An integrated system framework of building information modelling and geographical information system for utility tunnel maintenance management

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ABSTRACT

Utility tunnel should be well maintained for it services public pipelines and city operation. In the recent time, utility tunnel has been operated via computer maintenance management systems (CMMS) or building automation systems (BAS). However, CMMS or BAS lack of convenient visualization and interoperability. This paper aims to propose an integrated system of building information modelling (BIM) and geographic information system (GIS) to improve the performance of current maintenance management system. A system framework of BIM-3DGIS is proposed and required maintenance management functions are also developed based on practice demands. A real case of utility tunnel is used to demonstrate the system. Two scenarios and a questionnaire survey are conducted to validate the applicability and practicability. Results show that the proposed BIM-3DGIS system can ensure effective maintenance works and have well potential applications.

1. Introduction

Rapid growths of urban city and underground construction have resulted problems in arranging underground space for assorted utilities such as essential pipes and cables (Canto-Perello et al., 2013). The expanding population with demands of diversified services makes the maze of underground pipes and cables even more complex. Utility tunnel, an underground tunnel which includes electric power, water, communications, heating lines, gas and other public services, is introduced as a useful and sustainable solution (Canto-Perello and Curiel-Esparza, 2013). The utility tunnel enables installation, maintenance and removal of public service pipes and avoids street cuts or excavations. Meanwhile, it also avoids former messing underground pipeline layout.

The utility tunnel makes public service pipes more efficient and cost-saving management, but it also increases the complexity and difficulties among different public service pipes in a limited underground space. Moreover, utility tunnel is the lifeline of urban city since it contains essential public services which support residential life and industry. Therefore, the utility tunnel needs to be efficiently and effectively maintained as every equipment problem or failure needs to be solved immediately and precisely to avoid serious operational and economic consequences. Previous researches had studied the risks and compatibility among different pipes (Canto-Perello and Curiel-Esparza, 2003; Curiel-Esparza and Canto-Perello, 2005; Fouladgar et al., 2011;

Ghorbani et al., 2012) and the maintenance management issues (Ben-Haim, 2012; Canto-Perello et al., 2009; Curiel-Esparza et al., 2004). However, a visual and comprehensive maintenance management system with information technology still needs to be developed to protect utility tunnel from potential threats.

Computerized maintenance management systems (CMMS) support operators to make maintenance planning, execution, assessment, and improvement (Kullolli, 2008) and are proved to bring a lot of benefits to today's AECO (Architecture-Engineering-Construction-Operation) industry such as increased productivity, reduced costs, and effective utilization of assets (Durán, 2011). However, CMMS are not user friendly due to it fails to provide an easy-to-understand interface (Al-Jumaili et al., 2014), visualize related assets and interoperate with other facility management systems such as acquisition of monitor data (Al-Jumaili et al., 2014; Tretten and Karim, 2014). As utility tunnels are located under the ground and the entrances are narrow. Facilities in it are enormous and three-dimensional distributed. Two-dimensional visualization cannot meet the maintenance management needs. Thus, the demand of 3D visualization of utility tunnels is important. 3D visualization helps maintainers to realize utility tunnel environment and objects, and then facilitates better decision-making. Monitoring data enable managers to better understand current operating status of the utility tunnel, detect and treat equipment failure immediately. So, maintenance management system should also include monitoring data

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to support efficient maintenance and avoid problem accumulation.

Utility tunnels are long distance infrastructure, which sometimes across the city and usually have multiple entrances for staff to access. Operators have to consider the above-ground construction and surrounding environment when arranging maintenance work to choose the most suitable entrances and exits. Therefore, maintenance management of utility tunnels also needs to be considered in a wider range of geographic information.

Building Information Modelling (BIM) is a unified information exchange platform for AECO industry which contains detailed information about facilities and equipment, and Geographic Information System (GIS) is a computer system for entering, storing, querying, analyzing and displaying geographic data. Although researchers utilized BIM, GIS (or 3D GIS) to establish tunnel maintenance system (Li and Jiang, 2010; Liu et al., 2009; Sandrone and Labiouse, 2017; Suo and Wang, 2013; Vossebeld and Hartmann, 2014; Zhou et al., 2017), a BIM and 3D GIS integrated framework for utility tunnels maintenance management is seldom proposed. Previous research (Yamamura et al., 2017) figures out the integration of BIM and 3D GIS has advantages in visualization, data abundance, large area facilities interpretation, which would be the trend of computerized management and visualization of infrastructures (Breunig and Zlatanova, 2011; Döllner and Hagedorn, 2008; Liu et al., 2017). The above-mentioned demands for visualization and data interoperability may also be solved by BIM and 3D GIS framework. Therefore, this paper proposes a system based on BIM and 3D GIS to help operators to conduct a comprehensive and overall maintenance management of utility tunnels. BIM and 3D GIS provide a source of information to maintenance management system and ultimately used as a visualization platform. This paper contributes to the existing body of knowledge by implementing BIM and 3D GIS in utility tunnel maintenance management with a focus on visualization, monitor data integration and maintenance management system development.

The rest of this paper is organized as follows. Section 2 presents the introduction of the relevant infrastructure maintenance management methods. Section 3 presents a system framework of BIM and 3D GIS to support utility tunnel maintenance management. In Section 4, the application of this framework will be demonstrated via a real project. Finally, Section 5 concludes this study as well as some discussions.

2. Literature review

2.1. Applications of BIM on infrastructure maintenance

A well-maintained infrastructure is crucial to perpetual economic growth and social development of modern society (Frangopol and Liu, 2007). Several researches have introduced methodologies to support maintenance and management of multiple types of infrastructures, including bridges (Hu et al., 2015; Li et al., 2016; Sawo and Kempkens, 2017; Zhang et al., 2016), roads and railways (Khouzani et al., 2017; Pan et al., 2016; Sadeghi et al., 2017; Setianingsih et al., 2017), tunnels and underground spaces (Jia et al., 2014; Li and Jiang, 2010; Wang et al., 2017). Several basic researches aim to develop essential management framework for infrastructure maintenance management were also proposed, such as a condition, safety, optimization and life-cycle cost based civil infrastructure maintenance and management framework (Frangopol and Liu, 2007). However, infrastructure maintenance and management still faces challenges such as performance monitoring, data management, etc. (Atkan et al., 2000; Parlikad and Jafari, 2016).

BIM—an open standard and platform of facility information creating, storing and exchanging—has gained extraordinary consciousness and adopt in the AECO industry. BIM can leverage the overall management of infrastructures. By coordinating and visualizing various kinds of data (including non-graphical data), it can manage the asset network more effectively and optimal capital, time and resources for intended purpose (Bradley et al., 2016). Infrastructure contractors

and engineers have accelerated the application and deployment of BIM to replace the previous 2D management pattern and large number of static documentation (Chang and Lin, 2016; Ding et al., 2017; Hoeber and Alsem, 2016; Tezel and Aziz, 2017). However, there are four research gaps still exist: (1) information integration, (2) data integration engine, (3) BIM process and business process alignment, (4) information governance framework (Bradley et al., 2016).

Compared to other infrastructure projects, underground space projects are facing more complex geological conditions, unpredictable factors (such as water gushing and fragile surrounding rock), and higher requirements of operation and maintenance (Zhou et al., 2017). The current adoption of BIM in lifecycle operation and management of urban tunnels proved to be more efficient. (Min and Yi, 2016; Zhou et al., 2017).

To apply BIM in tunnels and underground spaces, several researches proposed data standards and modeling methodology (Koch et al., 2017; Lee et al., 2016). Xiong et al. (2016) developed an collaborative framework for tunnel construction and can be extended to operation and maintenance management phase. Hossam et al. (2016) attempted to establish a tunnel BIM model for tunnel structure maintenance and management.

Utility tunnel can be regarded as a special kind of tunnels or underground spaces, which contains massive public services pipelines and equipment. Researches on utility tunnels are mostly focused on planning (Canto-Perello et al., 2016, 2009), design (Canto-Perello and Curiel-Esparza, 2001; Chen et al., 2012; Luzhen et al., 2010) and construction phase (Mohamed and AbouRizk, 2005; Petrukhin et al., 2013). Few researches focus on operation and management, while mostly are about risk management (Canto-Perello et al., 2013; Curiel-Esparza and Canto-Perello, 2005; Mao and Zhang, 2017). There is still a lack of researches to support an effective utility tunnel maintenance management, especially with the application of BIM to provide an integrated system framework. As mentioned in Section 1, utility tunnels have characteristics such as long mileage and concealing under the ground, which BIM cannot completely solve the problem of navigation and surrounding environment visualization.

2.2. Integration of building information modelling and geographic information system (GIS)

While it represents facility's physical model, functional characters and rich construction information, BIM does not include much surrounding information which is needed to environmental evaluation, resource arrangement and safety analysis (Rafiee et al., 2014; Yau et al., 2014). For example, geological information, which is essential to the design, construction and operation of tunnels and underground spaces, can be accessed in GIS. At present, more and more researchers are trying to combine BIM and GIS.

GIS focuses on the shape of buildings and building components from a geographic perspective, while BIM focuses more on detailed building components and project information from an architecture and construction perspective (Cheng et al., 2015). Although BIM and GIS have dissimilarities such as different developmental stages, different spatial scales, different semantic and geometric representations (Liu et al., 2017), combination and integration of these two different concepts still attract many researchers, as it is an opportunity to make different information complement and develop a more comprehensive information platform to support facilities life-cycle operation and management.

2D GIS cannot explicitly support new applications such as facility management and risk management which require information about facility interiors and 3D geometry attributes (Breunig and Zlatanova, 2011). Researches focused on adding 3D models to 2D GIS and extending 2D GIS to 3D GIS have increased significantly (Breunig and Zlatanova, 2011).

To overcome data and format gap between BIM and GIS, new data standards or translation methods of existing standards are introduced

by several researches. For example, the InfraGML was proposed to cover the areas of land usage and civil infrastructure facilities (Aien et al., 2015). As well as GeoBIM was introduced to combine the strong part of BIM and GIS (Laat and Berlo, 2011). There is a review which has a good summary of these integration methods (Liu et al., 2017).

Several researches on underground spaces have benefited from the integration of BIM and GIS. GIS can be used to support data acquisition and analysis (Hijazi et al., 2012; Karan et al., 2015; Wu et al., 2014; Yamamura et al., 2017), feasibility study (Park et al., 2014), construction (Bansal, 2011; Castro-Lacouture et al., 2014; Irizarry and Karan, 2012), and management (Liu and Issa, 2012; Mignard and Nicolle, 2014; Shr and Liu, 2016) etc. In the scope of integrating BIM and GIS for tunnels and underground spaces, a risk control method was introduced to subway station construction (Du et al., 2015), an integrated design and simulation platform was proposed to shield tunneling (Ninić et al., 2017), a geometric-semantic modeling method was developed to support tunneling and subway planning (Borrmann et al., 2014) etc. But there still lacks of researches which focus on the integrating BIM, GIS and maintenance management information for effective utility tunnel maintenance management.

Comprehensive maintenance management of utility tunnels needs complete equipment-related information, geographic coordinate information, topographic information and surrounding environment information, which can be accessed in BIM and 3D GIS. Therefore, this paper proposed an integrated maintenance management framework for utility tunnels which utilized BIM and 3D GIS as data repository and comprehensive visualization platform.

3. The BIM-3DGIS framework of utility tunnel maintenance management

3.1. System structures

The prototype system contains data layer, data linking and processing layer as well as application layer. The structure of these three layers is shown in Fig. 1. The data layer contains geometry model files, a database of related information extracted from the BIM model and 3D GIS model, and a monitoring database acquired from building automation system. In the data linking and processing layer, data in the data layer will be processed based on design function. Finally, the prototype system will achieve maintenance management functions in the web-based management platform, as well as visualization and linkage functions in the BIM-3DGIS platform.

3.2. Data processing

The data layer is the foundation of the entire maintenance management system. Data origins are BIM model, 3D GIS model and related documents and information of utility tunnel maintenance management. Information processing process can be divided into data acquisition and data integration. During information acquisition phase, data from each information source are converted to a database acceptable format and then stored. In data integration phase, the linkage between each database and related documents will be established through the element ID, COBie/OmniClass based unique ID, coordinates and elevation. Fig. 2 shows the data flow chart of this maintenance management framework.

3.2.1. BIM data acquisition and processing

This phase will process the geometry information and attribute information of the verified and refined BIM model.

At first, the BIM model for design and construction, together with the blueprint for the construction, will be checked and verified to determine if the BIM model is consistent to the constructed utility tunnel. After checking and adding attributes information such as equipment suppliers, equipment serial number, a built BIM model will be created. Built BIM model should include utility tunnel's structural model, pipeline and equipment model, as well as sensors and devices model. The built BIM model requires high level of detail to be able to display and query element attributes in maintenance management system.

Elements' additional property fields should match the classification and coding of the maintenance management work (see Section 3.2.3 and 3.2.4). These attribute fields represent the business logic of maintenance management and facilitate the classification and query of components in future maintenance management system. It is also a preparation of data linking between BIM information and maintenance management information. Those attribute fields require a unique ID field assigned by maintenance managers. Table 1 shows the additional attribute fields and example values in a BIM component.

Sensors and devices in the built BIM model need to add monitor data attributes fields for later real-time monitoring data addition and linking. This work avoids the task of adding a data field to database again after exporting data to database and enables the information model to exchange information to database data and vice versa. Thus, BIM model with sufficient attributes would be ready for maintenance management. Information in it will be divided into visualization geometry data and attribute data, and then exported to the database.

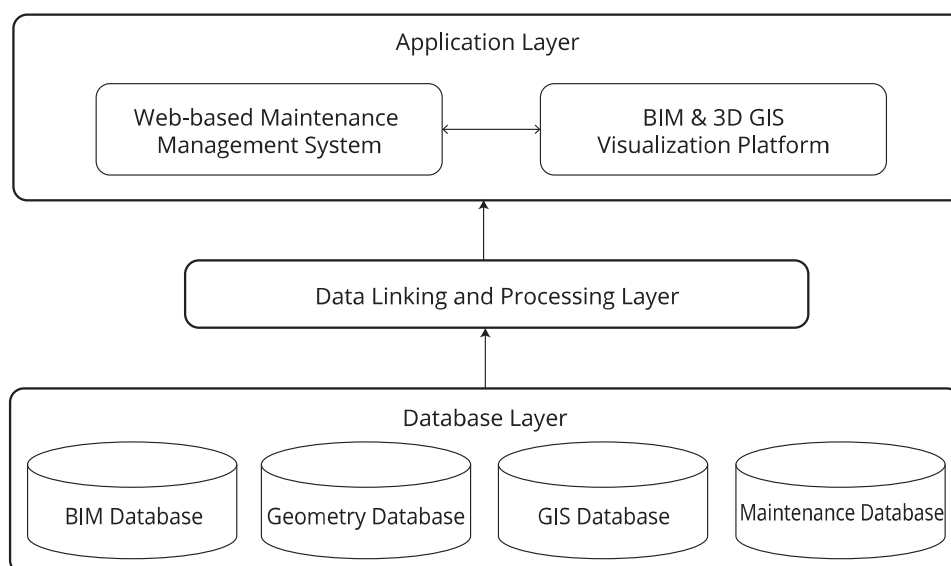This study chose FBX format as the format for exporting 3D data

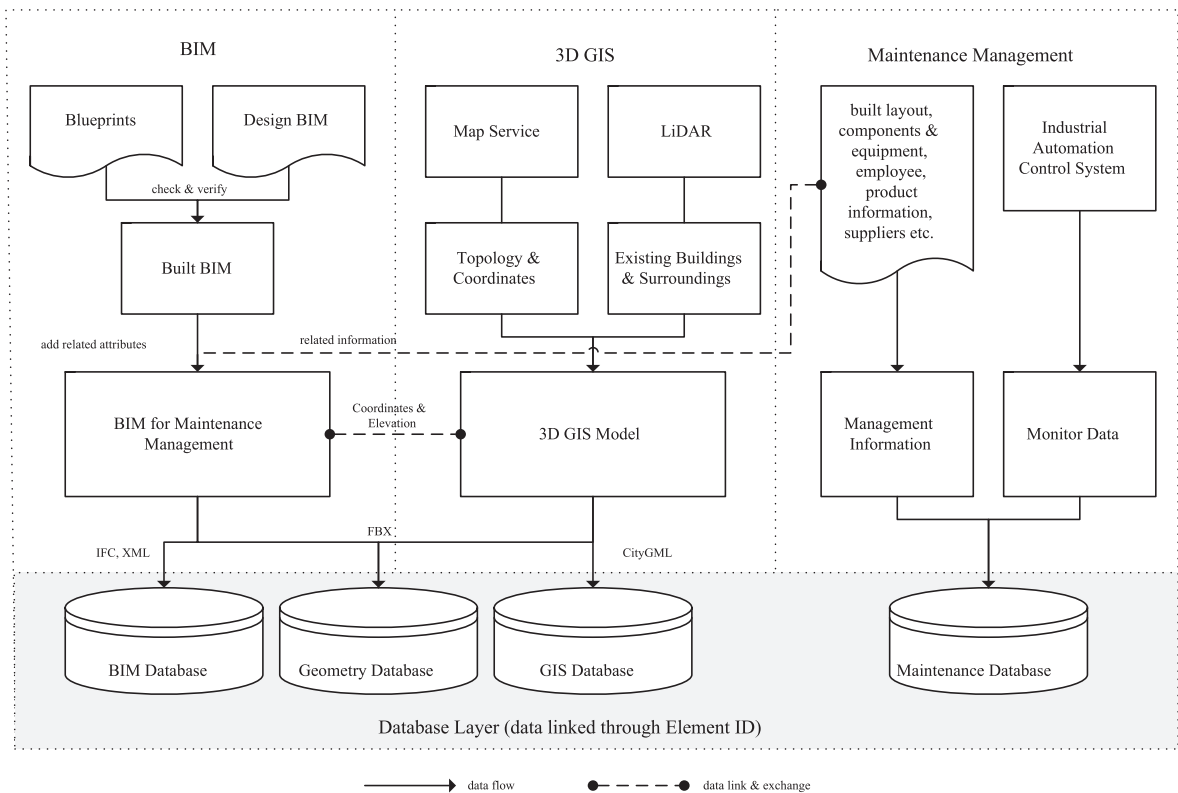**Fig. 1.** The Structure of the proposed framework.

Fig. 2. Data flow of the proposed framework.

from BIM model, as it can be exported and accept by most BIM modeling software and contain texture information. Since textures are exported at the same time when geometry data are exported, the material definition, material name, and material texture of BIM model need to be checked before exporting. BIM model is segmented according to the zoning plan for construction and management, which enables the final maintenance management system to partition the 3D model, highlight it separately and locate it quickly. Finally, exported FBX models are reviewed and processed again in professional 3D modeling software, including model checking (e.g. check the shape of the model, whether it is in the wrong position, whether the texture is correct, etc.), simplifying the model (e.g. reduce the number of model polygon surfaces, simplify the model details that are not needed in operation phase, etc.).

The IFC format, a wildly accepted BIM data format in AEC industry, allows researchers to import relevant property information from BIM model into database (Chupryn, 2013; Solihin et al., 2017). Database queries are used to read and refresh information within them, which is faster and more convenient than going back to BIM model to changing and exporting data again. By extracting this information to database, it allows management system to be expanded and updated to the latest information by merely adding additional data or just refresh data in the database, and avoids modifying the code of the system and BIM model.

Each entity in the IFC file is uniquely identified by a Global Unique ID (GUID), which is also exported to the database. The GUID in the IFC format consists of letters and numbers. For database performance it can be converted to a pure digital ID, which is called Element ID.
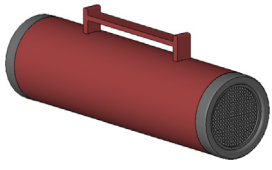
3.2.2. 3D GIS data acquisition and processing

3D GIS model in this system mainly contains topographic and co-ordinate information, as well as surrounding building information. The source of the terrain and coordinate information is the national map service database. Surrounding building model information can be obtained by UAV-Based Oblique Photogrammetry.

There is a unit, coordinate, elevation and other data exchange between 3D GIS model and Built BIM model. During building information modelling, the coordinates of the project's base-point location need to correspond to real project's geographic coordinates in 3D GIS model. The elevation of the BIM model also use the true altitude elevation obtained from the 3D GIS rather than the relative elevation.

The 3D GIS model, like BIM model, exports geometric visualization data via FBX and other attributes information to GIS database via CityGML. Each entity in the CityGML file is uniquely identified by a Unique ID (UUID), which is also exported to the database. The UUID in the IFC format consists of letters, numbers and dashes. For database

Table 1
Additional attribute fields of BIM element.

Attributes field	Example value	Annotation	Example element
eq_id	K1JFH138	Unique ID	
eq_std	FIRE-HYDRANT	Element Category (i.e. Lighting equipment, Electric wire etc.)	
domain	MEP	Element Domain (i.e. Structure, Architecture, MEP etc.)	
name	Ceiling Type Automatic Fire Hydrant	Element name	
rd_id	J12	Road Number	
rm_name	109	Room/Section Number	
ml_id	K1	Kilometer Mileage	
mp_id	700–720	Detailed milepost (this example means K1 + 700 − K1 + 720 of Road J12)	

performance it can be converted to a pure digital ID, which is called Element ID.

3.2.3. Maintenance data acquisition and processing

Maintenance management data sources include equipment maintenance plans, equipment and sensor lists, employee information, product data, supplier information and other traditional maintenance management data. Industrial automation and control system is the repository for automatic monitoring data.

Additional attributes added to BIM elements contains unique ID assigned by maintenance management department. Maintenance managers usually classify and number the assets according to the Construction Operations Building Information Exchange (COBie) or OmniClass Construction Classification System (OmniClass or OCCS) standards. Under the guidance of COBie or OmniClass standard, managers classify and assign unique ID to each equipment or asset. The codes used by maintenance managers are assigned according to business logic (such as by space or by category), while the unique ID in BIM and GIS are used to uniquely identify a component during computer internal processing, which is usually randomly generated. The unique code used by maintenance staff has meaning. By reading the code of an equipment, the staff can learn the relevant information about the component. The unique IDs in BIM and GIS are usually non-semantic for people. Other managers may build their own coding systems based on their business logic, but these coding systems generally have similar classification characteristics to those of COBie and OmniClass. As long as these coding systems can identify a device with a unique ID, the ID can be added to the BIM element attributes to enable data linking. The coding example in Table 1 is refers to the OmniClass standard, combined with the characteristics of the utility tunnel itself.

Traditional management data need to be converted into a computer-readable format and stored in the management information database. Since traditional management data are often reordered on paper materials, manual entry is necessary to import the data into the electronic database if users want to access the previous paper maintenance records in management system.

Monitoring data returned by industrial automation and control system will be stored in monitoring database after processing. Since different sensors and equipment may come from different suppliers, raw data extracted from automation control system need to be parsed and converted to correct format before importing the information into monitor database. Some sensor may return analog signal, which also needs to be converted to correct digital information.

Data in the two databases above (management information database and monitor database) will eventually be saved in maintenance database after adding element ID tag.

3.2.4. Data integration

Fig. 3 shows how the information in the data linking layer is linked. The data linking layer is based on the BIM component as a central information bridge. BIM, GIS and geometric information are connected by Element ID. In addition to Element ID, there are also coordinates and elevation link between BIM and GIS information. The data link between BIM information and maintenance management information is via COBie/OmniClass based unique ID.
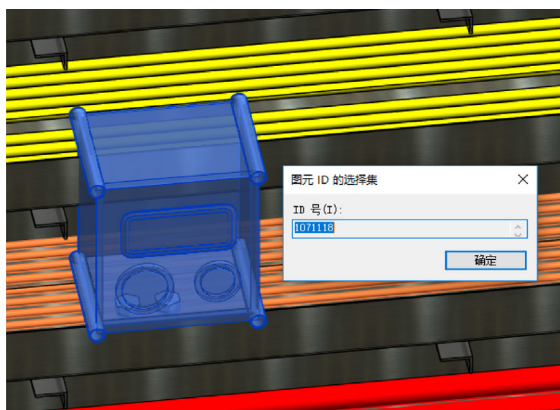
In the Element ID link aspect, the IFC and CityGML formats themselves contain the element IDs that uniquely identifies the artifact. At the time when 3D geometry data are exported, element ID is also exported with each model component or element, as well as the attributes data that exported from BIM and 3D GIS. By using element ID, maintenance management system can query database for related attributes and information or search the element in 3D model and highlight it. The coordinate and elevation connection between BIM and 3D GIS is mainly used to locate the BIM components or the section of the utility tunnel in 3D GIS, so as to show the relationship between the utility tunnel and the surface, as well as the surrounding environment. When we built the BIM model we added additional attribute fields to the BIM elements and filled in the unique IDs assigned by maintenance managers. In this way, we establish the corresponding relationship between the BIM information and the maintenance management information.

Fig. 4a shows the element ID of a component in 3D model, and Fig. 4b shows the element ID field of the component in database.

The process of integrating monitoring data into the management system is shown in Fig. 5. First, system receives relevant monitoring information through the industrial automatic control system and searches the relevant rules according to the element ID in database. Second, the system judges whether the monitoring information are normal according to the rules. If the information is normal, it indicates that the current operation status of this utility tunnel is normal, system will then store the latest information into database to form the historical data accumulation. If the information is abnormal, system will search maintenance database for historical maintenance data, search property database for relevant property information, and find the corresponding component in BIM-3DGIS model to highlight the component. Finally, the system will provide the user with a visual model with relevant information and a monitoring database with the latest monitoring data.

3.3. Prototype system functions design

In the aspect of the prototype management system designed, this study summarizes the functional requirements from practical experience and previous research literature of operation and management, including staff management, document management, equipment management, task management, periodic maintenance management, real

(a) Element ID in Geometry Model

(b) Element ID in Database

Fig. 3. Data linking layer of the proposed framework.

(a) Element ID in Geometry Model   (b) Element ID in Database

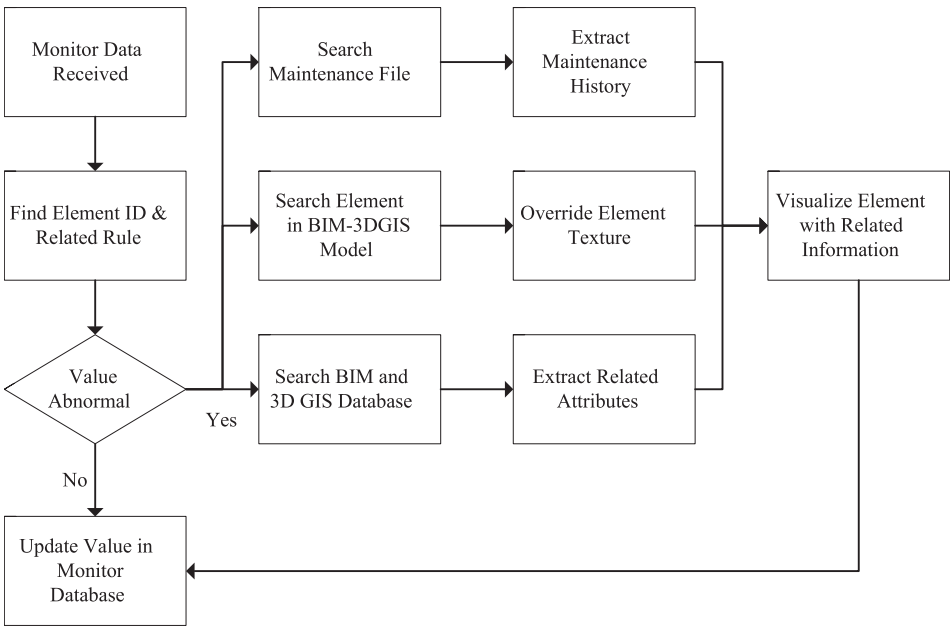**Fig. 4.** Element ID in the geometry model and database.

Fig. 5. Process of integrating monitoring data into the proposed system.

Table 2
Model elements and data sources of the illustrative example.

Model elements	Data sources
Topographical surface and information (GIS)	National open map database
Surrounding buildings	UAV-Based Oblique Photogrammetry
Utility tunnel model (BIM)	Design and construction plans
Sensors	Sensors installation plan

time monitoring and visualization functions. The function of this system includes interconnection and inter-query between visual graphics and electronic information.

Human factors like maintenance technicians and other stakeholders are the foundation of the maintenance management system (Simões et al., 2011). The effectiveness of maintenance management depends on a large extent about competency, training, and motivation of human factors. Staff management in this system enables the operator of the utility tunnel to have an overall grasp of the entire maintenance team.
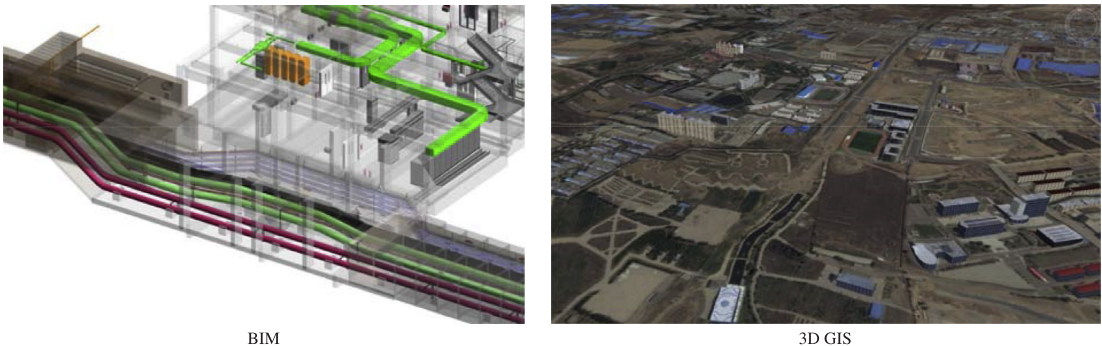

BIM   3D GIS

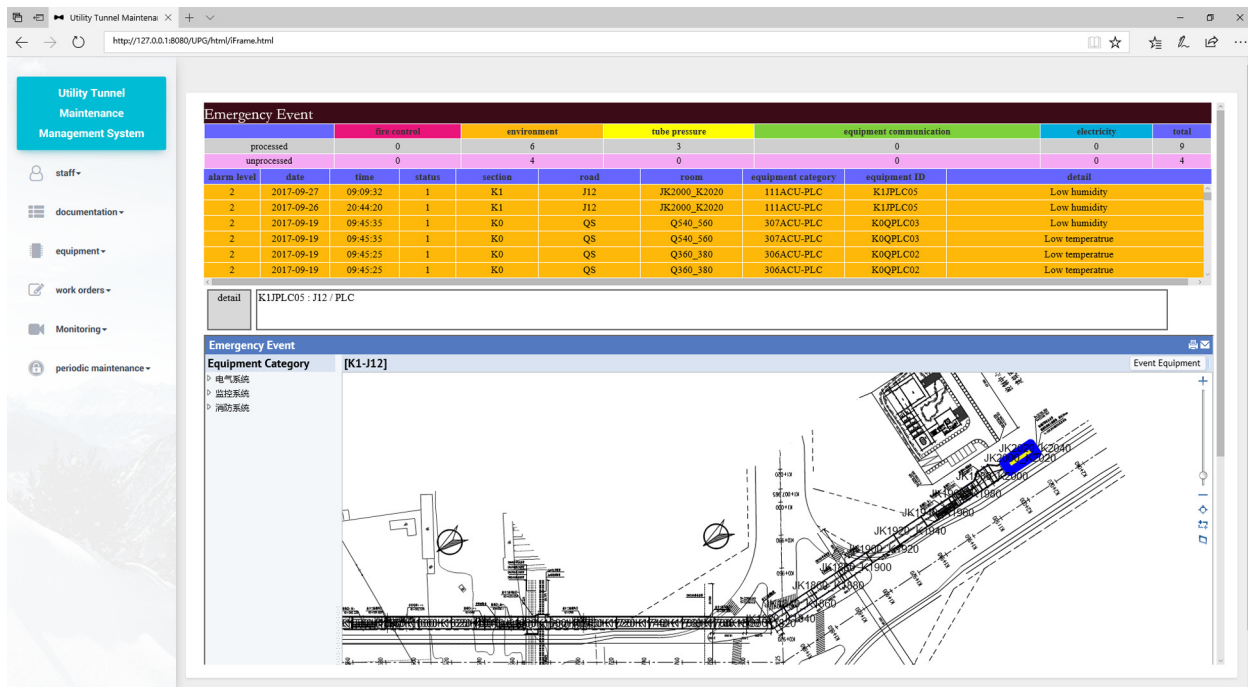**Fig. 6.** BIM model and 3D GIS model.

Fig. 7. Monitoring function of the prototype system.
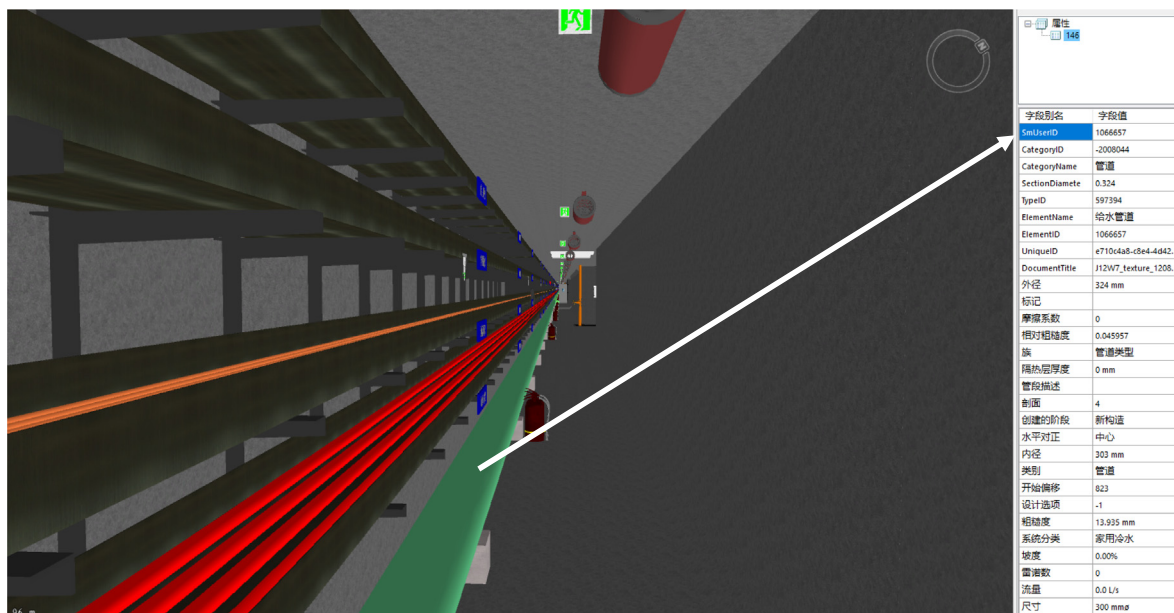
Fig. 8. BIM-3DGIS platform highlighting a device and displaying related information.

Table 3
Periodic maintenance process.
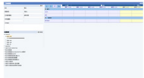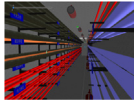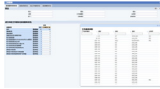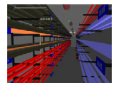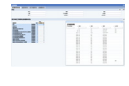
Process	Maintenance arrangement	Maintenance preparation	Maintenance	Report and analysis
Management	Manager: Periodic Maintenance work orders.	Staff: View work details; Prepare the task list.	Staff: Query device related information; Record the damage information; Fill in the report.	Manager: Check and analyze the report; Release maintenance tasks if fault inspected.
Management Interface or Visualization				

Table 4
Corrective maintenance process.

Process	Identify problem	Task arrangement	Task preparation	Repair	Report and analysis
Management	Manager: Show warning; View historical work status; Corrective maintenance decision making.	Manager: Corrective maintenance work orders.	Staff: View work details; Prepare the task list.	Staff: Query device related information; Fill in the report.	Manager: Check and analyze the report; Release new maintenance tasks if fault still exists.
Management Interface or Visualization					

Staff management makes maintenance team archive more flexible work, more collaboration and more reasonable allocation of responsibilities, as well as it allows maintenance staff to perform more technically challenging maintenance works (Richard et al., 2000).

Document management transforms the traditional paper-based document management into electronic documents. Computerized document management solves the problems faced by traditional documents management mode, such as difficult to carry and look up a lot of paper documents piece by piece, difficult to store paper documents and difficult to update the latest information to all paper records synchronously.

The importance of asset management for operation and management has been proved (Maring and Blauw, 2018; Schuman and Brent, 2005; Vanier, 2001). Technically asset management includes maintenance management activities. Since the maintenance management activities, such as work order management and preventive maintenance management, are included in other function module in the prototype system, this asset management function module focuses more based on storing and managing asset attribute information, such as supplier, serial number, production date, and maintenance history. The aim of asset management is to enable more efficient and cost-saving decision making towards maintenance of assets or equipment.

Work order management system including work order creation, scheduling, execution and completion is the essential function of maintenance management system (Cato and Keith Mobley, 2002; Crespo Marquez and Gupta, 2006). Work order system improves the intercommunication between all stakeholders in a maintenance task request. In this proposed maintenance system, all maintenance work is covered by work orders. No matter the problem comes from which public service system or equipment, the work order system utilizes a work order to record the details of this task, which can be accessed conveniently by manager and stuff. Managers can assign the work order to departments or employees based on work order information and the overall maintenance workload.

Previous research figures out that the preventive maintenance or periodic maintenance to reduce maintenance costs and extend equipment life (Swanson, 2001). It involves periodic measuring, detecting, analyzing, and correcting equipment problems to avoid failure. Preventive maintenance or periodic maintenance in utility tunnel is important to guarantee its operation for a long time. The traditional handmade and paper recorded inspection methods have disadvantages such as possibility of missing inspection, poor real-time data ability, inaccurate assessment and data isolation. This preventive maintenance system includes inspection arrangement, task list, history record, work order assignment and other functions to solve the problems listed above.

While sensors continuously monitor the performance of the utility tunnel, managers need a comprehensive visualization platform to understand and analyze these monitoring data. The monitoring function of the prototype system provide a visualization platform for managers to understand the current operating status of the utility tunnel and find emergencies and determine specific maintenance timing.

In the prototype system, BIM-3DGIS is also utilized as a visualization platform. Visualization provides functions of preview, roam, highlight and display related information for managers. Since the information of visualization platform is linked with the information of the above management functions, operators can obtain visual feedback on the visualization platform when doing management activities in the management platform and vice versa. For example, when managing the basic information of a device, the manager can see its 3D model, its space location and surrounding environment in visualization platform. When scheduling a periodic maintenance task, manager will see the highlighted equipment and tunnel zone involved in the task in visualization platform. Hence, the manager can plan work route in visualization platform.

4. Illustrative example

4.1. Case background

This study takes a practical utility tunnel project in China as an example. The mileage of the built utility tunnel is 50.57 km. There are electric pipelines, heating pipes, water supply pipes, communications cables, radio and television cables, sewage pipes and gas pipes in utility tunnel. The construction of this utility tunnel was started in 2014 and completed and put into operation in 2017.

The industrial automation system in this utility tunnel project includes equipment and sensors. Equipment such as drainage pumps, blowers, and manhole covers, play a role in the function of utility tunnel and return data at the same time. For example, draining pumps send back its current flow rate and exhaust fans send back its current rotation rate. The sensors return relevant monitoring data such as temperature, humidity, carbon dioxide concentration, and smoke, etc.

In this project, the utility tunnel is divided into several sections, each with a set of equipment and sensors. Multiple parts of the devices and sensors form a dynamic data monitoring network which is controlled by industrial automation system. The data of each device or sensor can be accessed through the unique intranet IP.

The main problems faced by the maintenance manager are summarized as follow:

(1) numerous staff and equipment;
(2) difficult to organize and manage paper document;
(3) real-time monitoring;
(4) existing CMMS cannot meet the management needs of the utility tunnel;
(5) visualization of underground utility tunnel.

This study applied the BIM-3DGIS maintenance management system to this actual case, to solve the maintenance and management problems and test the feasibility and practical value of the system framework.

4.2. System application

4.2.1. Model development and data processing

This study creates a BIM model of the utility tunnel which later became a data source for the facility and equipment information database. During modeling process, related property information is added

Table 5
Details of the survey.

Investigation item	Very agree (5)	Agree (4)	Neural (3)	Disagree (2)	Very disagree (1)	Mean score	Standard deviation
1. It is necessary and useful to integrate BIM and 3D GIS in utility tunnel maintenance management system	56.7%	33.3%	10%	0	0	4.47	0.681
2. BIM and 3D GIS can help traditional maintenance management system to solve the utility tunnel's unique maintenance problem	46.7%	43.3%	10%	0	0	4.37	0.669
3. This prototype management system proves that this information integration framework of BIM and 3D GIS is working	30%	40%	30%	0	0	4.00	0.788
4. The system can assist the user in visualization and analysis of the performance of the utility tunnel	43.3%	50%	6.7%	0	0	4.37	0.615
5. The system can assist the user in immediate treatment of monitored fault in the utility tunnel	23.3%	36.7%	30%	10%	0	3.73	0.944
6. The system can improve the efficiency of the maintenance work of the utility tunnel	23.2%	60%	10%	3.3%	3.3%	3.97	0.890
7. The system can reduce the total cost of utility tunnel maintenance	43.3%	40%	13.3%	3.3%	0	4.23	0.817
8. The system can help the operation company to get a higher rate in performance valuation	43.3%	46.7%	10%	0	0	4.33	0.661

to corresponding device or pipeline in BIM model according to the maintenance management document. Although sensors are not in design and construction drawings, it still needs to be modelled and numbered to link monitoring data later. This study obtains relevant DEM data through the national public database and establishes the terrain model in 3D GIS model. Surrounding environment model us built using UAV-Based Oblique Photogrammetry. Table 2 shows a table of the parts of the model and their corresponding data sources, and Fig. 6 shows the screenshots of BIM model and 3D GIS model.

After completing each model, the geometric data of the BIM model and 3D GIS model are exported via FBX format, and the attribute data is exported to the attribute database.

4.2.2. Maintenance management system development

The web-based maintenance management system is written in HTML, as well as JavaScript to link to database. Fig. 7 is a screenshot of monitoring function of the prototype management system. BIM-3DGIS visualization platform, and the linkage function between 3D model and management screen shown in Section 3.2.4 are written in C# language. Fig. 8 is a screenshot of a BIM-3DGIS screen highlighting a device and its related information.

4.3. Scenarios

This paper uses two scenarios to illustrate the workflow of the maintenance management system and its benefit. The first scenario is about periodic maintenance. The second scenario illustrates how to use this system to deal with monitored fault.

4.3.1. Periodic maintenance

The scheduled maintenance process flow is elaborated as shown in Table 3. In the first step, manager arranges date, location, and equipment of maintenance task, and chooses the staff who would later enter the utility tunnel to execute maintenance. The manager can also choose which equipment to be maintained by clicking it in the BIM-3DGIS model. In the second step, the staff would receive maintenance task notification in the management system. Then he can view maintenance task detail and print task list in the management screen. BIM-3DGIS screen helps him to understand the task by visualize the equipment and surrounding environment. In the third step, the system can help the staff finish maintenance task by providing related information. After maintenance, the staff fills a maintenance report on the management platform. At last, the manager analyzes the maintenance report. In this case, with the help of visualization of reported equipment and its surroundings, managers can issue a repair task to repair the reported equipment failure.

4.3.2. Corrective maintenance

Table 4 shows the process of equipment maintenance after a fault was monitored. In the first step, the system displays an alarm of abnormal monitor information to the manager. The manager inquires the value of sensors or equipment, historical working data, and equipment attributes, and also views the 3D model in the BIM-3DGIS model to get a better understanding of what happened in the utility tunnel without stepping into the tunnel to inspect. The manager then identifies the exact problem from the data and visualization model provided by the system. In the second step, the manager sets up a repair task to the staff. In the third step, the staff receives the repair task and made preparation just as maintenance preparation in Section 4.3.1. In the fourth step, the staff go into the utility tunnel and repaired the equipment. At last, the repair report is submitted to the manager with literal version in the management screen and model version in the BIM-3DGIS model.

4.3.3. Benefit form survey

To assess the potential value of this utility tunnel maintenance management system, a survey is conducted and shown in Table 5.

The questionnaire includes eight investigation items which require participants to give their opinions by rating their agreement level. A five level Likert-scale is used in this survey. Participants in this survey include contractors, operators, maintenance managers and field workers.

According to the details shown in Table 4, the overall feedback is on the positive side. All the participants think that BIM and 3D GIS technology are needed in utility tunnel maintenance management, and hold positive opinions about the feasibility of the integration framework proposed by this paper. The visualization function developed in this prototype system also gets approval of the participants. The survey shows that the prototype system can improve efficiency of maintenance, reduce operation cost and help operation company get higher performance evaluation rate. Few participants express their concern about the implementation process of integrating the prototype system on traditional maintenance management. Because the implementation process requires adequate system handling training and "information technology based problem-solving awareness" of employees.

Many participants show interest in the information provided by the prototype system when dealing with faults. They suggest that the prototype system should not only provides related information about the equipment, but also provides repair suggestions based on recorded historical cases. This suggestion will be taken into consideration in future research of this prototype system.

5. Conclusions

Utility tunnels put original complex underground pipeline under unified planning and management. These facilities are undoubtedly in requirements of long-time stable operation and well maintenance, as they contain most essential public utilities which serving large urban areas. Nowadays, facility operators depend heavily on CMMS for maintenance activities. However, traditional maintenance management systems lack practical visualization function and interoperability capabilities to manage real-time monitor data.

This paper presented a BIM and 3D GIS based maintenance management system that responds to the requirements of visualization, data interoperability and maintain management activities assistance. BIM is used as an information repository of facilities and utilities' geometry and attributes information. 3D GIS provide topology, altitude and surrounding environment information to this system to support long mileage and large area management. A maintenance management system linked with the BIM-3DGIS visualization platform was developed to support a series of management actions and decisions of utility tunnels. Monitoring data is also integrated and visualized so that managers can make more timely maintenance decisions and actions.

The concept of this system was proved feasible and valuable by involving into a real utility tunnel project. The preliminary feedback from the survey of utility tunnel operators, engineers and the council is positive and a number of benefits are highlighted. The contributions of this paper include: (1) a method that enables the integration of data required for maintenance management in BIM and 3D GIS environment; (2) a process to link monitor data, related maintenance information and visualization model; (3) a process to extend visualization function of maintenance management system; (4) a framework of system to support utility tunnel maintenance management. In addition, the proposed framework and methodology used in this research can also be used for other underground constructions and infrastructures to support maintenance management.

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