-time location information for FMM, an appropriate localization technology is needed. Three requirements have to be satisfied to guarantee the performance of localization and minimize the cost: (1) the technology can provide a high localization accuracy; (2) the technology needs to be suitable for indoor environment as a large amount of FMM activities are taken in indoor environment; and (3) the technology can be applied to common mobile devices (e.g. mobile phones and tablets) so that FMM staff can easily access the proposed technology. Currently, there are several localization technologies available, such as Global Positioning System (GPS), radio frequency identification (RFID), Bluetooth, ultra-wideband (UWB), etc. Although GPS has been widely used for markerless AR, the low accuracy of GPS has limited its application in FMM, especially in an indoor environment (Cheng et al. 2017). For some other technologies that can provide better accuracy in indoor environment, external devices are required to obtain real-time location information. For instance, RFID readers are needed for localization with RFID, Bluetooth beacons are needed for localization with Bluetooth, UWB beacons are needed for localization with UWB, etc. In comparison, Wi-Fi can be an ideal technology for localization for FMM as Wi-Fi can provide a high accuracy in indoor environment and can be applied to common mobile devices. Besides, it is very common nowadays that a building is entirely covered with Wi-Fi signals. According to a survey, the widespread use of Wi-Fi routers and mobile devices has made localization based on wireless signal detection possible (Vo and De 2016). Propagation of different Wi-Fi signals from different Wi-Fi routers can form unique 'fingerprints' at different places (Wang et al. 2016). Based on this Wi-Fi fingerprinting theory, the real-time locations of users can be obtained. As a result, this paper proposes to use Wi-Fi fingerprinting technique to provide accurate location information for FMM. Besides localization, a room identification method is also needed to link users with their surrounding facilities. Based on the results of localization and room information extracted from BIM, the room identification method can identify which room the user is currently in and display corresponding information.

In this paper, a BIM-based location aware AR collaborative framework is developed for facility maintenance management. Section 2 conducts a literature review of current existing BIM applications for FMM and AR applications for collaboration among multiple users. Section 3 presents the development of the framework. Section 4 provides an illustrative example to show the functionality of the developed framework. Section 5 describes an experiment conducted to evaluate the efficiency of the developed framework. The conclusion part summarizes the features and highlights of the developed framework and discusses the limitations.

2. LITERATURE REVIEW

2.1 BIM-based facility maintenance management

In recent years, BIM has been widely applied to the architecture, engineering, construction and operation (AECO) industry as BIM provides a platform for information sharing and collaboration. But BIM is not just popular among new buildings; demand for BIM among existing buildings is also increasing (Volk et al. 2014). Implementing BIM can facilitate decision making for facility related activities, as well as optimizing maintenance scheduling and space utilization planning (Liu and RA Issa 2014; Sabol 2008). Lin and Su (Lin and Su 2013) developed a BIM-based mobile FMM system which can be used for report management and facility monitoring. An integrated visualization platform was developed by Yang and Ergan (Yang and Ergan 2015) to support corrective maintenance of HVAC problems and the platform was evaluated through user studies.

On the other hand, BIM can enhance existing computerized maintenance management systems (CMMSs) and facility management systems (FMSs) by providing better information interoperability and better visualization. In order to better utilize the rich information of BIM, BIM tools can be integrated with existing facility management systems (Parsanezhad and Dimyadi 2013). A case study of the Sydney Opera House illustrated the benefits of BIM in information interoperability, allowing facility information management to be added to existing FM systems, such as Hardcat Asset Management (HARDCAT 2015), Mainpac (Mainpac 2015), and Trimtabs Asset Management (TRIM 2015). A BIM-based framework was proposed by Chen et al. (2018) to integrate BIM software with FM software to enable automatic scheduling of maintenance work order.

Information is critical for supporting efficient building maintenance management and daily operations (Atkin and Brooks 2014). Much research has been conducted to improve information interoperability and data transfer for BIM. An IFC-based data model was proposed in 2001 to achieve integrated maintenance management for a roof system (Hassanain et al. 2001). Two years later, the same research group presented a general object-based schema for asset maintenance management which could support data transfer from the construction to the operations and maintenance (O&M) stage (Hassanain et al. 2003). Another object-oriented model was proposed to support healthcare facility information management (Lucas et al. 2013). Furthermore, since the introduction of the Construction Operations Building information exchange (COBie) standard, people have been able to store maintenance information in BIM in a structured way (Eastman et al. 2011). COBie has been proven capable to improve the interoperability between BIM and CMMSs/FMSs (Bosch et al. 2015).

As mentioned in the Introduction section, location information is necessary for FMM activities. However, FMM staff cannot obtain real time location information (Chen et al. 2018). An efficient localization method is needed to facilitate BIM to obtain required location information. Besides, FMM staff currently cannot directly interact with their surrounding facilities using current BIM software. With AR devices, users can directly interact with the surrounding facilities by touching the facilities through a touch screen (Kwon et al. 2014), modifying the facilities using gestures (Wang et al. 2016), or reading and updating information with speech commands (Giesler et al. 2004). A more user friendly UI based on AR technology can achieve a better human-machine interaction.

2.2 AR-based facility maintenance management

Besides AR applications in architecture (Wang et al. 2008), engineering (Ayer et al. 2014), and construction (Behzadan and Kamat 2011), there have been several AR applications focusing on facility maintenance management. For example, Irizarry et al. (2013) proposed an AR system for facility managers to access maintenance information, which was proved to be able to improve efficiency during FMM. Hou et al. (2014) presented a novel framework which combined AR with photogrammetry to manage information for FMM. Alam et al. (2017) integrated augmented and virtual reality with internet of thing (IoT) to improve safety and reduce error for FMM activities. Similar applications have also been developed to apply AR to FMM (Liu and Seipel 2018; Ong and Zhu 2013; Williams et al. 2014).

A complete workflow of FMM contains several consequent tasks, such as inspection, reporting, repair, etc. requiring multiple people at different places to collaborate with each other. As a result, AR applications for multi-user collaboration are of vital importance. Current existing AR applications for multi-user collaboration can be classified into two categories – face-to-face collaboration and remote collaboration. With face-to-face collaborative AR, a group of users can stay together and interact with the same virtual objects, which is achieved by using a shared coordinate system. In 2002, several experiments were conducted to compare communication in a face-to-face collaborative AR interface with traditional approaches (Billinghurst et al. 2002). In 2005, a research team developed a mobile AR application that let two users play a game of AR tennis together (Henrysson et al. 2005). In the AECO industry, only few face-to-face collaborative AR applications have been implemented. In 2013, a software program named ARVita was developed, with which multiple users wearing head-mounted devices can observe and interact with simulations of engineering processes (Dong et al. 2013). A research team proposed an AR-based multiscreen environment to facilitate construction discussions and an experiment was conducted to evaluate the proposed AR environment (Lin et al. 2015). For remote collaboration, researchers use different electronic and communication technologies to achieve remote data sharing and interaction so that users at different places can collaborate with each other through the AR platform. Lee et al. (2009) proposed an approach using collaborative AR tangible interactions to evaluate the designs of digital products. Bottecchia et al. (2009) developed a prototype of a collaborative system for mechanical repairs based on AR to achieve remote communication among different users. In 2016, a user study was conducted to compare visual and audio notifications based on a developed AR collaborative system (Cidota et al. 2016).

As mentioned in the Introduction, FMM tasks often require multiple users to collaborate with each other and AR can provide a UI for FMM staff to directly interact with surrounding facilities. However, currently there are limited studies about implementing AR collaboration for FMM. Most of the existing collaborative AR applications in the AECO industry are face-to-face collaboration, which limits the communication and interaction among people at different locations. To further improve the efficiency of AR collaboration in the AECO industry, it is necessary to implement remote collaboration more.

To link virtual models with the real environment, a proper localization technique is required for AR spatial registration. GPS-based AR has been widely adopted in the AECO industry (Kim et al. 2013; Tsai and Yau 2014), but GPS is not appropriate for FMM activities in indoor environment due to the low accuracy. To implement AR in FMM activities, indoor localization techniques are needed. Bluetooth can provide better localization accuracy in indoor environment compared with GPS, and can be easily applied to smartphones (Feldmann et al. 2003; Zhuang et al. 2016). While the localization accuracy of Bluetooth is still limited and Bluetooth access points (APs) are needed (Zhao et al. 2014). RFID is a communication technology that has a wide range of applications including indoor localization (Landt 2005). RFID usually provides high localization accuracy (Yang et al. 2014). However, RFID-based localization requires RFID tags as references, limiting the convenience of using RFID for AR spatial registration. Other indoor localization techniques such as Zigbee (Chen et al. 2009) and UWB (Porcino and Hirt 2003), although can provide high accuracy in indoor environment, cannot be applied to smartphones directly. In comparison, Wi-Fi fingerprinting is a promising technique for FMM activities, as it can provide high localization accuracy in indoor environment and can be easily applied to common smartphones.

3. THE DEVELOPED FRAMEWORK

The developed BIM-based location aware AR collaborative framework is shown in FIG. 1, which contains three parts: (1) indoor localization, (2) shared database, and (3) augmented reality. As mentioned in the Introduction, localization based on Wi-Fi fingerprinting can provide convenience and a high accuracy in indoor environment. At the same time, Wi-Fi fingerprinting can be applied to common mobile devices to be easily accessed by users as long as the working area is covered by Wi-Fi signals. Therefore, Wi-Fi fingerprinting is used to achieve the localization function in this research. Mobile devices with a Wi-Fi receiver are used to scan Wi-Fi information (MAC addresses of surrounding routers and signal strength at the current location) to obtain Wi-Fi fingerprints. By comparing the fingerprint of a user's current location with the stored fingerprints for a certain area, the exact location of the user can be obtained. The current location is represented by the nearest Wi-Fi fingerprint, which is obtained using K nearest neighbor (KNN).

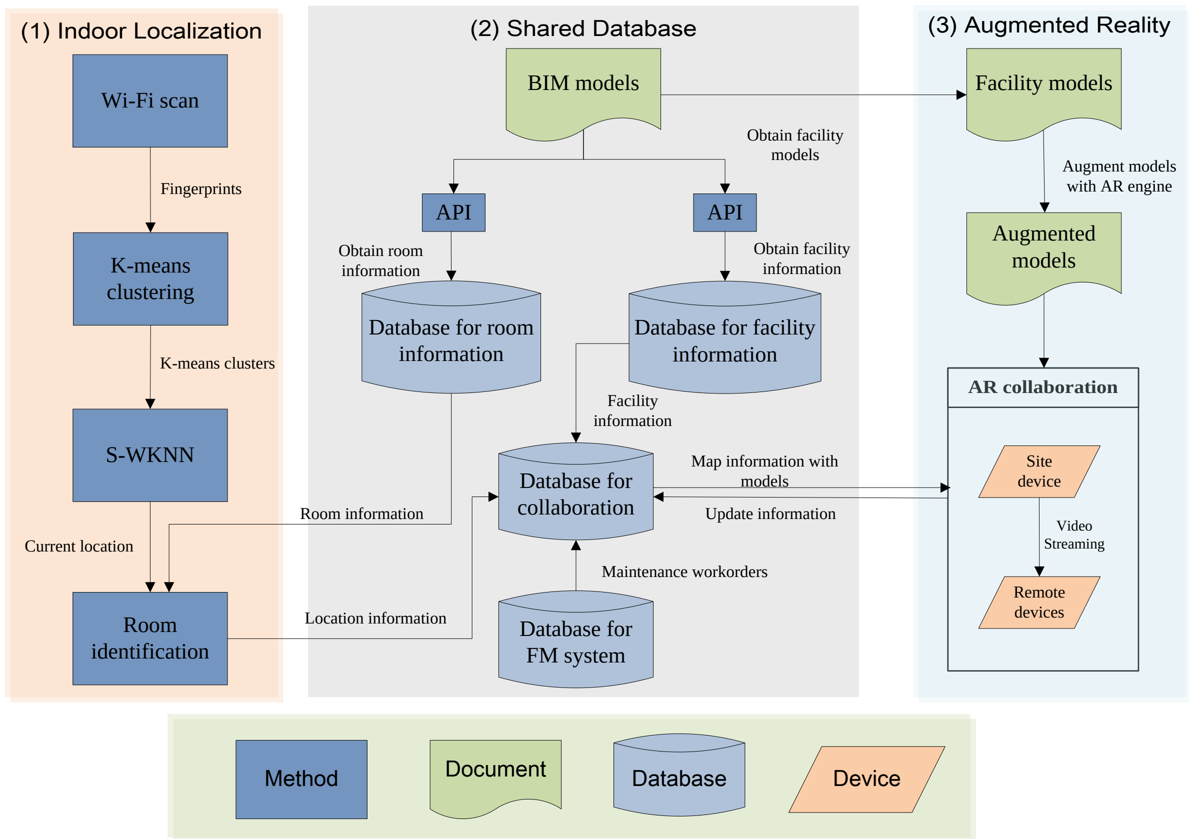

FIG. 1: The proposed AR framework

This paper proposes a new KNN algorithm named softmax-based weighted K nearest neighbor (S-WKNN) to improve the localization accuracy. A comparison between S-WKNN and the commonly used one nearest neighbor (1NN) has also been conducted to evaluate the performance of the proposed algorithm. K-means clustering algorithm has also been incorporated in the proposed algorithm to reduce the computation workload and improve the efficiency of localization. The framework can then use the obtained location information along with a proposed room identification method to identify which room the user is in, so that the users can be linked with their surrounding facilities. An online database is constructed to enable multiple users to access required facility information at the same time. The database contains the following information: geometry and semantic information of facilities extracted from BIM models, maintenance and inspection records from FM systems, and location information obtained by the localization function. The information of facilities and rooms are extracted from BIM models by using application programming interfaces (APIs) of different BIM software. BIM models are also imported into the AR developing engine to generate augmented facilities. As users visualize virtual facilities in the real environment, multiple users can also simultaneously read and update facility information by interacting with the constructed database. Furthermore, users at remote locations can view the site in real-time via live video streaming function. The three parts of the proposed framework are presented in Section 3.1, Section 3.2, and Section 3.3 respectively.

3.1 Indoor localization based on Wi-Fi fingerprinting

The indoor localization part of the framework has four elements, namely (1) Wi-Fi scan, (2) K-means clustering, (3) S-WKNN, and (4) room identification, which are discussed in the followings.

3.1.1 Wi-Fi scan

To use Wi-Fi fingerprinting for localization, Wi-Fi fingerprints need to be collected via Wi-Fi scan. Each Wi-Fi fingerprint consists of four attributes: (1) fingerprint ID, (2) the name of the indoor area, (3) the location of fingerprint in the indoor area, and (4) the measurements of Wi-Fi signal strengths obtained by Wi-Fi scanning. Attributes of a Wi-Fi fingerprint are shown in TABLE 1. Fingerprint ID can be assigned by users according to a particular principle (e.g. '00001' to '99999'). Name of the map is based on the area that the fingerprint is located at. The location of fingerprint is represented by the coordinate value in the corresponding relative coordinate system. The measurements of fingerprint refer to the Media Access Control (MAC) address and received signal strength indicator (RSSI) of each router in the fingerprint. After obtaining the information of each fingerprint, the framework will upload the information onto the constructed database. Mobile devices, such as a smart phone or a tablet, can be used to scan Wi-Fi signals to generate Wi-Fi fingerprints and upload the information onto database. As the user's location is represented by the nearest fingerprint, the density of fingerprint has a direct and significant effect on the accuracy and efficiency of the proposed method. FIG. 2(a) is an example of fingerprints created for localization, and FIG. 2(b) shows the attributes of one of the fingerprints.

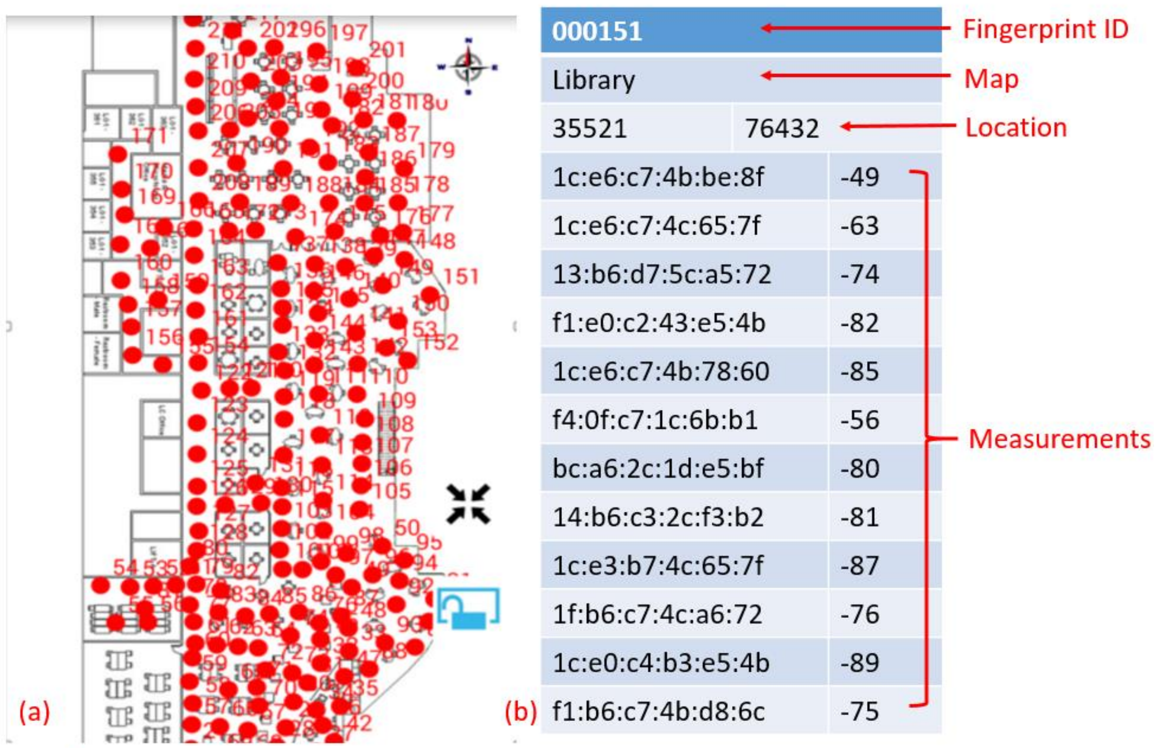

FIG. 2: (a) Fingerprints created in a building; (b) Attributes of a fingerprint

TABLE 1: Attributes of a Wi-Fi fingerprint.

Attributes	Remarks
Fingerprint ID	The ID of a Wi-Fi fingerprint
Map	Name of the map the fingerprint is located at
Location	(x, y) coordinates on the map
Measurements	MAC address and RSSI values

3.1.2 K-means clustering

To improve the performance of the localization method, KNN algorithm (Guo et al. 2004) and K-means clustering algorithm (Ruspini 1969) are used. Merely implementing KNN algorithm will create a huge computation workload because the signal measurements of every single Wi-Fi fingerprint need to be compared with the received signal measurements from the user position. To tackle the problem of huge computation workload, a K-means clustering algorithm is implemented first, as shown in FIG. 3.

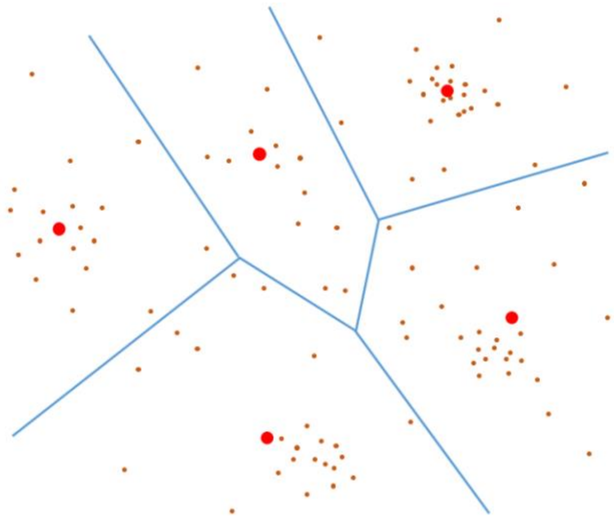

FIG. 3: An illustrative example of K-means clustering

K-means clustering can divide fingerprint points to different representation groups by an iteration process. The workflow of obtaining required clusters is described in the followings. Firstly, the centroids of clusters are randomly assigned to the area of Wi-Fi fingerprints. Secondly, fingerprints are assigned to the nearest clusters in terms of the distance between the cluster centroids and the fingerprint locations. Thirdly, the centroids of clusters are obtained from the coordinates of the assigned fingerprint locations. Then the second and third steps are repeated until convergence. While repeating the second and third steps of K means clustering, there is possibility that a cluster contains no fingerprints. In this case, errors will occur during the calculation of the centroid of the empty cluster and the calculation will also be stopped. The value of K is set according to a balance between the computation time and localization accuracy. Several K values will be tested until an appropriate K value that can provide less computation time and higher accuracy is obtained.

3.1.3 K nearest neighbor (KNN)

After generating the K-means clusters, the KNN algorithm is used to first find the nearest cluster, and then to find the nearest Wi-Fi fingerprint in the nearest cluster to represent the current location. It is important to emphasize that the K nearest Wi-Fi fingerprints are not based on calculating the geometric distance between the user position and the Wi-Fi fingerprints. Instead, the K nearest Wi-Fi fingerprints are based on the signal strength measurements of each Wi-Fi router in the environment. For example, if there are n routers in the surroundings, the nearest neighbor is found by the standard Euclidean distance of the difference of the Wi-Fi signal measurements which are obtained from the user position and the Wi-Fi signal measurements stored in the database.

(1) 1NN

A commonly used algorithm for Wi-Fi fingerprinting is 1NN, which is a special case of KNN (K=1). With 1NN algorithm, the nearest 'one' fingerprint can be obtained to represent the users' current location. The nearest fingerprint can be found with the following equation:

$$D = \sum_{i=1}^{n} (RR_i - RS_i)^2 \tag{1}$$

where D is the squared Euclidean distance; n is the total number of detected routers; RR_i is the real-time RSSI value from the ith router; and RS_i is the RSSI value from the ith router in the stored fingerprint. If a router is detected in real time but is not present in the stored fingerprints, the RSSI of the stored fingerprint is set to the minimum value that can be detected, which is determined by the sensitivity of the antenna of the device (e.g. in the illustrative example in Section 4, the minimum value of RSSI that can be detected with the tested smart phone is -119). Similarly, if a router is present in the stored fingerprints but not detected in real time, the value of the real-time RSSI is also set to the minimum value. Pseudo code for calculation of squared Euclidean distance is provided in FIG. 4.

```
Input:
stored_ID [] ← the Mac address of routers of the stored fingerprint
stored_RSSI [] ← the RSSI value of routers of the stored fingerprint
m ← total number of routers in the stored fingerprint
new_ID [] ← the Mac address of routers of the new fingerprint
new_RSSI [] ← the RSSI value of routers of the new fingerprint
n ← total number of routers in the new fingerprint
Output:
D ← squared Euclidean distance

For i =1 to m
  For j =1 to n
    If new_ID [j] = stored_ID [i]
      Then D = D + (new_RSSI [j] – stored_RSSI [i])^2
    End if
    If new_ID [j] ∉ stored_ID []
      Then D = D + (-119 – new_RSSI [j])^2
    End if
  End for j
  If stored_ID [i] ∉ new_ID []
    Then D = D + (-119 – stored_RSSI [i])^2
  End if
End for i
```

FIG. 4: Pseudo code for calculation of squared Euclidean distance

To find the nearest cluster, the squared Euclidean distance D is calculated for all clusters, which are measured according to the weighted average of the measurements of the Wi-Fi fingerprint candidates in each cluster. The cluster with the minimum D is the nearest cluster. After determining the nearest cluster, D is also calculated for all fingerprints in the nearest cluster. The fingerprint with the minimum D is selected as the nearest fingerprint to represent the current location. The density of stored fingerprints is an important factor that affects the accuracy of 1NN algorithm. The nearest fingerprint cannot accurately represent the real location if the distribution of fingerprints is relatively sparse. For instance, when the distances among adjacent fingerprints are set to 1m, the localization error can be 0.5m even if the nearest fingerprint is obtained accurately. In the meantime, there is no need to set the fingerprints too dense, as the algorithm cannot differentiate fingerprints if they are very close to each other.

(2) S-WKNN

For KNN algorithm, besides the above mentioned 1NN, K can also be set to an integer larger than one, so that multiple fingerprints can be used as reference points to calculate the current location. In this case, the current location is obtained by the weighted average of the K closest fingerprints, rather than merely using the existing fingerprints to represent the current location. In this typical KNN method, the current location is calculated based on the similarity between received signals and the fingerprints. A fingerprint contributes more to the final result if it has a higher similarity to the received signals. However, the typical KNN method does not take the factors of signal strength into account. Fingerprints with higher received signal strengths are more reliable, as they suffer less from the fluctuation due to multipath effect or attenuation. Therefore, weights of different fingerprints should be taken into account according to their average signal strength to improve the localization accuracy. The information of a fingerprint contains RSSI values from different routers. The RSSI value of a Wi-Fi router is determined by the performance of the router and the distance between the router and the fingerprint.

The S-WKNN algorithm is proposed based on the 1NN algorithm. The K nearest fingerprints are obtained using Equation (1). The softmax function (Nasrabadi 2007), which is a logistic function of probability distribution over K different possible outcomes, is used to assign weights to corresponding fingerprints. The softMax function is used to appreciate larger values that have more contribution to the estimated position, and depreciate smaller values that have less contribution to the estimated position. As a result, the estimated position becomes more stable and has less fluctuation. The current location is calculated with the following equation:

$$(X,Y) = \sum_{i=1}^{K} \frac{e^{\frac{RA_i}{D_i}}}{\sum_{i=1}^{K} e^{\frac{RA_i}{D_i}}} (X_i, Y_i) \tag{2}$$

where (X,Y) is the coordinates of the current location, (X_i, Y_i) is the coordinates of the *i*th fingerprint, RA_i is the average RSSI value of the *i*th fingerprint, and D_i is the squared Euclidean distance of the *i*th fingerprint calculated with Equation (1). In this paper, the value of K is set to 4, which has the best performance according to a series of tests. Therefore, the nearest four fingerprints with different weights are used as reference points to calculate the current location.

(3) Comparison between 1NN and proposed S-WKNN

Both 1NN and S-WKNN algorithms were developed and tested in the library of the Hong Kong University of Science and Technology (HKUST). The library has a large open space with around 30 Wi-Fi routers covering an area of 3,600m^2. The distances among adjacent fingerprints were set to 1m as the algorithms cannot differentiate fingerprints that are closer than 1m. Both algorithms were tested with 10 random locations and the errors for each testing location were recorded. The obtained locations were projected onto the real environment based on the coordinates. The error is defined as the distance between the location obtained by the localization method and the real location of the device. Results of the test are shown in TABLE 2.

TABLE 2: Statistical results on errors of localization.

	Average (cm)	Standard deviation (SD)
1NN	151	32
S-WKNN	102	23

As shown in the above table, the error of localization for S-WKNN is around 100cm. Compared with the traditional 1NN algorithm, the localization error of S-WKNN increases by 32%. On the other hand, the SD of errors for S-WKNN is much smaller than that of 1NN, illustrating that the stability of S-WKNN is better than 1NN. As mentioned in previous sections, the 1NN algorithm uses only one fingerprint to represent the current location. The localization error is affected by the distance between the real location and the nearest fingerprint even if the nearest fingerprint can be obtained accurately. While the S-WKNN uses multiple fingerprints as reference points to calculate the current location so that the locations between fingerprints can also be represented accurately. It can be concluded from the test that the localization accuracy and stability of the proposed S-WKNN have been greatly improved compared with the commonly used 1NN algorithm.

3.1.4 Room identification

After obtaining the exact location of a user, a room identification method based on the ray casting algorithm (Shimrat 1962) is also proposed in this framework to identify which room the user is in. Coordinate information of the endpoints of walls extracted from BIM models can be used to generate polygons to represent the actual area of rooms (extracting room information from BIM models will be discussed in the next section). The system can automatically compare coordinate information from the Wi-Fi fingerprint database with the current location of the user using Wi-Fi fingerprinting. In the proposed coordinate system, rooms are represented by polygons and users are represented by points. Set a point P1, which is very far away from the polygon, and connect this point and the user point with a segment, as shown in FIG. 5 (a). Let f(x, y) represent the line of PP1. If $f(x_A, y_A) \times f(x_B, y_B)<0$, then points A and B are on different sides of line PP1. If points P and P1 are also on different sides of the line AB, then these two segments intersect with each other, as shown in FIG. 5 (b). The number of intersection points between this segment and all the edges of the polygon are then calculated. If the number of intersection points is odd, then this user point is inside the polygon. Several exceptions (e.g. the intersection point is one of the vertices of the polygon) have been ruled out to guarantee the reliability of this algorithm.

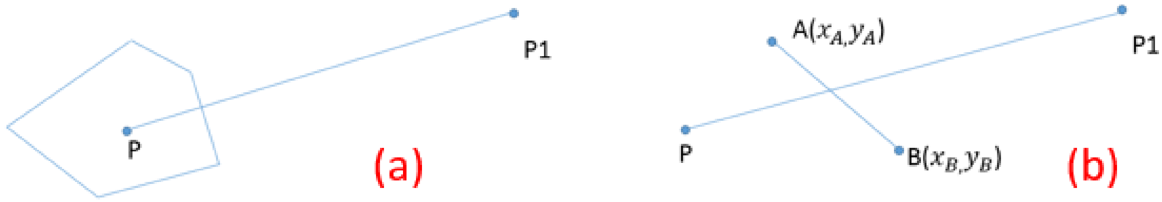

FIG. 5: (a). Deciding whether the user point is inside the given room or not; (b) Deciding whether two segments intersect with each other or not

Two examples of the proposed room identification method are provided in Figure. 6. In the first example (FIG. 6(a)), line PP_1 has 1 intersection point with the polygon, which means P_1 is inside the room, while PP_2 and PP_3 have 0 and 2 intersection points respectively, indicating that P_2 and P_3 are outside the room. In the second example (FIG. 6(b)), PP_1 has 1 intersection point with the polygon, which means P_1 is inside the room, while PP_2 has 4 intersection points with the polygon, indicating that P_2 is outside the room. Based on the above proposed room identification algorithm, the developed system can automatically identify which room the user is in, and help FMM staff get real-time corresponding information of the identified rooms.

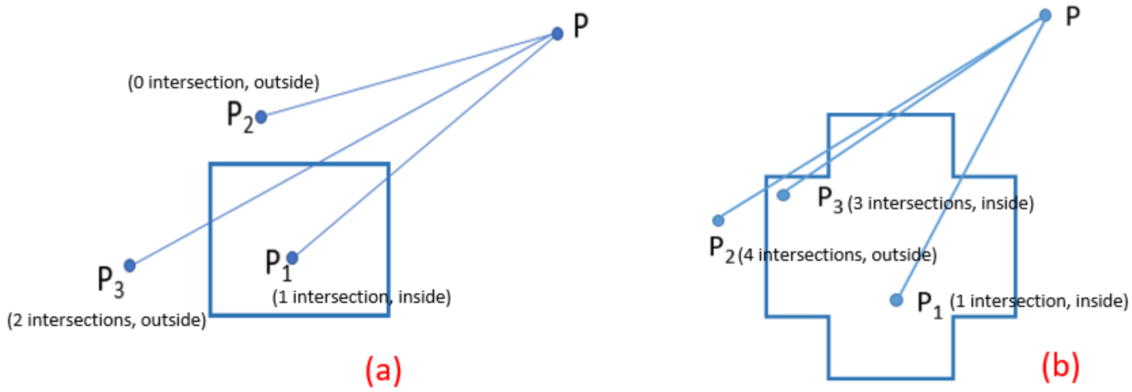

FIG. 6: (a) Example of room identification with a rectangular room; (b) Example of room identification with an irregular room

3.2 Construction of the shared database

A database that can store all related information for FMM and can give simultaneous access to multiple users is required to achieve collaborative AR for FMM. The information stored in the database includes: (1) dimensions and coordinates of each facility, (2) semantic information (e.g. material, model, manufacturer, etc.) of each facility, (3) room information (coordinates of boundary and ID of each room), (4) inspection and maintenance record of each facility, (5) fingerprints information (Fingerprint ID, MAC address, RSSI, etc.), and (6) location information of each potential users (the location of the user and which room the user is in). This research uses the design concept of a relational database. Different modules of the database are designed based on the requirement and logic of the system framework, and are linked to each other by facility ID.

APIs of BIM software are used to extract required information of facilities. The extracted information includes dimensions, family type, system type, material, manufacturer, etc. and is then stored in the constructed database. Facility ID is used to link each module in the database, and link each item in the database to its corresponding BIM models and augmented models, as shown in FIG. 7.

ID	X	Y	Z	Scale
281716	-21	35	10	1

ID	Family Type	System Type	Connection Type	Material
281716	6 PVC	Hydraulic supply	Generic	PVC

ID	Inspection date	Condition	Instructions
281716	2017-11-05	Good	

ID	Inspecting	Updating
281716	1	0

FIG. 7: Different tables of the shared database

Room information is also extracted from BIM models using APIs of BIM software. The extracted room information includes room name/number and coordinates of corners of rooms. The coordinates of corners of rooms are used to generate the polygons to represent the room for the proposed room identification method. Examples of the extracted room information are shown in TABLE 3.

TABLE 3: Examples of extracted room information

Name	Corner Coordinates						
	(X_1, Y_1)	*(X_2, Y_2)*	*(X_3, Y_3)*	*(X_4, Y_4)*	*(X_5, Y_5)*	……	*(X_n, Y_n)*
Restroom_ Female	*0.1509999, 0.4937937*	*0.1509684, 0.4611835*	*0.2216164, 0.4937582*	*0.2215172, 0.4612221*	*N/A*		*N/A*
Restroom_ Male	*0.2215153, 0.4597059*	*0.1509684, 0.4596584*	*0.1509999, 0.4309104*	*0.2215172, 0.4309104*	*N/A*		*N/A*
Lift C	*0.2478163, 0.1742855*	*0.2477532, 0.1962367*	*0.3253756, 0.1962416*	*0.3252796, 0.1742733*	*N/A*		*N/A*
LC 1	*0.4590897, 0.6650434*	*0.4590897, 0.6352694*	*0.4084207, 0.6352694*	*0.4084207, 0.6605043*	*N/A*		*N/A*
LC 2	*0.5139868, 0.6352694*	*0.4630960, 0.6352694*	*0.4630960, 0.6605043*	*0.5133395, 0.6605043*	*N/A*		*N/A*
LC 3	*0.4082547, 0.6084946*	*0.4084207, 0.6337673*	*0.4590897, 0.6084704*	*0.4590428, 0.6337284*	*N/A*		*N/A*
LC 4	*0.5139868, 0.6084946*	*0.4630329, 0.6084927*	*0.4630329, 0.6337667*	*0.5139868, 0.6337738*	*N/A*		*N/A*

The database of FMSs is incorporated into the shared database to provide information of inspection and maintenance record. The shared database also contains the information of the users' current location. Once the location of a user is detected, the location information will be automatically uploaded onto the database so that the other users can also get to know the location of the site user. Besides, the information of Wi-Fi fingerprints, including the fingerprint ID, the name of the indoor area, the location of fingerprint in the indoor area, and the measurements of Wi-Fi signal strengths, are also stored in the shared database. The shared database is a link connecting localization, BIM, FMM and AR. The database incorporates real-time location information obtained by the localization method, facility information from BIM models, maintenance information from FM software, etc. With the shared database, users are linked with their surrounding facilities and the rich information of BIM can be better utilized in the AR-based UI. Besides, the shared database allows multiple users to access through the Internet simultaneously so that multiple users from different locations can collaborate with each other in real time.

3.3 AR collaboration

The proposed AR framework in this paper is location aware and information rich because of its integration with BIM and indoor localization. With the real time location information, users are linked with the surrounding facilities. Various interaction methods (e.g. screen touching, gesture commands, voice commands) can be used for users to read and update the information of surrounding facilities. The required information for FMM activities are identified and extracted from BIM and FM software to facilitate the AR part for FMM. With the friendly UI, users can better utilize the rich information from BIM and FM. On the other hand, remote collaboration among multiple users is achieved by the developed screen sharing function and the shared database.

BIM models of facilities generated from BIM software are transferred to an AR engine. In the AR engine, all models are grouped according to the room they are in. Once the current location of the user is obtained and the room is detected, corresponding models will be displayed in the user's surrounding environment. A virtual camera in the developing environment is used to decide the real view of users. Once the current location is obtained, the coordinate values of the location will be assigned to the camera automatically so that users can get the correct view through the view camera. For example, if a user is standing under a fire sprinkler, the system can assign the coordinate values of the current location to the view camera so that the user can see the fire sprinkler above his/her head when he/she looks up with a given device.

With the proposed localization method, the system can detect the current location of a user and display corresponding virtual facilities with appropriate relative position relationship. However, the alignment of facilities cannot be decided merely using the localization method. For instance, in the fire sprinkler example mentioned before, the user may find himself standing exactly under a virtual fire sprinkler while the whole virtual fire pipe system may have a 90 degree error from the real fire pipe system. To deal with the alignment problem, the gyroscope and compass of mobile devices are used in this research. In the selected AR engine, the gyroscope is enabled to track the rotation of the mobile device and the compass is enabled to read magnetic information of the environment. As a result, once the virtual facilities in the AR engine are set according to their real direction, the AR device can display the facilities with proper alignment. For example, in the case of the developing environment of this research, the positive direction of the Z-axis of the coordinate system is set to represent north. Once the virtual facilities are aligned with the Z-axis, the facilities will be displayed with direction from south to north on the AR devices.

In the UI of the system, besides the virtual models of facilities, information panels are used to display different required information, including room information, facility product information, facility maintenance and inspection information. HP: Hypertext Preprocessor (PHP) files with SQL query commands are used to link the system to the constructed database, based on which multiple users can read and update information in the database. To enable users to interact with the system, different interaction methods have been applied. For mobile devices, users can directly use the touchscreen and virtual keyboard to interact with buttons on the UI or directly interact with facilities. For laptop computers and desktop computers, a mouse and keyboard are used to interact with the system. For AR head-mounted displays (HMDs), users can interact with facilities using voice commands and gesture commands. Besides text instructions, a function of animation-based instructions is also developed for the AR part, as shown in FIG. 8. Animations for basic operation and repair of facilities are incorporated into virtual models to facilitate FMM activities. Site users can follow the animation instructions step by step to operate or repair corresponding facilities. On the other hand, with remote devices, users can also give some basic animation-based instructions to site users, such as ‘move’, ‘rotate’, and ‘remove’.

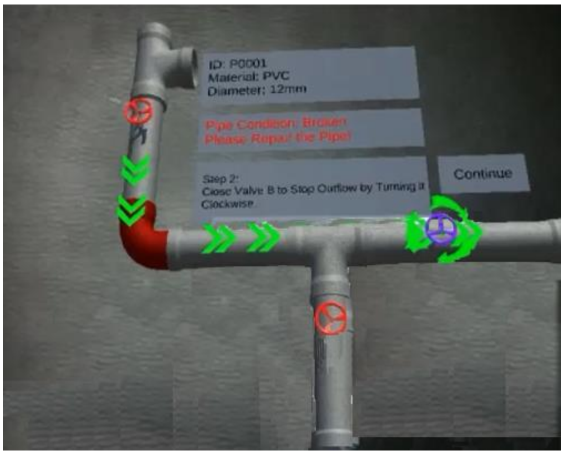

FIG. 8: Animation-based instructions for FMM activities

A function of screen sharing among different users is needed to enable users from remote places to have a direct and clear understanding of site situation in real time. MJPEG (or motion JPEG) format is used to achieve live video streaming. MJPEG is a video compression format with which each video frame is compressed as a JPEG image and the video stream can be sent over HTTP protocol (Chen et al. 2012). TCP protocol is used to establish a network connection among different devices. A server device is connected to client devices using sockets, which are internal endpoints for sending or receiving data in a computer network. Live video streaming is achieved by the following steps: (1) the system captures each frame of the server screen; (2) each frame of the captured screen is compressed as a JPEG image; (3) the system sends the stream of JPEG images from the server device to the client devices through the network; and (4) the system decompresses the received images and displays the video on the remote devices.

Although researchers in the AECO industry have studied AR for years, the integration of AR with indoor localization and BIM and the feature of remote collaboration among multiple users are new and ideally suitable for FMM activities. The proposed AR-based UI is designed particularly for typical FMM activities. The workflow of a typical FMM activity may include site inspection, problem report, decision making, instruction and repair. With the proposed AR system framework, the above mentioned activities can be completed more efficiently and the efficiency of communication can be greatly increased.

4. ILLUSTRATIVE EXAMPLE AND USER TEST

4.1 System setup

An illustrative example is used to demonstrate the functionality of the developed framework. For indoor localization, a smart phone was used to scan Wi-Fi signals to obtain Wi-Fi fingerprints. Then the smart phone was also used to obtain the real-time Wi-Fi information and compare with the stored Wi-Fi fingerprints using KNN and K-means algorithm, so that the nearest Wi-Fi fingerprint can be found to represent the user’s current location. Based on the obtained location and the proposed room identification method, users were aware of the room they are currently in. For the shared database, MySQL, which is an open source relational database management system (Oracle 2012), was used to construct the collaborative database. MySQL supports the SQL language for data query to achieve reading and writing of information efficiently. The stored information included geometric and semantic information of each facility (dimensions, coordinates, family type, system type, material, model, manufacturer, etc.), room information, inspection and maintenance record of each facility, fingerprints information and location information of potential users. Autodesk Revit was used to generate facility models. Two plug-ins of Autodesk Revit were developed using Revit API to extract facility information and room information. The required information was exported into a CSV file and imported into the MySQL database. In this paper, ARCHIBUS (ARCHIBUS 2014) was used as the FMS, whose database was also incorporated into the constructed MySQL database. For augmented reality, the selected AR engine in this paper is Unity 3D (Unity 2018), which was used

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to develop the AR UI for smart phones, tablets, computers and AR HMDs. For devices, a smartphone with Android operation system (OS) is used as the site device and a desktop computer with Windows OS is used in a remote office. The developed framework can be applied to different mobile platforms, including smartphones/tablets with Android OS, smartphones/tablets with ios OS, and Microsoft HoloLens with Windows OS. The proposed localization method, as well as the compass and gyroscope of the smart phone, were used to display virtual facilities with correct location and alignment. The developed screen sharing function was used to stream the site view from the smart phone to a remote computer.

The developed system in the example mainly used scripts with C# programming language in Unity 3D. There is one exception: to get the MAC address and RSSI of routers, a Wi-Fi scan function is needed. However, for Android devices, the Wi-Fi scan function cannot be enabled through Unity 3D directly. Therefore, an alternative approach was used in this research to complete the development of the Android version of this system. For the Android version, the Wi-Fi scan function was first developed in Android Studio with Java. Then the generated project and corresponding libraries in Android Studio were exported into a compressed file in arr format. In the end, the arr file was imported into the Unity 3D project as a plug-in and the Wi-Fi scan function can be called in Unity 3D.

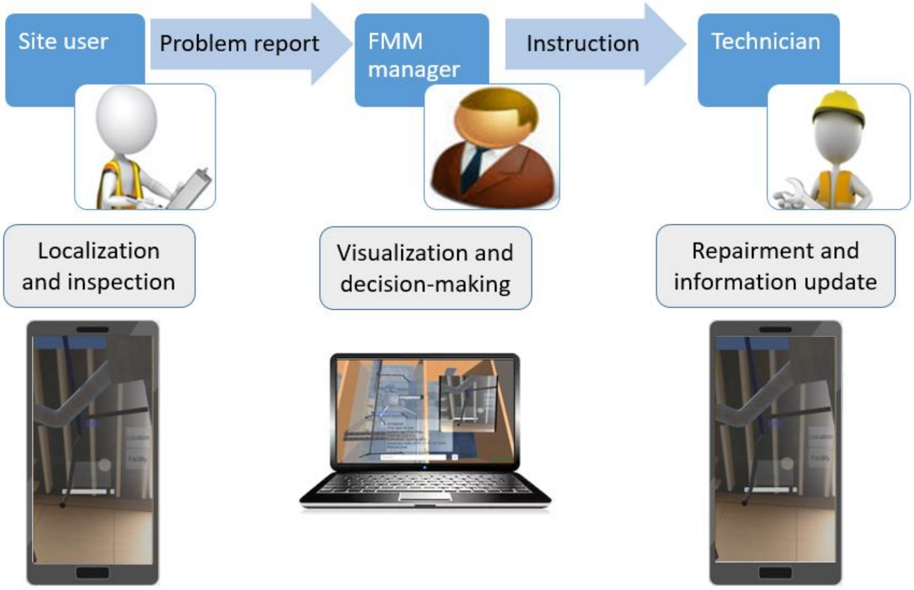

FIG. 9: Workflow of the illustrative example

The general workflow of FMM is as follows. Facilities are inspected by FMM staff regularly. When a facility failure occurs and is spotted during an inspection or by site users, the problem will be reported to the FM office. In the FM office, the person in charge will make decisions according to the received information and instruct corresponding technicians to take appropriate measures. In the end, the technicians will go to site to repair or replace the failed facility. FIG. 9 illustrates the workflow of the illustrative example. When a user on site opened the app installed on his/her smartphone, the app scanned the surrounding Wi-Fi information. Based on the proposed algorithm for localization, the nearest Wi-Fi fingerprint was obtained and the room number was detected. Then corresponding facilities and information were displayed on the device with the correct relative position relationship and relative angle relationship. At the same time, corresponding facilities and information were also displayed on a remote computer in the office. Both the user on site and the user in a remote office could interact with the facilities. The site user selected a fire pipe to check its information and the pipe was highlighted automatically so that all users knew which pipe was being inspected by site user. Then the site user updated the 'Condition' of the pipe from 'Good' to 'Leak' and the user in the remote office could see the updated information immediately. Once the facility was marked as failed, the color of the model turned red. Furthermore, the user in the remote office visualized the site situation in real time through the screen sharing function, which would facilitate his/her decision-making. Afterwards, the user in the remote office gave 'Instructions' to the site user. The site user would act according to the received 'Instructions' and update the condition information after repairing the pipe. All changes of facility information and the exact time of changes were recorded in the developed system database. Screenshots of the site device and the remote device are shown in FIG. 10.

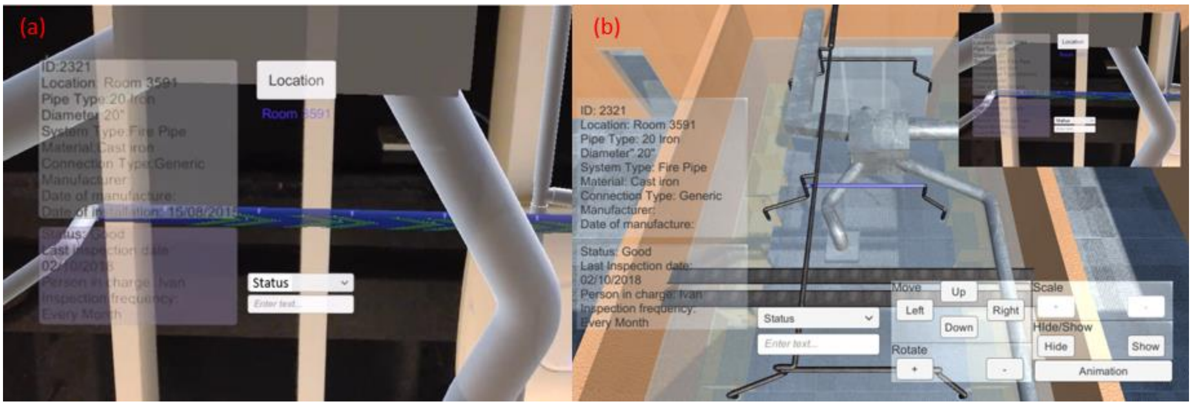

FIG. 10: (a) Screenshot of the on-site device, (b) Screenshot of the remote device in office

4.2 Experiment design

After developing the AR collaborative system, a user test was conducted to evaluate the feasibility and efficiency of the system. The scenario of the user test focused on inspection and repair of facilities. Specifically, a failure of facility occurred on site and was noticed by a FMM staff during inspection. The FMM staff reported the failure to the FMM office. Then the person in charge of the FMM office arranged corresponding technicians to check and repair the facility.

The user test was designed in a way that participants were required to use the developed AR system and traditional method to perform two levels of tasks: inspection and repair. An office in the Academic Building of the HKUST was selected as the test site. All participants were grouped into different teams, each of which contains 3 participants, with one as a FMM inspector, one as a FMM manager and one as a technician. During the test, a marker was attached to a water pipe above the ceiling of the office to represent failure. In the inspection level, another marker representing water leakage was attached to a ceiling panel next to the ‘failed’ pipe. For the proposed AR method, the FMM inspector first noticed the water leakage on site. He then used the developed AR system to locate the pipe and reported the failure to the FMM manager. In the end, the FMM manager could get to know the failure and the exact failed pipe. For traditional 2D drawing-based method, when the FMM inspector noticed the failure, he/she then called the FMM manager. The inspector needed to report the failure, the room number and exact location of the failure (according to his/her estimation). Then the FMM manager needed to find the pipe on the corresponding CAD drawing based on the given information. Five entries were recorded in the inspection level: (1) the total time from the inspector noticing the failure to the FMM manager finding the exact facility, (2) the time for operation, which refers to the time for the inspector to locate the failed pipe, (3) the time for communication, which refers to the time for the inspector to report the failure to the FMM manager, (4) the localization accuracy of both methods, and (5) whether the failed pipe found by the FMM manager is the one with the failed marker. In the repair level, the marker representing water leakage was removed. For the proposed AR method, the FMM manager gave instructions to the technician through the AR system. Then the technician went to the office to check the failed facility. Once the technician arrived at the office, he/she found the failed facility through the system. For the traditional vision-based method, the FMM manager gave instructions to the technician through a call. Once the technician arrived at the office, he/she used a ladder to remove the ceiling panel and found the failed pipe. Two entries were recorded in the repair level: (1) the time from the technician arrived at the office to the technician found the failed pipe through the AR system; and (2) whether the failed pipe found by the technician was the one with the failed marker. Detailed workflow of the designed user test is shown in TABLE 4.

TABLE 4: The workflows of the designed user test.

	AR method	Traditional 2D drawing-based method
Inspection	1. The inspector notices the problem. 2. The inspector uses the developed system to locate the pipe and report the failure to the FMM manager. 3. The FMM manager receives the updated information in the system and get to know the exact failed pipe.	1. The inspector notices the problem. 2. The inspector calls the FMM manager and report the failure based on his estimation. 3. The FMM manager searches for the pipe on corresponding CAD drawing based on the given information.
	AR method	Traditional vision-based method
Repair	1. The FMM manager gives instructions to the technician through the AR system. 2. The technician goes to the office to check the failed facility. 3. The technician uses the AR system to find the failed pipe.	1. The FMM manager gives instructions to the technician through a call. 2. The technician goes to the office to check the failed facility. 3. The technician uses a ladder to remove the ceiling panel and searches for the failed pipe.

48 students, aged from 23-29 and with background in Civil Engineering, were invited to do the user test. The 48 participants were grouped into 16 teams randomly, with 3 students in each team. Then a counterbalanced measures design was used in this user test to rule out the effect of test order. 2 groups were formed from the 16 teams, with 8 teams in each group. Group 1 was required to perform the task using the AR method first and perform the task again using the traditional method. Group 2 was required to perform the task using the traditional method first and perform the task again using the AR method. The target pipes for the AR method and the traditional method were different, so that the participants cannot use their memory to find the target while using the second method. Before the user test, a basic training was conducted to teach the participants how to use the AR collaboration system. During the user test, a tablet (Google Pixel C) was used by the FMM inspector and technician, while the FMM manager used a laptop computer (MSI MS-16JC).

4.3 Results and Discussion

A comparison of completion time of the assigned tasks using different methods was made to evaluate the efficiency of the system, while the comparison of accuracy of finding the correct facility using different methods was made to indicate the quality of the system. Based on the results recorded during the user test, the following analysis was made.

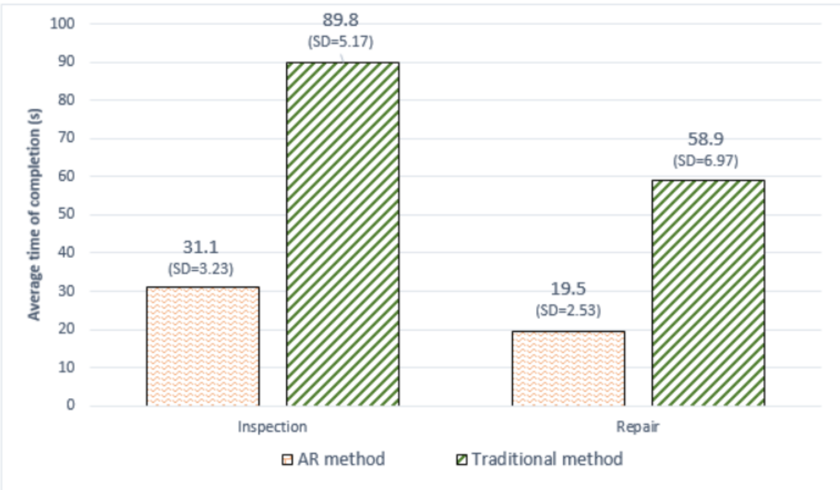

FIG. 11. Statistical results on time of completion

As shown in FIG. 11, the average time of completion in the inspection level using the developed AR system was 31.1s, while the average time of completion using traditional 2D drawing-based method was 89.8s, which means that the AR system can reduce the completion time by 65.4% during inspection compared with the traditional method. In the repair level, the average time of completion using the developed AR system was 19.5s, while the average time of completion using traditional vision-based method was 58.9s, which means that the AR system can reduce the completion time by 66.9% during repair compared with the traditional method. On the other hand, in the inspection level, the SD of the result using the AR method was 3.23 and the SD using traditional method was 5.17, while in the repair level, the SD using the AR method was 2.53 and the SD using the traditional method was 6.97. The deviation of using the AR method was mainly due to the fact that different participants have different levels of proficiency in operating the AR system – someone might need more time to find the correct button or update the information. For the traditional methods, the deviation mainly came from the communication among different users, as it was difficult for the inspector to let the FMM manager fully understand where the failed facility exactly was. Someone could explain the problem and location more clearly and efficiently than others. In the inspection level, as the p-value was less than 0.05, it could be indicated that the null hypothesis of analysis of variance (ANOVA) was rejected and the result was statistically significant. Similarly, in the repair level, the p-value was also less than 0.05, it can be indicated that in the repair level, the null hypothesis of ANOVA was also rejected and the result was statistically significant as well. Therefore, it can be concluded that the developed AR system has a significant advantage in reducing the completion time compared with the traditional methods.

The total time of completion included time of operation and time of communication. As shown in TABLE 5, the average time of operation for the AR method was 11.1s, while the average time of operation for the traditional method was 13.3s. It can be concluded that locating the failed facility using 2D drawings was almost as efficient as using the AR system if sufficient information have been provided. However, the difference between the time of communication for these two methods was significant. Compared with the traditional method, the time of communication for the AR method has been reduced by 73.9%, indicating a great improvement on remote collaboration.

TABLE 5: Statistical results on time of operation and communication.

		Average (s)	SD
AR	Operation	11.1	2.06
	Communication	20.0	2.72
Traditional	Operation	13.3	3.02
	Communication	76.5	5.34

As shown in TABLE 6, the average localization error of the AR method was around 102cm and 15 out of the 16 teams found the correct pipe from the remote office. While the average localization error of the traditional method was around 185cm and only 9 out of the 16 teams found the correct pipe from the remote office. It can be concluded that the capability to find the correct facility is determined by the localization accuracy of the method. The AR method has an advantage in locating the correct facility compared with the 2D drawing-based method. Failure to find the correct facility with the 2D drawing-based method was mainly due to the inaccurate estimation by inspectors.

TABLE 6: Statistical results on localization errors and correct ratio.

	Error (cm)		Correct ratio
	Average	SD	
AR	102	13.1	15/16
Traditional	185	53.7	9/16

The capability of the AR system to find the failed facility depends on the accuracy of the proposed localization method, which can be affected by several factors, such as the distribution of routers, the stability of Wi-Fi signals, the density of stored Wi-Fi fingerprints, etc. With the experimental conditions mentioned in the previous section, the localization accuracy of the AR system was around 1m. As a result, the system cannot differentiate two pipes if the distance between them is less than 1m. In the user test, the distances among each facility were larger than 1m. The correct ratio to locate the failed pipe would decrease if the pipes has a higher distribution density. On the other hand, with the developed AR system, users cannot differentiate facilities that are above the ceiling and horizontally overlapping with each other. Although the localization method based on Wi-Fi fingerprinting can achieve both horizontal and vertical localization, users cannot know which the failed facility is if facilities are overlapping above the users.

5. CONCLUSIONS

FMM, which refers to activities taken to prevent facility failure, incurs a large amount of operational cost of building facilities. To improve the efficiency of FMM, a BIM-based location aware AR collaborative framework is developed, with BIM as the data source, AR for interaction between users and facilities, and Wi-Fi fingerprinting for providing real-time location information. The developed framework has the following features: (1) a proposed S-WKNN algorithm, which has been proved to have better accuracy and stability than the commonly used 1NN, is used for Wi-Fi fingerprinting to obtain the current location of users; (2) a room identification method, based on BIM, the obtained location, and ray casting algorithm, is proposed to identify which room the user is currently in; (3) according to the obtained location and the identified room, users can visualize and interact with their surrounding facilities through the AR devices; and (4) users in a remote location can visualize site situation and interact with site facilities in real time through video streaming and the shared database. An illustrative example is also used to demonstrate the functionality of the proposed framework.

As shown by the results of a designed user test, the developed AR collaborative system in the user test has an advantage in improving the collaboration efficiency for FMM. Specifically, the AR system can reduce the completion time by around 65% compared with traditional 2D drawing-based method, which is mainly due to an increase of communication efficiency. Furthermore, the AR system can provide a localization accuracy of 1m so that the capability to find a certain facility is promising if the distances among each facility are larger than 1m. However, the developed system cannot find a certain facility accurately if the facilities are arranged in a very high density. Another limitation of the developed AR framework is its high dependence on the environment. The whole area should be covered with Wi-Fi signals. Therefore, the developed system can hardly be used in outdoor environment or during a power failure period. Furthermore, varying Wi-Fi signals can influence getting the nearest Wi-Fi fingerprints, thus reducing the localization accuracy. Therefore, the future work of this study will focus on improving the localization accuracy and reducing the dependence on the environment.

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