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Review

3D reconstruction in underground utilities

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ABSTRACT

Underground utilities (UU) play a vital role in modern life. Creating an accurate, up-to-date, and comprehensive digital representation of underground infrastructure has become a top priority for the infrastructure planning, (re)development, construction recording, and safety management of UU projects. However, both industry and academia lack a common understanding of the latest progress, challenges, and decision-making frameworks for UU 3D reconstruction technologies. Therefore, 323 related articles are investigated and provides a scientific basis for selecting different technologies for various scenarios. First, the advantages, limitations, and the best performance of each technique are analyzed. Second, the current applications of UU 3D reconstruction are reviewed. Third, a decision-making framework is proposed for selecting 3D reconstruction technologies to help stakeholders scientifically choose appropriate technology routes. Finally, limitations and future work in this field are discussed.

1. Introduction

Underground Utilities (UU), such as water and sewage pipelines, gas and oil pipelines, communications, and data cables, are the lifeblood of modern human society and play a vital role in maintaining the lives of all urban residents. However, as the global population density continues to increase, the density of UU pipelines is also increasing. In the UK alone, there are over 600,000 km of sewerage pipes [1]. In China, according to data from the National Bureau of Statistics, at the end of 2017 there were 797,000 km of water supply pipes, 11,716 km of gas supply pipes, 630,000 km of drainage pipes, and 276,000 km of urban district heating pipes. In total, the length of the comprehensive urban underground pipe corridor is 2418 km [2]. The incomplete three-dimensional (3D) location information about these key urban assets has caused significant impacts, such as urban road congestion owing to the inaccurate excavation of public utilities, economic losses caused by water and power outages, and even human casualties resulting from the incorrect excavation of gas pipelines. The Pipeline and Hazardous Materials Safety Administration (PHMSA) of America reported that from 2001 to 2020, 12,505 pipeline accidents occurred, resulting in 270 deaths, 1176 injuries, and approximately $9.95 billions of property damage [3]. According to an investigation report released by the Underground Pipeline Professional Committee of the China Urban Planning Association, from October 2019 to September 2020 alone, there were 737 underground pipeline damage accidents in China, resulting in 166 casualties, representing an increase of 130.14% compared with the previous year [4]. Therefore, effective and accurate 3D reconstruction of UU is a critical need.

The 3D reconstruction of UU refers to the process of creating a digital representation or model of the underground infrastructure, including various utility systems [5,6]. This involves capturing and integrating spatial data from multiple sources, such as depth detection, horizontal localization, direction positioning, size detection, and other semantic information collection (e.g., materials, ownership, and functions) [7–9]. By generating a 3D visualization, UU 3D reconstruction can help accurately depict the physical location, geometry, and attributes of UU, enabling better planning, design, maintenance, and decision-making for infrastructure projects [10–12].

Various 3D UU reconstruction techniques have been applied; however, existing reviews have the following limitations: (1) while some studies review the development of 3D reconstruction technology and analyze technical details, they focus solely on the 3D reconstruction

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technology itself, neglecting the analysis of UU engineering practice and application scenarios. For example, Smith and Yu et al. [13–15] provide a detailed summary of the principles of each technology but lack an in-depth discussion of the characteristics and limitations of technology applications in engineering; (2) other reviews fail to comprehensively evaluate more recent technological advances. Examples include the summary of underground utility positioning technology and requirements conducted by the US Federal Laboratory in 2000 [16], the 2017 review by Metje et al. [17] on Mapping the Underworld (MTU) technology, and the 2013 review by Liu et al. [18] on technologies for underground water pipe exploration. Therefore, these studies are not currently sufficiently specific to, or provide a comprehensive assessment of, the field of UU 3D reconstruction and cannot, therefore, guide the selection of UU 3D reconstruction technology in modern engineering practice; and (3) current reviews also lack research on science-driven decision-making regarding the selection of UU 3D reconstruction technology.

Therefore, this study offers a contemporary and comprehensive review of 3D UU reconstruction technologies, with particular emphasis on their engineering application implementation. First, the latest state-of-the-art performance of various 3D reconstruction techniques are presented to help understand current progress. Second, from the perspective of a range of engineering scenarios, the application principles and key considerations relating to UU 3D reconstruction technology are reviewed to address the current gap in research on engineering application. Lastly, a first route selection framework is presented for the field of UU 3D reconstruction, which is aimed to assist practitioners when selecting appropriate 3D reconstruction technologies based on specific project requirements.

2. Review approach

Methods proposed by Thome et al. [19] were used to identify and review articles, as shown in Fig. 1. First, the scope of the review was defined as 3D reconstruction technology and its application in the field of UU, and the databases and keywords for the search were identified. Web of Science and ASCE databases were selected because of their wide coverage and high quality. The core search keywords included “underground utilities”, “subsurface utilities”, “pipelines”, “cables”, “3D reconstruction”, and “mapping”. In the first round of screening, in addition to the above keywords, additional keywords were also included, such as “detection”, “management”, and “depth”, so that the search would cover a wide range of related disciplines. The initial search yielded 323 highly relevant studies. Next, to ensure the quality of the articles, the following two criteria were applied for selection: (1) the articles had to be peer-reviewed, and (2) the abstract of each article was checked to verify its alignment with the scope of the study. Following this initial screening, a total of 187 articles were obtained and reviewed (Fig. 1).

3. Review of the key technologies for 3D underground utilities reconstruction

Based on several years of development in the field of 3D reconstruction in underground engineering, numerous techniques and methods have been developed. This section summarizes the main characteristics of these existing 3D reconstruction technologies by categorizing them into non-destructive technologies (NDT) and destructive technologies (DT), which differ according to (1) differing data-acquisition methods; NDT does not destroy the soil layer above the UU during data acquisition, while DT do; (2) differing reconstruction outputs; NDT reconstruction results represent the horizontal position and burial depth of the target UU (and some NDT technologies can obtain additional information such as diameter and material), and further processing is then required to generate intuitive 3D model information (e.g., a point-cloud model); and (3) differing reconstruction accuracies; the reconstruction accuracy of DT is typically much higher than that of NDT. As these three differences have an important impact on decision-making during the life-cycle management of UU projects, for the purposes of this review, UU 3D reconstruction technology is divided into NDT and DT. In Section 3.1 and 3.2, NDT and DT for UU 3D reconstruction are introduced respectively; and, finally, the advantages and limitations of these technologies are summarized in Section 3.3.

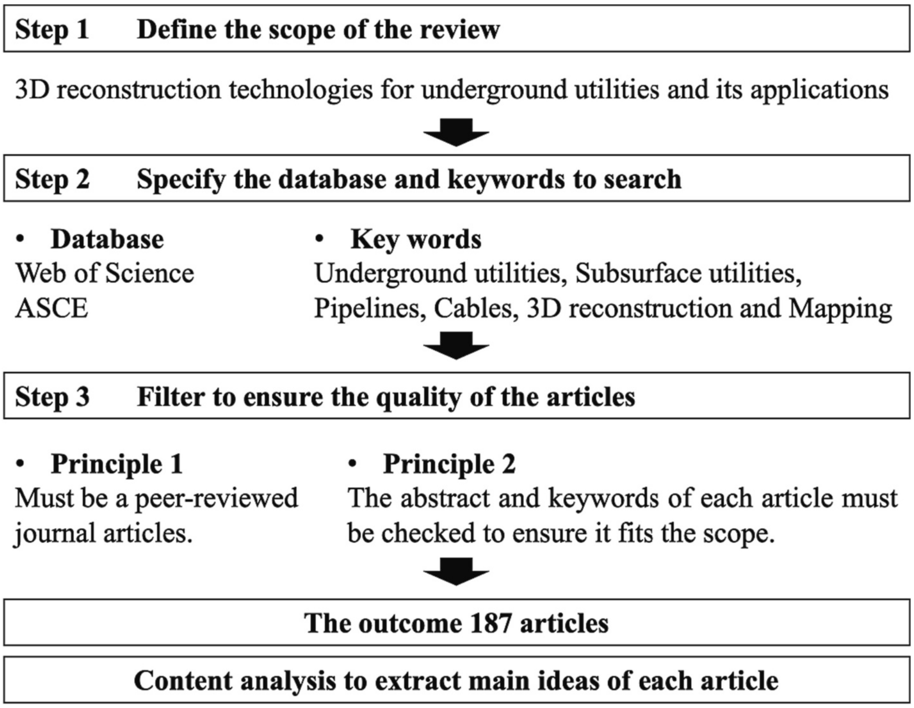

Fig. 1. Summary of research steps.

3.1. Non-destructive technologies

3.1.1. GPR

Ground-penetrating radar (GPR) is one of the most commonly used and efficient non-destructive 3D reconstruction techniques for UU. This operates by transmitting and receiving high-frequency electromagnetic waves using antennas to detect characteristics and distribution patterns within a target area [20,21] (Fig. 2). In the context of UU, GPR equipment is always employed to scan designated ground areas (such as the section, wide-angle, and transmitted-wave methods) and gather the reflection characteristics (mainly referring to B-scan images) of the underground hierarchy of the target area. Based on the dielectric coefficient and waveform characteristics, the location and characteristics of the pipelines can then be further analyzed, allowing the creation of 3D models of UU within the target areas using relevant engineering expertise [22–26]. In a recent study by Li et al. [27], the fusion of GPR and camera technology enabled the reconstruction of an underground pipeline model, resulting in an average localization error of 4.47 cm. However, it is important to note that this approach often exhibits lower accuracy in practical engineering applications for two main reasons. First, the complex real-world engineering environment introduces numerous factors that can cause interference, such as high-voltage line magnetic fields and iron pipe corrosion products [14,28–30]. Second, the accuracy of the final model reconstruction heavily relies on manual expertise, necessitating extensive experience in both GPR and UU engineering [26].

3.1.2. Radio frequency identification

Radio Frequency Identification (RFID) is a non-contact technology that enables fast information exchange and storage using radio waves. In the context of UU reconstruction, this technology typically requires the attachment of RFID tags containing specific information during the construction of underground utilities (Fig. 3). This can be combined with engineering data, GPR, and other methods to achieve three-dimensional pipeline reconstruction [31–34]. Compared with GPR, RFID technology offers two significant advantages. First, this approach can overcome the challenge of the weak radar signals of plastic pipes [33,35], especially in situations where the surrounding soil causes signal attenuation or the pipes and soil exhibit similar electromagnetic characteristics. Thus, RFID often serves as a good supplement to GPR. Second, owing to its relatively low operating frequency (tens of kHz to tens of MHz), RFID has a broader coverage range than most pulsed GPR systems used for practical detection (hundreds to thousands of MHz). For example, Kumar et al. [34] developed an RFID-based 3D positioning model for underground assets and verified a 3D reconstruction accuracy of ±100 mm. However, the shortcomings of RFID technology include its cost is high, the difficulty of maintaining and replacing RFID tags after their initial embedding, and the corrosion of tags in the underground environment, which affects the reception of the signal [33,34].

3.1.3. Electromagnetic induction

Electromagnetic induction (EMI) is used to locate and map UU. The basic assumption of this method is that the location of the device at which the magnetic field peak is measured (directly above the UU) represents the horizontal location of the target UU (Fig. 4). The buried depth of a pipeline can then be estimated based on signal strength. Electromagnetic technologies can be classified into active and passive modes [20,36,37]. In active mode, a voltage is applied to the end of an underground metal pipe, and the pipe position and depth are determined by measuring the peak position and strength of the generated magnetic field. In the passive mode, the UU itself generates a certain magnetic field strength (such as a cable), which is then detected using an ultrasensitive magnetic detection device to determine the depth, from which a 3D model of the UU is generated. Magnetic technologies commonly used equipment including a Cable Avoidance Tool (CAT), Pipe and Cable Locator (PCL), Flux-gate Magnetometer (FM), Proton Precession Magnetometer (PPM), Alkali Vapour Magnetometer (AVM), and superyacht Quantum Interference Device (SQUID) [36,38,39]. Magnetic technologies serve as valuable complements to GPR detection and reconstruction methods because magnetic signals are less attenuated in wet soils with high clay content than in conventional GPR. The accuracy of this method is 3% within the 3-m depth range and 5% in the 3–5-m range [10]. When combined with Geographic Information Systems (GIS), which are promising technologies for utility location and attribute data storage, EMI methods can achieve good 3D reconstruction [39,40]. However, it is important to note that this method is only effective for metal pipelines, and similar to other techniques, it is very difficult to apply when dealing with complex underlying infrastructure, such as multiple staggered metal pipelines [36,37]. Therefore, the application range of the EMT-based UU reconstruction methods remains limited.

3.1.4. Acoustic emission

Acoustic emission (AE) methods involve the use of sensors, such as

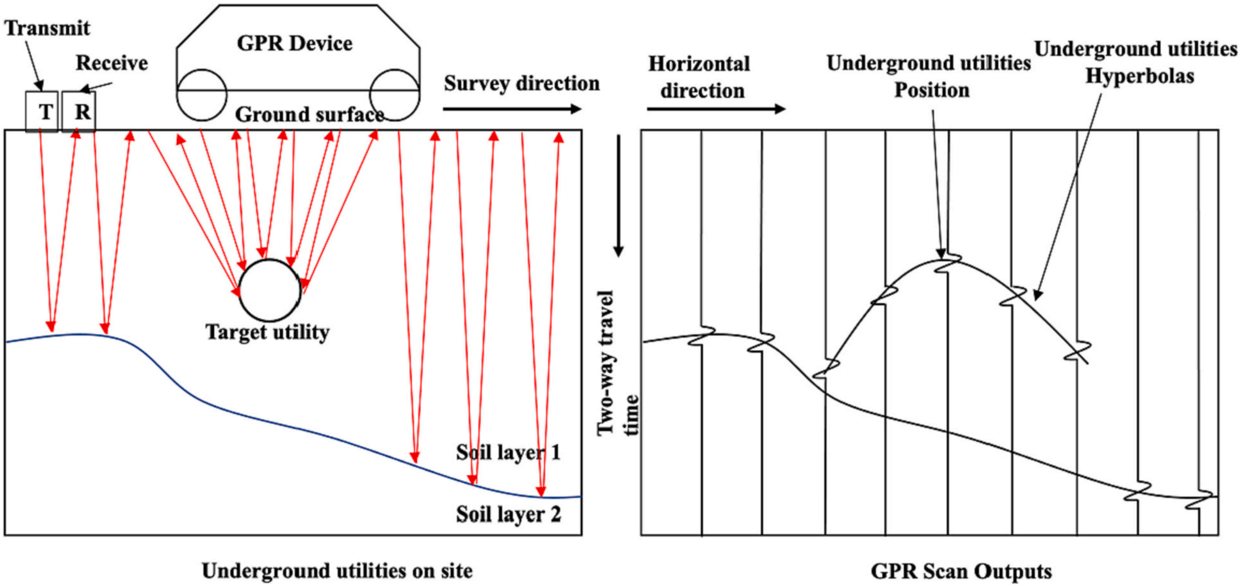

Fig. 2. Schematic of group-penetrating radar (GPR)-based underground utilities detection.

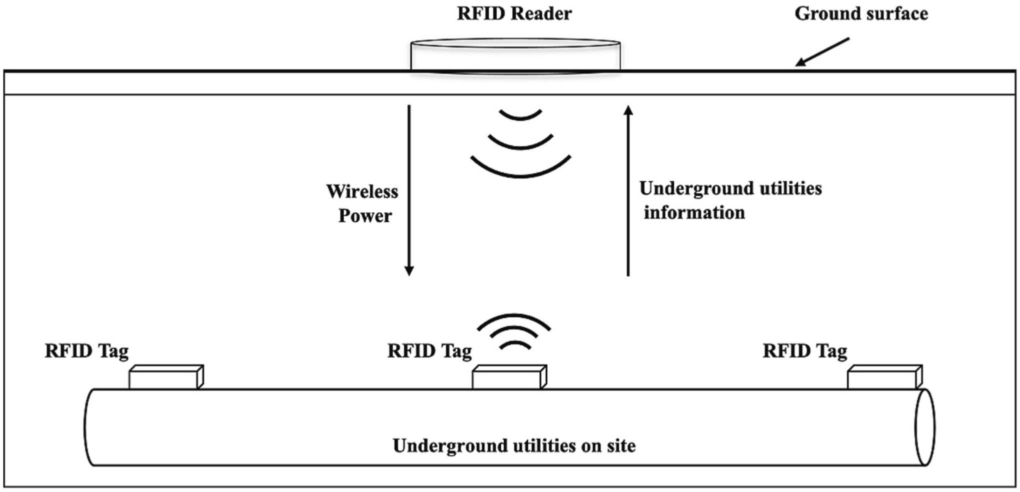

Fig. 3. Schematic diagram of Radio Frequency Identification (RFID)-based underground utilities detection.

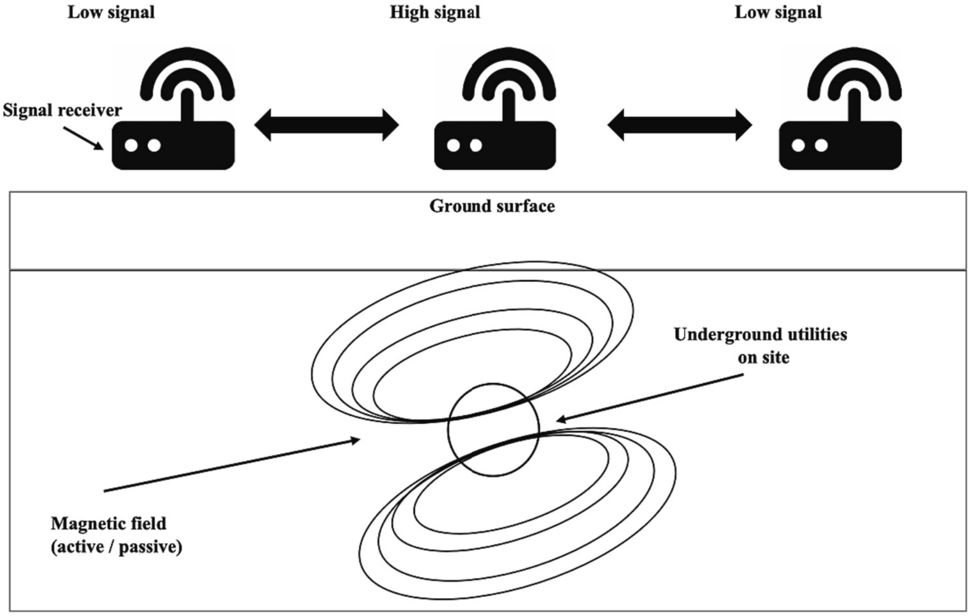

Fig. 4. Schematic representation of electromagnetic induction (EMI)-based underground utilities detection.

hydrophones, to detect and measure acoustic signals generated by UU. These methods are used to locate and map various utilities including pipes, cables, and other infrastructure [41–44]. AE methods detect the sounds or vibrations generated by utilities during their operation (Fig. 5). For example, the flow of water in a pipe can generate a distinct acoustic signal that can be detected and used for location. Similarly, the movement of electrical cables can generate an acoustic signal that aids in cable location. AE methods can be applied to both metallic and nonmetallic utilities and are often employed alongside other methods, such as EMI or GPR, to obtain a more comprehensive understanding of the underground environment. The acoustic method offers advantages including low acoustic attenuation and effective propagation in both solids and liquids [45,46]. However, ultrasonic technologies also have some limitations, including soil dryness or moisture content, the presence of hard surfaces (such as pipes under concrete), possible proximity of target pipes to rock formations, and interference from other pipes, all which can affect measurement accuracy [47–49]. This method is generally capable of tracking pipelines buried at depths <0.5 m [17] without noise interference.

3.1.5. *Thermography*

Thermography is a technique in which invisible infrared (IR) energy emitted by underground utilities is converted into visible thermal images, enabling the acquisition of location information for 3D pipeline reconstruction. Infrared thermography (IRT) is typically used, which involves the use of an infrared detector and an optical imaging objective lens [50,51]. IRT-derived UU data are obtained by detecting and measuring the emitted infrared radiation energy and capturing the energy distribution pattern using the photosensitive component of the infrared detector (Fig. 6). The resulting thermal image corresponds to the thermal distribution field of the object at the surface. Similar to acoustic and electromagnetic wave methods, thermography can contribute to trenchless reconstruction [52,53]. A recent study conducted in Singapore by Luigi et al. [53] explored this approach, and showed that this technique could be used to derive accurate distances between utilities but did not accurately define their depth (approximately 0.2 m in this study) nor the characteristics of the surrounding media. Therefore, thermography is not considered a reliable method for NDT reconstruction.

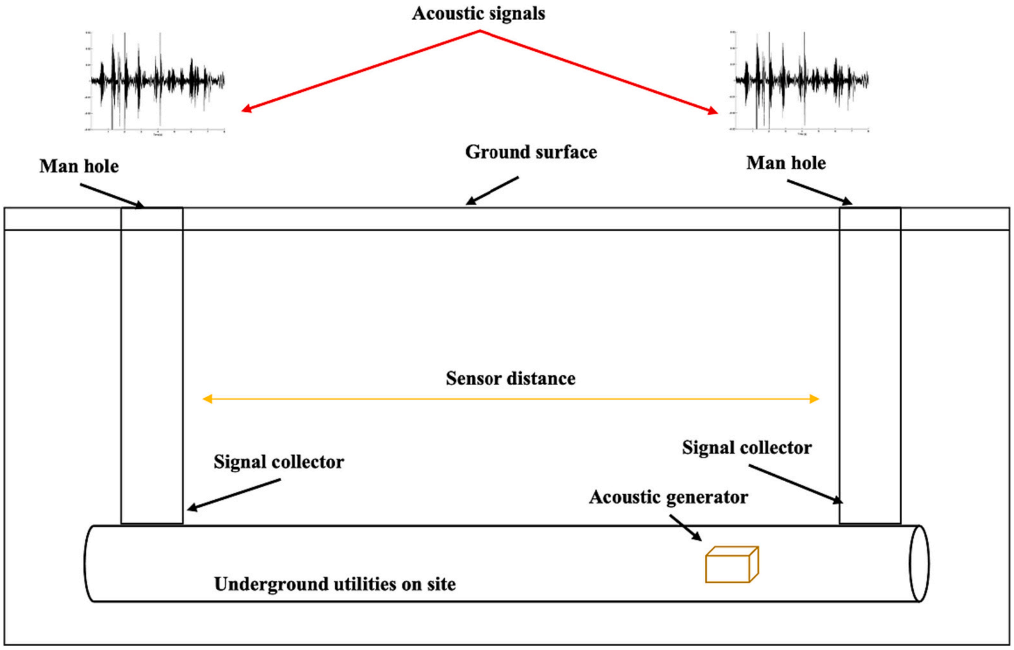

Fig. 5. Schematic representation of acoustic emission (AE)-based underground utilities detection.

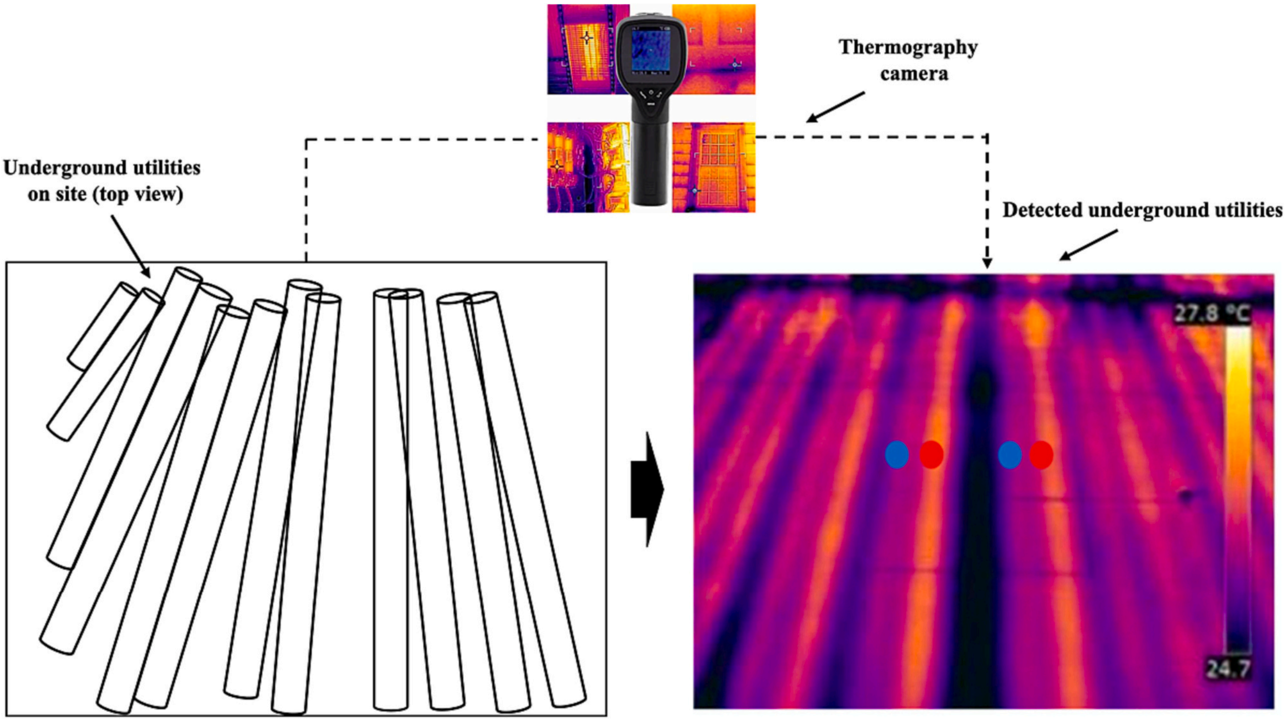

Fig. 6. Schematic representation of thermography-based underground utilities detection.

3.1.6. *Inertial measurement unit-based systems*

An Inertial Measurement Unit (IMU) refers to a sensor that records the speed, acceleration, and direction of rotation of its inertial frame. As a trenchless pipeline-detection modeling method in the field of UU, this method primarily records the velocity, rotation angle, and other parameters using an IMU sensor mounted on robotic equipment to obtain the depth and strike data of the target pipeline, and finally draws a 3D model of the UU [54–56] (Fig. 7). The IMU method provides the most accurate 3D pipeline reconstruction data under non-destructive conditions, with a general horizontal accuracy of 0.25% of the total pipeline length and a corresponding depth accuracy of 0.1% [10]. In the recent study by Zhang et al. [57], it was reported that the maximum horizontal and height errors of this technique were 0.10 m and 0.04 m, respectively, for 5 × 6 m pipes with four joint sockets. Given that this study used low-cost IMU equipment, higher accuracy can likely be achieved if cost is not considered a limiting factor. Additionally, the IMU-based method has the advantage of being unaffected by soil conditions (e.g., soil composition and water content) and can be applied at to significant depths. However, compared with other trenchless methods, the IMU method has several notable limitations including that it is vulnerable to

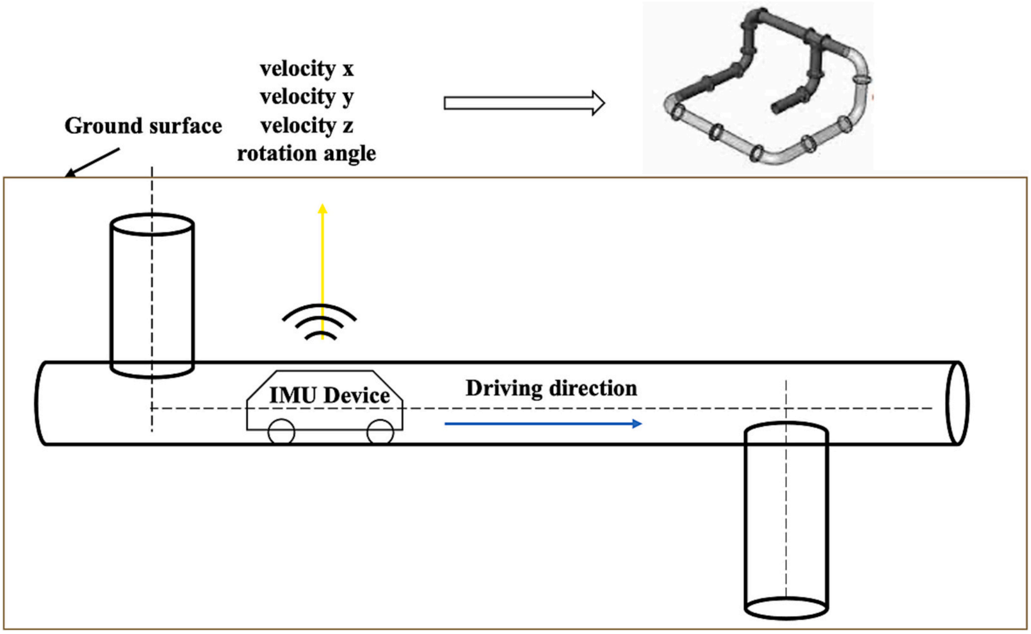

Fig. 7. Schematic representation of Inertial Measurement Unit (IMU)-based underground utilities detection.

electromagnetic interference, it cannot be used in active pipes (such as water pipes), and it is not applicable to solid pipes, such as cables [55,58,59]. These limitations restrict its applicability to only a few scenarios. Furthermore, implementation of IMU-based methods is relatively tedious compared to other approaches.

3.2. *Destructive technologies*

3.2.1. *Laser scanning*

Laser scanning has been widely used for the 3D model reconstruction of pipelines during the excavation stage [60,61]. This method is based on the laser ranging principle, which captures the spatial positions of surface points on the target utility to generate a 3D model (Fig. 8). Similar to total station technology, laser scanning requires pipeline exposure and excels in obtaining high-precision object surfaces in large-scale environments. Compared with other methods, laser scanning offers advantages of (1) excellent automatic performance [62–64], (2) millimeter-level accuracy model reconstruction [65–67], and (3) robust resistance to environmental interference, making it highly suitable for the large-scale 3D reconstruction of UU in open environments [68,69]. The main drawback of this approach is that it cannot be employed during the pre-excavation phase, which significantly reduces its engineering practicability. Moreover, while laser scanning alone can reconstruct the spatial information of the reconstructed objects, obtaining additional information beyond the surface morphology can be challenging.

3.2.2. *Photogrammetry*

Photogrammetry can only be employed in open, excavated settings. Photogrammetry refers to the technique of using optical sensors to capture images of target objects and analyzing their shape and spatial position through image features [70] (Fig. 9). In 1998, Veldhuis successfully used this technique for the 3D reconstruction of pipeline utilities [71]. Photogrammetry offers the advantages of (1) convenient data collection via photography, the low cost of data-acquisition equipment (e.g., a simple digital camera or, increasingly, a mobile phone camera),

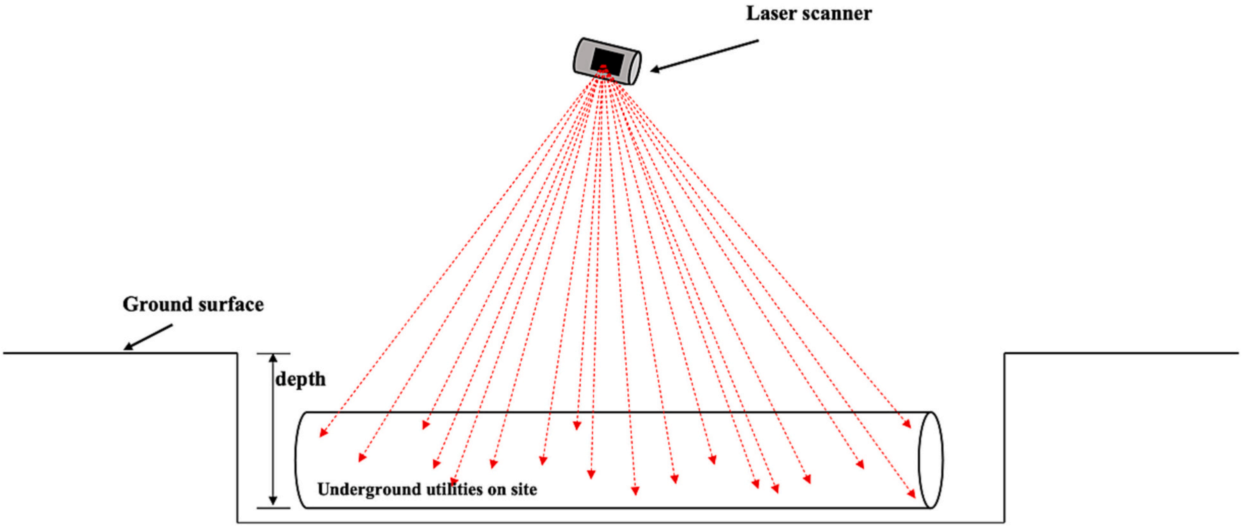

Fig. 8. Schematic representation of laser scanning-based underground utilities detection.

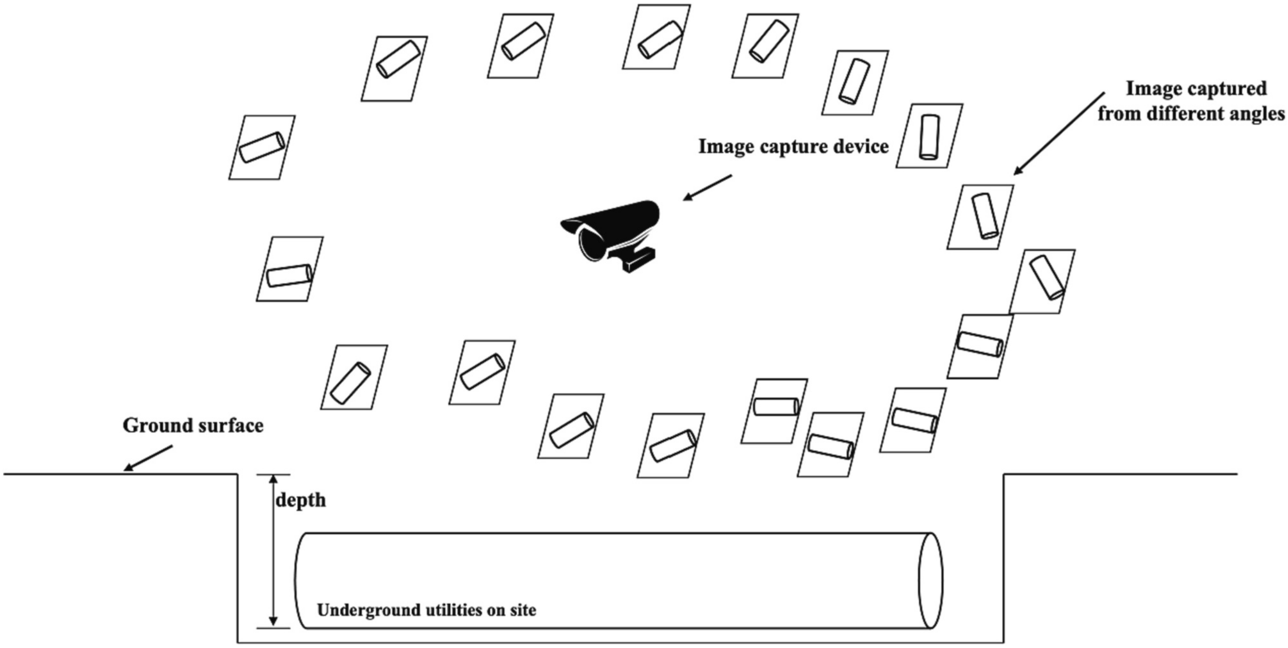

Fig. 9. Schematic representation of photogrammetry-based underground utilities detection.

and (3) the acquisition of RGB information alongside the spatial features of the target, which can be used for further analysis of the target object [72–75]. Similar to total station and laser scanning techniques, photogrammetry can only be used for 3D reconstruction of UU during specific stages of pipeline exposure. However, compared to laser scanning, photogrammetry provides high accuracy, automation, and low cost, making it an attractive engineering solution with significant potential [74,76,77]. Notably, several research teams have successfully combined photogrammetry, laser scanning, and GPR technologies in 3D reconstruction tasks for UU [10,27], demonstrating promising results.

3.3. Summary

Table 1 summarizes the advantages and limitations of the mainstream DT and NDT used in the 3D reconstruction of UU, and also indicates the best performance characteristics of each technique as reported in the current literature.

Multi-sensor fusion is another important approach in the field of underground 3D reconstruction. This primarily takes three forms. First, NDT + NDT approaches include, for example, using a PCL and GPR together to improve depth measurement accuracy to 15% of the buried depth compared to 40% when used individually [10]. GPR and acoustic technologies have also been successfully nitrated for the 3D reconstruction of UU [10] alongside enhanced positional accuracy using GPS [41,78,79]. Second, DT + DT approaches often involve combining DT with GPS to improve the accuracy of reconstructed positions [68]. For example, photogrammetry has been successfully combined with laser scanning to overcome the lack of geometric features using laser scanning alone as well as the accuracy limitation of photogrammetry when used alone [80,81]. First, NDT can be integrated with other sensors. For example, GPR can be combined with visual simultaneous localization and mapping (vSLAM) based on photogrammetry in a 3D reconstruction system for multi-pipeline groups [27]. More recently, Virtual Reality (VR), Augmented Reality (AR), and other technologies have been

Table 1
Advantages, limitations, and best performance characteristics of destructive and non-destructive underground utilities reconstruction technologies.

Categories	Technologies	Advantages	Limitations	Best performance
DT (Destructive Technologies)	Ground Penetrating Radar (GPR)	High reconstruction accuracy; Adapt to various material targets; Convenient operation	Difficult data analysis	Centimeter-scale accuracy can be realized
	Radio Frequency Identification (RFID)	Wide range of application depth; Stable signal strength	Low reconstruction accuracy; Labels are susceptible to corrosion	3D reconstruction accuracy of ± 100 mm
	Electromagnetic induction (EMI)	Stable signal strength	Low reconstruction accuracy; Mutual interference between multiple targets	3% below 3 m depth; 5% at 3–5 m depths
	Acoustic emission (AE)	Signals propagate in various media; Small signal attenuation	Low reconstruction accuracy; Vulnerable to noise interference; Narrow applicable depth range	Working range of 0–0.5 m below ground
	Thermography	Convenient operation	Low reconstruction accuracy; Narrow applicable depth range; Wide temperature difference scenes only	Working range of 0–0.2 m below ground
	IMU-based system	Low cost; High reconstruction accuracy	Narrow scope of application; Complicated operation	Horizontal accuracy: 0.25% of the total length of the target pipeline; Depth direction accuracy: 0.1% of the total depth
NDT (Non-Destructive Technologies)	Laser scanning	High reconstruction accuracy; Simple operation	The operation is complicated; High equipment cost	Millimeter-scale accuracy can be realized
	Photogrammetry	High reconstruction accuracy; Low equipment cost; Rich semantic information; Simple operation	Vulnerable to light conditions	Centimeter-scale accuracy can be realized; Rich semantic information

increasingly used in 3D reconstruction to improve data visualization [82,83].

4. Current applications of 3D reconstruction methods

While classified as UU 3D reconstruction methods, the techniques reviewed in Section 3 vary considerably in their suitability under specific scenarios, which significantly affects their selection. This section provides an overview of the current applications of 3D reconstructed models, which can assist decision-makers in identifying suitable technologies (or combinations thereof) for different situations.

4.1. Application before construction

Prior to UU construction, 3D reconstruction techniques—primarily NDT—are commonly employed for UU inspection and planning in unknown target areas.

4.1.1. UU inspection

While electronic or paper drawings exist for various types of urban UU, issues such as record loss, deviations from construction drawings, and location changes owing to pipeline settlement present significant challenges for city management, particularly in older urban areas. Thus, NT 3D reconstruction techniques enable the reconstruction of UU under unpredictable conditions and at minimal cost. The accurate determination of the precise locations and depths of these unknown utilities is crucial for effective urban management. Only with a comprehensive understanding of the detailed underground location of various pipeline types can authorities establish a complete and efficient asset management system.

4.1.2. Network planning

Planning of UU networks is an essential aspect of urban design and planning. This is particularly crucial for areas undergoing urban development because inadequate UU network planning can result in a significant waste of resources. Proper pipeline network planning requires comprehensive coordination, with the key component being the accurate reconstruction of the locations and dimensions of various utilities. With a clear 3D reconstruction of the existing UU network, unnecessary duplication with the network can be avoided, construction timelines for utilities can be reduced, and optimal layout paths can be determined. The incorporation of UU in new urban development is driven by multiple factors, including the efficient utilization of land resources; considerations of accessibility; the desire to overcome challenges faced by older cities; cultural and modernization concerns; and the aim of creating intelligent, environmentally friendly, and sustainable urban spaces.

4.2. Application during construction

4.2.1. Machine guidance

Mechanical excavation is an integral step in the construction of UU projects. However, accidental damage to pipelines during construction poses a significant risk; in the event of pipeline damage, project progress may be halted, traffic congestion around the site may occur, and there is potential for serious casualties from, for example, explosions by the accidental damage of gas pipelines. Real-time 3D reconstruction of UU can effectively address the issue of critical pipeline damage by providing visual construction guidance to construction machinery, primarily excavators [93].

4.2.2. 3D record generation

During the construction stage of UU projects, the precise location, size, and even materials of the UU may be subject to change owing to various environmental factors. In such situations, UU 3D reconstruction technology, primarily DT, can effectively assist construction and owner units in creating reliable 3D records of UU construction information. Laser scanning and photogrammetry methods are well-suited to meet the accuracy and reconstruction speed requirements. Compared to complex two-dimensional (2D) information recording, 3D reconstruction enables managers to quickly generate clear and intuitive engineering models, laying a solid foundation for subsequent communication. Accurate electronic models and comprehensive information, such as pipeline material, construction time, and construction units as well as the construction method associated with the 3D pipeline model, can effectively prevent loss or deficiencies in existing drawing information, thus facilitating the maintenance and management of the UU throughout its life-cycle.

4.3. Application after construction

4.3.1. Asset management (information exchange)

For UU managers, the most challenging task after the construction of UU is managing a vast amount of hidden assets. As mentioned previously, the application of 3D reconstruction technology facilitates resource coordination, information sharing, and efficient communication between construction personnel and utility owners, thereby providing significant convenience. This technology enables the easy identification of relevant objects and facilitates the effective management of underground assets.

4.3.2. Detection of pipe defects and settlement

The UU 3D reconstruction process involves the identification of utility anomalies associated with various issues that may occur over time, such as congestion, settlement, and blockage. Owing to the hidden nature of these utilities, detecting such problems can be challenging for managers yet they can have severe consequences. Sewage pipeline leaks can significantly harm the ecological environment of surrounding areas and affect nearby residents; water supply pipe leaks can lead to water shortages for many urban residents; settled pipes are a major cause of road collapses; and congestion within pipelines can completely disrupt their functionality. All of these problems incur substantial annual costs for both governments and private entities. Through the use of various non-destructive 3D reconstruction techniques, these hidden utility defects can be identified.

4.4. Summary

3D reconstruction technology plays a pivotal role in the comprehensive management of urban UU across pre-, construction, and post-construction stages, as shown in Table 2. Before initiating construction activities, the application of non-destructive 3D reconstruction techniques, notably NDT, is especially important for UU inspection and planning in unfamiliar target areas. These methodologies address significant challenges such as archival loss, discrepancies between construction blueprints and as-built conditions, and modifications in pipeline placement owing to settlement. By effectively reconstructing UU under unpredictable circumstances, precise information pertaining to their location and depth can be obtained. This in turn fosters efficient urban management and facilitates the establishment of a comprehensive asset management system. Especially during the planning phase, the 3D reconstruction of UU networks is of paramount importance for minimizing redundant construction, optimizing construction timelines, and determining the most favorable layout pathways. These decisions ensure the judicious allocation of resources, enhance accessibility considerations, and enable the creation of intelligent and environmentally sustainable urban spaces.

Throughout the construction phase, real-time 3D reconstruction serves as an invaluable guide for machinery, mitigating the risk of inadvertent damage to pipelines, and guaranteeing the safety of the construction equipment. In addition, 3D reconstruction technology contributes to the generation of precise and reliable UU construction

Table 2
Applications of the 3D reconstruction models of underground utilities (UU).

Stage	Classification	Category	Application details
Before Construction	UU Inspection	GPR RFID EMI AE Thermography IMU-based system	Hebsur et al. [84] utilized GPR technology to reconstruct the UU of ancient cities to establish an information base for urban models. Ristic et al. [85] used GPR technology to identify the subterranean structure of a flood bank in Novi Sad, Serbia, and for delineating the geometry of public utilities pipelines. Shifan et al. [86] applied GPR technology to detect and reconstruct water supply pipelines in older communities of China. Cai et al. [87] established a robust and accurate method for inventorying UU by integrating GPR with existing utility records.
	Network Planning	GPR RFID EMI AE Thermography IMU-based system	Mooney et al. [88] used multi-channel GPR to conduct 3D reconstructions of underground cables in Yonkers, NY, to verify the influence of this technique on the design and planning of a UU project, identifying many unknown public utilities that were in major conflict with the planned construction. Harbin et al. [89] collected UU data to reconstruct an existing pipeline network and inform new UU designs and potential expansion areas of the existing network. Zhang et al. [90] proposed the UU occupation index (UUOI) based on existing UU, occupied underground space, and space models for future use. This approach is used to provide abstract utility and space-use information for urban planning and development.
During Construction	Machine Guide	GPR EMI Laser scanning Photogrammetry	Talmaki et al. [91] developed a comprehensive computing framework for real-time monitoring of construction activities in a concurrent 3D virtual world to reduce the possibility of accidental pipeline collision by excavators. Ahmed et al. [92] collected and analyzed 11,160 damage events in the state of North Carolina, USA, to reduce the risk of damage to UU during future works. Waqas et al. [93] proposed a new approach to modeling UU based on machine navigation systems to provide visual guidance to operators and prevent accidental damage to underground pipes.
	3D Record generating	Laser scanning Photogrammetry	Hyojoo et al. [94] developed a fully automatic system for as-built pipeline 3D reconstruction based on laser technology. Stylianidis et al. [95] validated a new system (LARA) that integrates handheld and mobile devices for monitoring, recording, and managing utility-based geospatial data products and services.
After Construction	Asset management	GPR RFID EMI AE Thermography IMU-based system	Ortega et al. [96] demonstrated an effective way to manage urban infrastructure by visualizing underground infrastructure in an interactive 3D immersive environment. Yan et al. [10] connected a UU 3D model to the government database of cadastral plots for land management in Singapore. Yan et al. [97] developed the Underground Utility Data Model (UUDM) to help ownership management, land acquisition, planning, and (re)development of UU.
	Defect Detection	GPR AE IMU-based system	Ji et al. [98] introduced a methodology for detection abnormality in heating pipelines, employing accelerometers and acoustic emission signal, achieving a classification accuracy surpassing 90%. Zhang et al. [99] verified the rapid and high-precision detection of pipelines based on internal images of pipelines with good experimental results. Nurhazimah et al. [100] accurately mapped old corroded pipes in Malaysia.

information records. By meticulously capturing crucial details, such as buried locations, dimensions, and materials of UU, these records facilitate effective communication, circumvent potential loss or deficiencies in drawing information, and bolster the maintenance and management of UU assets throughout their life-cycle.

During the post-construction phase, 3D reconstruction technology continues to be instrumental in asset management and the detection of pipe defects and settlement. This enables seamless resource coordination, fosters information sharing, and facilitates efficient communication among UU managers, thereby simplifying the management of subterranean assets. Furthermore, by promptly identifying anomalies within buried utilities, such as congestion, settlement, and blockages, 3D reconstruction techniques enable timely intervention and minimize the adverse impacts of these issues on the surrounding environment and inhabitants.

Overall, through the utilization of both NDT and DT, 3D reconstruction technology significantly assists UU inspection, network planning, machine guidance during construction, 3D records generation, asset management, and the identification of pipe defects and settlement during the entire life-cycle of UU. By providing accurate spatial information, supporting effective communication, and enabling proactive maintenance measures, 3D reconstruction technologies can significantly contribute to the efficient management of urban underground areas and the sustainable development of cities.

5. A decision-making framework for selecting 3D reconstruction technologies

Based on our review, a decision-making framework for selecting UU 3D reconstruction technologies to assist in the scientific selection of technological options was proposed. Section 5.1 summarizes the factors that should be considered in engineering applications based on the literature review, and Section 5.2 demonstrates the selection framework in detail.

5.1. *Criteria*

5.1.1. *Destructive*

Whether trenchless or not is the most important distinguishing criterion for various types of UU 3D reconstruction. Scenes suitable for DT and NDT in 3D reconstruction differ significantly. When selecting the UU 3D reconstruction technology, the state characteristics of the target utilities should be considered first [94,101]. DT and NDT cannot be interchanged under specific scenarios. Therefore, our proposed framework uses ‘destructive’ (trenchless or non-trenchless) as the primary criteria for technical screening.

5.1.2. *Depth*

Compared to the horizontal location features of UU, depth features are of utmost concern to managers and frontline construction personnel in the UU 3D reconstruction process [102]. Different UU 3D reconstruction technologies have varying application depth ranges. For instance, passive mode PCL depth detection is reliable only above 3 m [37], while the application range of acoustic detection cannot exceed depths of 0.5 m [17]. Therefore, ‘depth’ was selected as one of the important screening criteria due to the significant differences in applicable depth features.

5.1.3. Accuracy

Similar to depth, the reconstruction accuracy of each UU 3D reconstruction technology varies significantly [10,78]. However, in specific projects, a higher demand for reconstruction accuracy from the owner does not necessarily imply better results, because the cost and other specific requirements need to be considered. Certain applications, such as pipeline inventories [103,104] and machine guidance, require a higher level of reconstruction accuracy. However, other applications, such as utilities inspection [105], may not require the highest level of accuracy to meet the established requirements. Therefore, 'accuracy' was included as a criterion in the proposed technical screening framework.

5.1.4. Material

In addition to the embedment depth, the materials used in UU is are important characteristics. Historically, many underground utilities were constructed using metals; however, in recent years, nonmetal utilities, such as plastics, ceramics, and concrete, have become increasingly common. Notably, the efficiency and accuracy of various UU 3D reconstruction techniques can vary significantly [86,106] or even fail depending on the target material. In certain applications, choosing the wrong technology can be dangerous if the buried utilities are not accurately detected, such as in pipeline machine guidance [92,93]. Therefore, the selection of technology for UU 3D reconstruction should consider the utility 'material' (metal or nonmetal in our proposed framework) as an important criterion.

5.1.5. Cost

The final and most easily understandable criterion is cost. 3D reconstruction of UU involves large-scale projects. Therefore, cost must be considered when selecting 3D reconstruction technology. In scenarios where the target area is small and the budget is sufficient, high-cost technologies can be used to ensure accuracy and to meet other criteria. However, low-cost and, ideally, high-performance technologies can be utilized in those scenarios where requirements are less demanding.

5.2. Decision-making framework

Based on the selection criteria outlined in Section 5.1, Table 3 summarized a proposed a decision-making framework for selecting 3D reconstruction technologies to help managers and stakeholders make informed decisions.

6. Challenges and future research

6.1. Discussion

From an engineering practice perspective, this section summarizes the core challenges often encountered during UU 3D reconstruction based on our literature review and analysis. This summary of core issues will contribute to the advancement of research in this field.

6.1.1. Accuracy

The most significant challenge is the accuracy of 3D reconstruction in the context of UU. This challenge pertains to the achievement of accurate 3D reconstruction models in non-destructive contexts. The accuracy of the UU 3D reconstruction can be primarily assessed based on depth and size accuracy.

The depth of a pipeline utility is a critical factor in UU 3D reconstruction tasks. Unlike typical 3D reconstruction, UU applications present unique difficulties owing to the underground location of target utilities and the strict spatial requirements set by the owners. The spatial position of a pipeline is determined based on its orientation and depth. Obtaining information about the orientation of a pipeline is relatively straightforward, usually involving the determination of the positions of two distal points (or more in the case of curved utilities, such as cables) [107,108]. However, obtaining accurate depth information is often challenging because of complex underground ambient noise [109–111]. Nevertheless, regardless of whether GPR or other technical methods are used, determining pipeline depth under trenchless conditions yields unsatisfactory results [102,112]. According to various technology and engineering reports, the accuracy of pipeline depth determination is approximately one-tenth that of the actual buried depth of the pipeline.

Another challenge related to the accuracy of UU 3D reconstruction is the determination of pipeline size. Information on the diameter of pipelines is often of significant importance in engineering practice, particularly in 3D reconstruction projects involving old utilities [113,114]. For instance, Naghshbandi et al. [115] highlighted the importance of pipeline size, as it provides valuable insights into the purpose and operational conditions of pipelines, including the presence of deformations. However, current non-destructive methods often lack the capability of accurately determining the size of utilities [10,116].

The accuracy challenge is of significant importance in the context of the 3D reconstruction of UU for the following reasons: (1) Safety considerations: ensuring accurate knowledge pertaining to the precise location and depth of UU is imperative for maintaining safety. Activities such as excavation, construction projects, and other subterranean operations can pose substantial risks if utility lines are not accurately mapped [42,117]. Inaccurate or outdated information can result in inadvertent utility strikes, leading to injuries, service disruptions, and even fatalities [93,118]. Consequently, addressing the accuracy challenge aims to enhance the precision of utility mapping, thereby safeguarding the well-being of workers and the public. (2) Cost effectiveness and operational efficiency: achieving precise 3D reconstruction of UU facilitates optimal project planning and execution. Equipped with accurate information regarding the exact location, depth, and dimensions of utilities, construction teams can plan excavation or installation activities with greater efficiency [12,119]. This, in turn, minimizes project delays, streamlines resource allocation, and generates cost savings [92,93,120]. The challenge of accuracy has stimulated the development of advanced techniques that augment the overall efficiency of utility mapping processes. (3) Effective asset management: UU represent valuable assets that require efficient management and maintenance. Through accurate 3D reconstruction, a comprehensive representation of the utility infrastructure is obtained, enabling utility operators to make informed decisions regarding asset management, repair, and replacement [121,122]. The availability of precise mapping data also aids in long-term planning and diminishes the likelihood of conflicts with existing utilities during subsequent construction and expansion works [123,124].

6.1.2. Automation

The second challenge that is widely acknowledged in the field is the automation of 3D reconstruction for UU. As observed from the review of various techniques in Section 3, all NDT require additional processing steps to convert the acquired data into final 3D models [125,126]. However, only a few methods, such as laser scanning and photogrammetry, offer partial automation and are primarily applicable when pipelines are exposed during the construction or maintenance stages. Despite the varying degrees of automation in intermediate data-processing for these NDT, substantial manual operations are still required and are often performed by experts with specialized knowledge. For example, in the case of GPR, feature extraction from GPR B-scan images requires expert experience [127]. The reconstruction accuracy also depends on the expertise of the user when using EMI [128], AE [129], and thermography [130].

This significantly hampers the efficiency of the UU 3D reconstruction. Using the widely adopted and mature GPR method as an example, the processing of raw data output by GPR equipment typically involves data conversion (i.e., raw data decoding, image conversion), data-processing (i.e., noise filtering, frequency adjustment, etc.), manual

Table 3
Decision-making framework for selecting 3D reconstruction technologies.

Criteria	3D Reconstruction Technologies for Underground Utilities								
		Ground Penetrating Radar (GPR)	Radio Frequency Identification (RFID)	Electro-magnetic induction (EMI)	Acoustic emission (AE)	Thermo-graphy	Inertial Measurement Unit (IMU)-based system	Laser scanning	Photogram-metry
Destructive	Trenchless	✓	✓	✓	✓	✓			
	Trench required				/		✓	✓	✓
Depth	>2000 mm	✓	✓				✓	/	/
	<2000 mm	✓	✓	✓	✓	✓	✓	/	/
Accuracy	>10 mm	✓	✓	✓	✓	✓	✓	✓	✓
	<10 mm	✓	✓				✓	✓	✓
Material	Metal	✓	✓	✓	✓	✓	✓	✓	✓
	Concrete	✓	✓		✓	✓	✓	✓	✓
	Plastic	✓	✓		✓	✓	✓	✓	✓
Cost (US dollar)	> 1000	✓		✓	✓	✓			
	< 1000		✓				✓	✓	✓
Automation degree	Semi	✓	✓	✓	✓	✓			
	Auto						✓	✓	✓
Application scenarios	UU inspection	✓		✓	✓	✓	✓		
	Network planning	✓	✓	✓	✓		✓		
	Machine guide	✓	✓	✓					
	3D record generating	✓					✓	✓	✓
	Asset Management	✓	✓	✓			✓	✓	✓
	Detection of pipe defects and settlement	✓	✓		✓		✓		

"✓" indicates that the technique is more applicable to the corresponding criteria subcategory; "/" indicates that the technique cannot be applied under the corresponding conditions and, therefore, should be avoided.

interpretation (i.e., analyzing specific target conditions through B-scan images), and other stages [78,131,132]. During B-scan image interpretation, users require extensive professional knowledge and years of engineering experience. Recently, significant progress has been made in automated research in this field [133–135]. However, achieving reliable automatic UU reconstruction without manual involvement remains an ongoing challenge.

6.1.3. Semantic enrichment

The challenge of semantic enrichment in the 3D models of urban underground projects represents a significant aspect of 3D reconstruction. Stakeholders involved in UU projects not only require geometric information but also seek semantic details regarding the entire system. Semantic information encompasses material properties, slopes, manufacturer specifications, and ownership, which are crucial for economic benefit and safety considerations [97,136].

Semantic enrichment plays a vital role in ensuring the safety of construction personnel and preserving the integrity of UU systems. For instance, a study conducted by Waqas et al. [93] highlighted that incorporating rich semantic information, such as the characteristics of a natural gas pipeline system, significantly enhanced the personal safety of construction personnel. Semantic data provide essential insights into the properties and behavior of UU infrastructure, enabling effective risk assessment and proactive safety measures.

Furthermore, semantic information contributes to the detection and prevention of pipeline leakages. By combining 3D pipeline reconstruction with relevant prior information, such as historical data and maintenance records, it is feasible to identify potential leakage points and implement timely remedial actions [137]. Thus, the inclusion of semantic details enhances the accuracy and reliability of leakage-detection systems, minimizes environmental hazards, and ensures an uninterrupted supply of essential resources.

Beyond the construction phase, semantic information continues to be of paramount importance during the maintenance management stage of a UU throughout its life-cycle. The integration of semantic data enables intelligent asset management and maintenance. With semantic enrichment, maintenance personnel can access critical information regarding the UU infrastructure, including its components, specifications, and maintenance requirements. This empowers decision-making processes, facilitates targeted maintenance interventions, and optimizes resource allocation for the efficient upkeep of the UU system. Moreover, the research and development of semantic information has significantly contributed to the intelligent progression of UU engineering maintenance. By leveraging semantic data, maintenance activities can be streamlined, allowing predictive maintenance strategies, early fault detection, and the efficient utilization of resources. Semantic enrichment enables automated monitoring systems, intelligent data analysis, and implementation of advanced maintenance practices, ultimately enhancing the performance, reliability, and longevity of the UU infrastructure.

In summary, the significance of semantic enrichment in the 3D modeling of UU projects cannot be understated. The inclusion of semantic information provides stakeholders with crucial insights into a system's characteristics, enabling enhanced safety measures, improved leak detection, and intelligent maintenance management. By embracing semantic enrichment, UU projects can benefit from optimized decision-making processes, reduced downtime, and cost-effective asset management throughout the infrastructure life-cycle.

6.2. Future research

6.2.1. Integration of artificial intelligence technologies and methods

From the perspective of 3D reconstruction technology, the replacement of human labor with artificial intelligence (AI) in complex UU 3D reconstructions is inevitable. In recent years, the integration of AI technology and 3D reconstruction technologies has provided promising solutions for the reconstruction and management of UU underground utilities [138,139]. The research in this field is currently in its early stages. Among NDT technologies, GPR shows the highest potential in this context, offering fast and convenient usage, a wide range of applications (including both metal and non-metal pipelines [10,140]), and provides uniform and rich data suitable for data-driven methods. Therefore, GPR applications are highly suitable for integration with AI algorithms. In terms of DT technologies, the most promising approach is automated and cost-effective 3D reconstruction achieved through a combination of laser scanning, photogrammetry, and AI technology [73,80,81]. Considering the large-scale and extended duration of UU projects, such endeavors are generally cost sensitive [97,141]. Hence, there is significant potential for the development of low-cost laser scanning and photogrammetry fusion for 3D reconstruction.

Specific integration has been developed to enhance the performance of the 3D reconstruction of UU. Examples include automated object detection and classification and augmented reality (AR) visualization. In the case of automated object detection and classification, AI algorithms can be used to automatically detect and classify underground utility objects in 3D reconstructions [104,142]. By training AI models on large datasets of annotated UU images, algorithms can learn to identify different types of utilities, such as pipes and cables [143]. This automation significantly speeds up the process of identifying and labeling utilities in the reconstruction, thereby saving time and improving accuracy. Furthermore, AI-powered AR applications can overlay 3D reconstructions of UU onto real-world views captured by cameras, smartphones or smart glasses [82,144]. AI algorithms can even help align and accurately register virtual 3D models with live video feeds, allowing users to see UU in real time [95]. This technology can assist utility workers or construction crews in navigating underground spaces, identifying potential conflicts, and making informed decisions at job sites.

6.2.2. *Underground world digital twin*

The underground placement of utility pipes and cables serves various purposes including protection from surface activities, exposure to harsh weather conditions, and reinforcement against differential movements. However, when it comes to the maintenance or establishment of new service connections, the subterranean environment presents a significant challenge as it hampers our ability to accurately locate and understand the nature of the subsurface infrastructure.

Therefore, from a management perspective, the construction of a virtual representation of an UU project spanning its entire life-cycle can be the most effective approach for addressing various challenges. An Underground World Digital Twin (UWDT) can be created by incorporating sufficient geometric and semantic information. UWDTs can be used to simulate scenarios, analyze performance issues, and generate potential improvements, all of which aim to gain valuable insights that can be applied to physical projects. Currently, this concept has been explored in research endeavors worldwide [145]; however, further research is needed to integrate existing data acquisition, data-processing, project practices, and other studies to establish a comprehensive underground system and standard decision-making framework. In summary, establishing digital records during the initial stages of a UU project using 3D reconstruction technologies can serve as the foundation for implementing the vision of UWDTs. Furthermore, accurate reconstruction of as-built underground utilities is crucial for realizing UWDTs. This approach can provide sophisticated virtual replicas or simulations of a physical asset or system, encompassing both the physical and digital realms and enabling the real-time monitoring, analysis, and simulation of an asset's performance and behavior. Digital twin technology amalgamates data from diverse sources, including sensors, the Internet of Things (IoT) devices, and modeling software, to generate a dynamic and interactive digital representation of an asset.

By integrating the data obtained from 3D reconstruction with sensor data and other relevant semantic information, UWDTs can provide a comprehensive and real-time depiction of UU. This integration will facilitate a deeper understanding of an asset's behavior, performance, and conditions; stakeholders can monitor an asset's health, detect anomalies, simulate various scenarios, and optimize operational and maintenance activities.

6.2.2.1. Negative side of UWDTs. The negative impact of digital twins is mainly reflected in the following two aspects. First, data security and privacy risks may exist. For example, digital twins rely on the collection, storage, and analysis of vast amounts of data, including sensitive information about UU and their operations. As such, unauthorized access, data breaches, or misuse of data can have severe consequences, including operational disruptions and compromises to the integrity of critical infrastructure [146]. Second, cost and complexity challenges remain. Indeed, implementing and maintaining a digital twin system can be expensive and complex. This requires significant investment in hardware, software, and skilled experts [147]. Consequently, small or financially constrained organizations may find it challenging to afford and manage the necessary resources required to implement this technology.

7. Conclusions

UU play a vital role in urban infrastructure. An accurate and up-to-date 3D information model of these utilities is crucial for effectively managing complex underground environments in cities. However, limited knowledge is available that provides a comprehensive overview of the latest advancements, challenges, and research trends in UU 3D reconstruction technology. A comprehensive review of existing research in this field has been provided, offering insights into the progress being made and current achievements in UU 3D reconstruction.

323 journal papers on the progress, advantages, limitations, and best performance characteristics of 3D reconstruction technology and its application were reviewed. In order to assist stakeholders in making informed decisions when selecting 3D reconstruction technology routes, a decision-making framework was also proposed. Furthermore, the core challenges frequently encountered in the process of UU 3D reconstruction, and outlined future research trends in the field were discussed.

The contributions of this review are as follows. First, it provides an up-to-date account of the current state of mainstream UU 3D reconstruction technology, offering academia and industry a comprehensive overview of this field. Second, by addressing the needs of engineering practice, this review proposes a scientific and concise technology selection framework that can establish a clearer working logic for UU 3D reconstruction. Third, this review has revealed the common challenges and future research directions in the field of 3D reconstruction of UU, offering a roadmap for researchers seeking to contribute to the existing body of knowledge.

Declaration of Competing Interest

None.

Data availability

No data was used for the research described in the article.

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