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Review

A Review of Augmented Reality Visualization Methods for Subsurface Utilities

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Abstract: Subsurface utilities are important assets that need to be perceived during any construction activities. Positioning and visualizing the subsurface utilities before the construction work starts has significant benefits for the effective management of construction projects. Augmented Reality (AR) is a promising technology for the visualization of subsurface utilities. The aim of this paper is to provide a comprehensive review of the state-of-the-art in AR visualization of subsurface utilities, including existing AR visualization methods, categorization of the methods and their drawbacks, comprehensive discussion on the challenges, research gaps and potential solutions. The paper begins with an introduction of current practice of locating subsurface utilities and an overview of different reality technologies including AR. We propose a taxonomy of AR visualization methods including X-Ray view, transparent view, shadow view, topo view, image rendering and cross-section view. We provide a comparison of existing methods in terms of quality of depth perception, occlusion of real world, complexity of visualization and parallax effect followed by a discussion of the drawbacks in these methods. Poor depth perception, poor positional accuracy in Global Navigation Satellite System (GNSS) deprived or indoor area and the parallax effect caused by the user movement are identified as the main challenge and topics of future research in effective visualization of subsurface utilities.

Keywords: Subsurface utility, visualization, augmented reality, depth perception, parallax effect.

1. Introduction

Locating subsurface utilities such as pipes buried under the ground surface or wires within walls, is a crucial step in renovation and construction works as such activities can potentially alter or damage any existing subsurface utilities in the construction site. Despite the importance of locating existing subsurface services, the process is still greatly based on using paper (PDF) plans in the current practice. There are various methods for locating indoor and outdoor sub-surface utilities including Ground Penetrating Radar (GPR), Electromagnetic Locators for outdoors and wire tracers for indoors. Depending on the situation, utility locators use these devices to locate subsurface utilities and mark the location on the surface. However, when the exposing begins, the marks will be lost and locating the subsurface services needs to be repeated.

There are several challenges in accurately locating outdoor subsurface utilities using utility locating devices. All those locators come with their own limitations and their results can be restricted by several factors such as the geological condition of the site, characteristics of the surveyed utilities, accessibility of the surveyed utility, utility density in the surveyed area, experience of the operator, etc. [5]. For instance, GPR transmits microwave pulses into the ground and measures the incoming reflections which can be highly affected by the characteristics of the ground. Conductive/clay and rocky soils limit the reflection of microwave pulses due to their nature of signal scattering [5-14]. Moreover, the locating process can be time consuming, expensive, and complex to mark on the surface depending on the number of the utilities that need to be located. Dial Before You Dig (DBYD) is a calling service in Australia that connects the clients who require information about underground assets with asset owners to assist with excavation. According to DBYD, not all the outdoor underground utilities in Australia have accurate 3D location information (Quality Level A) for excavation purposes. Information of many underground utilities is in a schematic format and only indented to indicate their presence (Quality Level D) in the work site [15]. Moreover, many assets owners are not members of DBYD, and the service cannot provide subsurface asset information if the particular asset owner is not a member of DBYD.

Traditional method of locating subsurface utilities indoors also faces several challenges, for example, using wire tracers for locating and marking subsurface utilities within walls can be tiring and the positional certainty of the located utility highly depends on the efficiency of the device sensing strength. It can also be complicated to locate and mark when there are multiple assets are congested in a small area, for example locating a specific type of electrical wires where there are multiple types of electrical wires and pipes within walls or above ceilings.

Lack of consideration for the location of subsurface utilities can result in utility strikes causing damage to the services during construction activities. Utility strikes incur significant costs depending on the type of the service being struck, the time spent on repair and the delay in the construction work. Most importantly, utility strikes pose a risk to the safety of the workers. Inaccurate location of the utility, poor planning and negligent excavation or exposing techniques have been identified as main causes of utility strikes [16]. To avoid utility strikes, there is a need for a suitable and effective approach for locating and visualizing the hidden assets.

AR is a promising technology which has already shown its significance in medical applications [17-19], tourism [20], automotive [21-23], education [24,25], military [26,27] and gaming industries [28,29]. AR superimposes digital contents generated by computer software on the real world which can provide an effective solution for visualizing the hidden subsurface utilities [30,31]. AR can deliver several benefits to architectural engineering and construction (AEC) industry. Shin, et al. [31] discussed eight work tasks that AEC could be benefitted from AR, namely layout, excavation, positioning, inspection, coordination, supervision, commenting and strategizing.

To achieve a quality AR visualization of subsurface utilities, accurate 3D location information of the subsurface utilities is the utmost importance. Additionally, the correct integration of virtual model with physical environment spatially as well as visually is crucial. Incorrect overlay of the virtual model over the real-world would create depth perception issues or wrong perception of the objects order, confusion due to motion parallax, virtual model misalignment with the real world [32] as well as poor positional accuracy in GNSS deprived or indoor environments. Several attempts have been made to compare different AR visualization techniques for subsurface utilities in the past to address the depth perception issue [4,33-40]. Yet, a comprehensive review on AR visualization methods for subsurface utilities discussing the other challenges of AR visualization for subsurface utilities has not been conducted. The scope of this paper is to review all the existing methods of AR visualization for subsurface utilities and discuss their drawbacks in terms of identified visualization challenges, research gaps and potential solutions.

In this survey, we analysed journals, conference papers and books published from 1992 to 2021 that have discussed the visualization of subsurface objects using AR. The articles that are reviewed in this paper were acquired via Google Scholar and Scopus search engines by using all possible combinations of following keywords “Augmented Reality”, “visualization techniques”, “AR”, “subsurface utilities”, “underground utilities", "hidden objects", "Mixed Reality", "MR", "underground assets" and "subsurface assets". We also reviewed relevant articles that cited the above found articles as well as articles that have been cited by the above found articles. Additionally, we have reviewed magazine articles and commercial products' guides of latest development in the context of AR and AR visualization of Subsurface utilities. Since the topic is still being explored in the research community and the industry, the search of the articles continued during writing of this paper. This paper fully reviewed 28 articles published from 2009 to 2021 and one article that was published in 1992. We have excluded articles that are not in English.

The remainder of this paper is structured as follows; Section 2 discusses the different types of reality technologies including AR in general, different aspects to consider when developing an AR application and section 3 discusses challenges in visualizing subsurface utilities using AR. Section 4 explores the existing AR visualization methods for subsurface utilities. Section 5 compares the visualization techniques discussed in Section 4 and discuss their drawbacks in terms of the challenges discussed in section 3. In Section 6, we further discuss drawbacks in existing AR visualization of subsurface utilities followed by the conclusion and future works in Section 7.

2. Overview of AR Technology

AR is commonly defined as a useful technique that superimposes computer generated virtual contents with the real environment to create an informative hybrid environment to aid the sense of sight. But AR can also be applied to other senses, including hearing, touch, and smell [41]. AR gained popularity with technology like depth cameras and computer vision available in mostly commonly used mobile phones and tablets.

There are several competing reality technologies that facilitate the visualization of virtual and physical objects for various applications. These include Virtual Reality (VR), Augmented Virtuality (AV), AR, Mixed Reality (MR) and Extended Reality (XR). VR creates a user experience that is completely based on virtual information [42-44] and disconnects the user from the real world. VR is mostly suitable for small indoor environments and is not recommended for a field worker due to safety consideration in the work environment. AV introduces slight reality fusion to virtual environment by overlaying real objects on top of virtual environment when necessary. But the user is still relatively disconnected from the real environment depending on the number of real objects being projected [45-48]. AR enhances the user visualization by integrating digital contents with the real world to provide visual guidance to the user [30,31,41,49-51]. It basically supplies additional information of the real environment which are not visible to bare eyes in different forms from wearables such as smart glasses to handheld devices such as smart phones and tablets [52]. MR is a recent development of reality technologies, which not only overlays the virtual contents on the real world, but also allows interaction between them [53-59]. MR blends the virtual contents with the virtual build of the real world to facilitate the interaction. For example, in MR, virtual objects can be placed behind real objects to create a sense of occlusion. As shown in Figure 1, the flying saucer (virtual object) is occluded behind the ceiling lights (real object). Finally, XR is an emerging technology that covers VR, AR and MR technologies and is referred to as an umbrella which bring all the reality technologies under one term [60-64]. For instance, while VR Head Mounted Displays (HMD) are not capable of providing MR visualizations, and MR HMDs are not capable of providing quality VR experience, XR HMDs are video see-through devices consisting of cameras that act as virtual eyes with spatial mapping capability for MR experience but can completely disconnect the user from the real world for quality VR experience as well. Varjo XR-3 is a perfect example for an XR device which is available in the market [65]. It is worth mentioning that with continuous development of new devices, there are VR HMDs with camera in front such as HTC Vive or attachable cameras such as ZED Mini (MR Stereo camera) to a VR HMD for user convenience and MR experience within VR HMDs. Since the use of VR is limited in the context of visualizing subsurface utilities and MR and XR are emerging technologies which are yet to be explored for visualizing subsurface utilities, in this paper we focus only on AR technology.

Figure 1. The Difference between VR AR and MR

2.1 *History of AR*

Even though AR is a widely explored topic in recent years, it was first used during the World War 2 when the British military developed a technology to display the radar information on the planes windshield [50]. But the official beginning of AR can be considered as Sutherland's work in 1960 followed by his creation of the first see-through head-mounted AR display in 1968 [66]. Even after the invention of the AR head mounted display, AR was not a very popular topic until the term "Augmented Reality" was officially established in 1990 and gained popularity in many industries thenceforwards. Figure 2 shows a summary of the main development and events in the history of AR starting from 1945 to 2019.

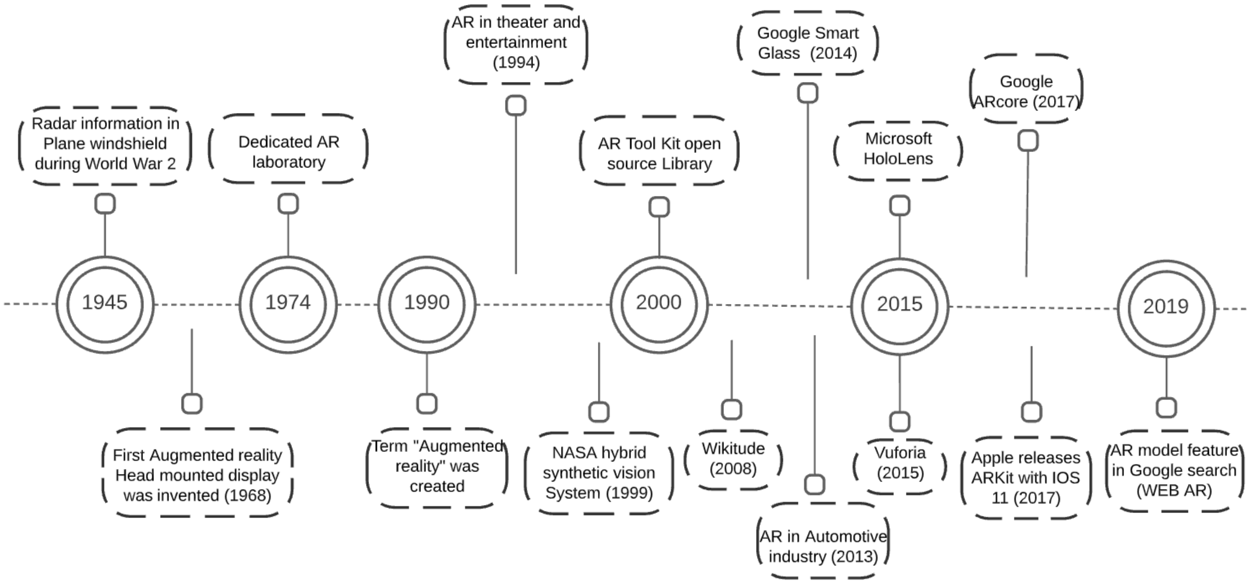


Figure 2. Timeline of AR

2.2 AR in AEC

AEC industry is slowly moving into digital transformation with the advancement of digitization, automation and integration which is also referred to as Construction 4.0. The use of digital data enables the implementation of AR in AEC industry [67]. There have been numerous research studies have been conducted on different use cases of AR in AEC [31,67-72]. Albahbah, et al. [70] reviewed seven applications of AR that can benefit construction industry including safety management, communication and data acquisition, visualization, construction management education, progress tracking, quality management and facility management. Alizadehsalehi, et al. [71] developed a framework for automated construction progress monitoring called DRX, which integrates XR, reality capturing technologies like 3D laser scanning and wireless sensors, Building Information Model (BIM) and Digital Twin (DT) of actual physical assets, devices, systems, process, places, and people. Their work also discusses the strengths and the challenges of the system in terms of cost, quality, and time. Davila Delgado, et al. [68] analyzed six possible applications of AR in AEC industry namely stakeholder engagement, design support, design review, construction support, operation and management support and training. Their study also shows that the AR has a long way to go for achieving its full potential in AEC because of the limitations of presently available AR devices including comfort and safety, high accuracy tracking, improved indoor localization, dynamic 3D mapping of changing environments and longer battery life. They also identified challenges in workflow and data management such as developing data exchange standards, archiving AR contents and integration with other built environments as well as challenges in new capabilities like real time virtual model modifications, real-time integration with internet of things (IoT) [72] object and gesture recognition and real-time physics simulations, predictive and prescriptive analytics. Noghabaei, et al. [69] investigated the trends in adopting AR/VR technologies in the AEC industry by conducting two user surveys in two consecutive years (2017, 2018) involving 158 industrial experts. The results show potential for a solid growth of AR/VR technologies in AEC industry in the next 5 to 10 years and significant rise of use of these technologies from 2017 to 2018. The survey also highlights some limitations of adopting AR/VR in AEC industry such as “lack of budget,” “upper management’s lack of understanding of these technologies,” and “design teams’ lack of knowledge.”

2.3 AR Application

There are several aspects to be well-thought-out before developing an AR application as different domains have different AR requirements. For example, an AR game application requirement might be different from those required in AR medial application. In the context of visualizing subsurface utilities, there are number of aspects that need to be explored when developing an application including accuracy of the data for generating virtual model to be displayed, Software Development Kit (SDK) and game engines to be used for developing, AR devices to be used, positioning, anchoring methods of virtual model and localization methods of the AR device and the nature of the environment where the application is used such as indoor or outdoor.

2.3.1 Accuracy of the data for virtual model generation

In the context of AR visualization of subsurface utilities, the uncertainties of the data that is used to generate the virtual model plays a major role in an effective AR visualization. Uncertainty is an inherent part of any spatial data and virtual models of subsurface utilities are no exception. For example, according to DBYD there are four categories of quality levels for utilities data, namely Quality Level (QL) D to QL-A. QL-D provides the least accurate information such as indicating the presence of the utility without any depth or dimensions. QL-C uses available information from QL-D together with ground features such valves, hydrants pit lids. QL-B delivers information about underground utilities with an accuracy ranging from ±300 mm horizontal and ± 500 mm vertical. Basically, it provides relative location and depth from another feature, for instance, a water pipe may be 1 m lower from the ground surface and 2.4 m from the edge of a foot path. QL-A information is the only validated data with ±50 mm vertical and horizontal accuracy with additional information of the utility such as owner type, status, material, size, installation date, surveying methods used to capture etc. [15]. If the AR visualization is to be used for excavation purposes, QL-A is the recommended data to be used for generating virtual model to be displayed. But the challenge is when the accurate 3D location information of the subsurface utilities is not available to visualize in AR. On such occasions, geo-referenced information captured by utility locators need to be integrated with AR system for accurate location of subsurface utilities

2.3.2 *Software Development Kits (SDKs) and Game engines*

AR SDKs are a set of tools, codes, libraries, documentations and examples to help developers to build the AR software for a specific platform [73]. There are a number of SDKs available in the market depending on the device and features to be used in the AR application. Thorough research has to be performed to choose the correct SDK as they can be unique in terms of their license type, supported platforms, virtual model anchoring method, 3D object tracking, geolocation or location-based AR, etc. [73]. Most of the SDKs support devices with operating system (OS) of iOS (iPhones/iPads), Android (Android phones and tablets) and Universal Windows Platform (UWP) (Microsoft HoloLens) and free for startup developments and educational purposes. Vuforia, Wikitude, Mapbox, ARkit, ARcore, EasyAR, Maxst are few of the popular SDKs available in the market.

Game engines or software framework are the main software that are used to build 2D and 3D games as well as AR applications. They provide almost all the supported programs and function needed to develop an AR application. Unity3D is one of the most popular game engines in the AR industry for a variety of reasons. First, it is free for small development companies and students. Therefore, there is an active community using Unity3D for building software and plenty of supports and training materials are available on the internet. It is a cross-platform game engine that allows to build software for devices in different platforms like Windows, IOS, Android etc. Most of the SDKs are developed to be used within Unity3D. Unreal Engine is another example of a free game engine available. It offers similar framework for developing 3D games and AR and VR applications for a wide range of devices with different OS platforms [73-75].

2.3.3 AR devices

AR devices can be classified into three main groups, namely video see-through (VST), Optical see-through (OST) and projective based [73]. Video see-through technique utilizes Hand Held Displays (HHD) such smart phones, tablets and video see-through HMDs to capture the real environment using the devices' camera and the virtual objects are superimposed in the video [76]. Mobile phones and tablets are widely used AR devices due to their public availability and useful suitability for light weight AR applications. Optical see-through technique utilizes optical see-through HMDs or smart glasses by projecting the virtual content on a planer screen while the user can see the real environment through the optical lenses to create the AR scene. Smart glasses can only render 2D virtual contents for instances photos, videos, webpages etc. Epson Moverio BT-300, Solos, Vue are a few examples for 2D smart glasses in the market. Optical see-through HMDs such as Microsoft HoloLens and Magic leap are capable of processing 3D virtual contents allowing seamless transition between real environment and virtual model with advanced computational ability [76]. For example, Microsoft HoloLens Gen 2 consists of multiple environmental understanding sensors such as depth camera for simultaneous localization and mapping, Inertial Measurement Unit (IMU), hand, head, and eye tracking sensors, together with Holographic Processing Unit (HPU). Smart glasses are relatively cheaper, light weight and comfortable while see-through HMDs are expensive and heavier than smart glasses. AR HMDs are much more capable of performing computational-heavy tasks for more advanced AR experiences [77]. In addition to that, they allow the user to freely move around utilizing their hands on performing other tasks rather than holding a mobile phone or tablet. The projective-based or spatial AR technique requires one or more projectors to project the virtual content on to the real environment [78]. The spatial AR technique is limited to static applications but is advantageous in terms of resolution, focus and field of view as compared to video see-through or optical see-through AR [79].

2.3.4 Positioning, anchoring, and localization in AR

Generally, AR can be divided into two main categories in terms of the localization methods used to superimpose virtual contents with the real environments; marker-based and markerless AR [80]. Marker-based AR uses one or more printed images, QR codes or physical objects to anchor virtual model with real environment [80-83]. The main limitation of this method is that the user mobility is restricted to areas where the markers are available [84]. Markerless AR method utilizes multiple types of sensors to obtain information of real-time position of the AR device for accurate placement of the virtual contents in the real environment [80,84,85]. GNSS is the most common method used in AR applications in outdoor environments [3,4,32,35,86-88]. This method is also referred to as location-based or Geolocation AR [81]. Depending on the positional accuracy required for a particular AR application, different accuracy level GNSS sensors could be used from inbuilt GNSS of HHD AR devices such as Mobile phone or tablets with few meters' accuracy to survey grade GNSS with centimetre level accuracy. Since GNSS is not an option in indoor environments, different visual positioning methods are being explored nowadays such as visual relocalization [89] combined with Visual SLAM (VSLAM), Visual Inertial SLAM (VISLAM) and RGB-D SLAM [90]. One of the key problems with markerless method is its relatively lower positional accuracy as compared to marker-based AR [80]. Hence, lots of research is being undertaken to increase the positional accuracy in indoor environments [90-102] and outdoor environments with restricted GNSS signal [103,104].

2.3.5 Indoor and Outdoor AR

The environment in which the virtual contents are augmented is one of the important factors to be considered in achieving quality visualization. The nature of the environment can influence the effectiveness of visualization techniques that are used. AR environment can be classified as indoor and outdoor in the context of subsurface utilities visualization. Outdoor environments are more dynamic and can be unsafe due to busy traffic. As the user can be very engaged with the AR application, he/she can be easily distracted from the environment, which could lead to accidents [105]. Hence, projecting too many virtual contents in the AR scene could lead to severe consequences and it needs to be considered when deciding on the visualization methods for outdoor environments to let the user be conscious about the surrounding. While indoor environments are relatively safer than outdoors in terms of motor traffic, it is still important to be mindful of the surrounding when using AR in deferent scenarios such as indoor construction sites, crowded areas, and narrow walkthroughs.

Moreover, the depth perception of the virtual model can vary in indoors and outdoors according to the experiment conducted in [106]. In this study, an AR model with longer lines and different coloured reference model of known distance was projected using mobile AR to test the users' depth perception in both indoor and outdoor. The research found that distances were overestimated in outdoor. The indoor environment was a narrow walkway with doors on both sides and outdoor was an open car park. Therefore, an AR visualization method does not necessarily provide the same results in different environments. This indicates that visualization strategies should be implemented according to the nature of the environments where the AR application is used.

2.3.6 Commercial Products

Commercial products for AR in construction can be divided into two main categories namely Virtual model generating software products and visualization software products. There are a number of companies such as ESRI, Autodesk, Bentley that make variety of 3D modelling software products for generating 3D models that can be used to visualize in AR. ESRI provides ArcGIS Utility Network that allows creating 3D models of utility network as well as providing tools to visualize logical views of the network and filters for specific selection of the network [107]. Autodesk provides a range of products for generating 3D models in its AEC collection for infrastructure design including Revit, Civil 3D, InfraWorks and Navisworks. Revit is a BIM software that provides tools for planning, designing, constructing, and managing building and infrastructure. Civil 3D is a civil engineering design and documentation software which also supports BIM. InfraWorks is an infrastructure conceptual design software with numerous modelling and visualization tools such as generate features from point clouds, creating realistic images, videos and animations and other analysis and simulations facilities. Navisworks is a project review software that enables co-ordination and project analysis. It also can integrate design and construction datasets into one model for virtual inspections and clash detection [108]. Bentley offers modelling and visualization software products such as MicroStation, Bentley LumenRT and Bentley that can be used to create 3D utility models for AR visualization.

Many companies have launched software to achieve quality visualization of subsurface utilities using AR technique. VGIS is one of the companies based in Canada that develops AR application to visualize spatial data, BIM using variety of handheld devices as well as head-mounted displays. They also develop different visualization methods for subsurface utilities to easily identify them using different colour codes for different utilities [1]. Leica geosystems also uses software from VGIS with their GNSS antenna to achieve higher positional accuracy. Trimble SiteVision launched by Trimble which also provides similar service to VGIS products. Trimble SiteVision offers subsurface utility visualization called Pit view where a virtual pit model is formed to visualize underground utilities [2]. Augview is another example of a company that develops AR GIS products for mobile phones and tablets. Most of the products allow real time interaction with visualized 3D models and the real environment such as measuring distance, depth as well as letting user make changes to 3D models.

2.3.7 Standards and data formats

Standards is all about interoperability; it emerges when several organizations require the same data format to solve a problem and provide guidance to verify if the data is properly organized for sharing [109]. Setting standard for AR requires strong understanding of different AR conditions from different fields as they can be diverse based on their use cases [110]. Currently there are three type of AR solutions namely Dedicated Device-based, App-based and web AR. Device-based AR solutions such as HMDs are expensive and can be inconvenient to carry and use. App-based AR solutions require downloading and installation prior to use and are inconvenient for cross-platform deployment. For instance, an event of a particular AR app may not be able to use in another AR app. Web AR provides low cost and cross-platform AR solutions using a web browser without needing any prior installation.

Virtual models for visualizing subsurface utilities in Device-based and App-based AR solutions come in many standards depending on the requirement of the AR applications installed in the AR device. The most popular standards are in Computer Aided Design (CAD), BIM and Geographical Information System (GIS). There are a number of file formats are being used in CAD domain such as Drawing (DWG), Document Exchange Format (DXF), Object (OBJ), Collaborative Design Activity (COLLADA); Industrial Foundation Classes (IFC) and Green Building Extensible Markup Language (gbXML) in BIM domain and Geography Markup Language (GML), City Geography Markup Language (CityGML) and Keyhole Markup Language (KML) in GIS. Each of these file formats represents varying degree of information of 3D models in terms of geometry, semantics, Level of Details (LoD), texture, etc, and conversion between them can cause loss of information [111]. In the absence of 3D models of subsurface utilities, paper plans can be used as an alternative to provide information to manually generate 3D models in different file formats using various CAD and GIS software.

Web AR is mostly targeted hand held devices such as mobile phones and tablets and has its own limitations compared with device-based and app-based AR such as limited computation, visualization capacity, lack of web AR standardization between different web browsers and limited hardware capabilities of mobile phones [112,113]. Web AR applications developed can be classified into two categories which are location-based and non-location/vision-based. Location-based AR is usually designed for large-scale outdoor applications and non-location/vision based is usually for small-scale indoor application such as tabletop applications. Location-based AR uses GNSS to track the location of the AR model based on Point of Interest (POI) which can be presented in a standardized method [114]. POI is a marker that contains its location information in geographic coordinate system (latitude, longitude). There are popular standards for location-based AR such as Augmented Reality Markup Language (ARML) 1.0, KARML, Layar JSON etc. which are specifically targeted for mobile applications [114]. ARML and KARML are based on KML, which enables direct use of POIs from existing GIS systems. The latest standard for location based AR is ARML 2.0 which was introduced in 2015 by the Open Geospatial Consortium (OGC), one of the Standard Development Organizations (SDOs) [110]. ARML 2.0 is completely different from its previous version and supports both location-based and non-location/vision-based AR applications which are based on different AR anchors such as Geospatial (latitude, longitude), Trackable (QRcodes, images, Objects) and Relative To (an anchor relative to other objects) [115].

2.3.8 Standardization of AR applications

With many AR applications in various industries in the market, a question arises if MR/AR needs standards. Skarbes, *et al.* [116] claims that setting standards for MR would harm the research community. They argue that there is no measurement tool to establish standardization of MR/AR/VR as they are different as to different user bases, different purposes, and technological needs. Perey, et al. [109] states that there will not be one "global" standard for AR as it requires the convergence of numerous technologies and there will be set of standards for AR applications. Ritsos, *et al.* [117] discussed the importance of AR standardization from a user experience (UX) perspective and introduced a theoretical framework called UX for AR (Ux4AR). Ritsos, et al. [117] reviewed multiple questionnaire-based research that can affect user experience to identify the important elements to be mindful for setting standards for AR application such as Use case, Health and safety, integrity, privacy, and security as well as context awareness. When developing AR application to visualize subsurface utilities, context awareness, health and safety elements may be the most critical elements to be considered. Context awareness demonstrates of being conscious about the nature of user's location, how virtual contents are used, placed spatially and temporally. Health and safety are a matter of the utmost importance. For instance, utilizing AR HMDs for extensive period can cause fatigue and visual induced motion sickness, side effects of poor ergonomics etc. [118-121]. Similarly, walking unobservantly of the environment holding a mobile or tablet running AR application could meet with serious accidents.

3 Challenges of AR visualization for subsurface utilities

Although AR has been a widely discussed topic in recent years, the full potential of the technology is still not realized due to different challenges. To achieve a quality AR visualization, the smooth integration of the virtual content with the physical environment both spatially as well as visually is important. AR for subsurface utilities comes with various challenges in terms of the quality of the visualization. Current commercial products for visualizing subsurface utilities in an AR scene suffers with several challenges including occlusion of real world, scene complexity, poor depth perception, parallax effect and positional inaccuracy of the device and the virtual model.

3.1 Occlusion of real world and scene complexity

The most common challenge with any AR visualization of virtual models is the extent of occlusion of real world by the virtual contents. It is an essential part in visualization of subsurface utilities in terms of safety of the user. Usually in construction sites, identifying potential hazards in real world is utmost importance. Generally, OST-HMDs can show the real-world behind the virtual contents depending on the natural light intensity of the environment. Higher natural light in the environment provides higher transparency to the virtual model and visibility of the real world. But it can also be a problem for visualizing holograms in outdoor environment on a bright sunny day. Simple solution for this could be to use dark tint film to reduce sun glare when needed. In HHDs like phones or tablets, adding transparency manually to the virtual contents is the only way to see the real world in the background. However, virtual model transparency can lead to scene complexity due to the crowdedness of the real world and virtual contents information. There are various factors that contributes to the occlusion of real world and scene complexity including the size of the virtual contents, the amount of opacity/brightness/texture used for virtual contents, the period of continuous visualization of virtual contents, the number of virtual contents visualized in a single frame and the device used for AR visualization. It can be really challenging to overcome the occlusion of real world and scene complexity at the same time.

3.2 Poor depth perception

Improving depth perception in AR scene has been a widely researched area [36,122-127]. Correct depth perception of virtual contents with real world depends on the number of depth cues including relative size, height, brightness, shadow effects, occlusion of virtual contents, and binocular-disparity of AR system

[36,126]. AR in handheld devices is commonly implemented using a single camera and a flat screen (monocular) where the binocular-disparity is removed which is critical for depth perception [123,128]. Recent Development of scene understanding HMDs offer better depth perception by displaying stereoscopic images for both eyes that changes in accordance with the user's head motion [129]. Therefore, HMDs works well in terms of binocular disparity for above surface AR scenes with minimum additional visual cues for virtual models. However, it is very challenging to achieve improved depth perception when it comes to visualize subsurface objects as the virtual contents are always rendered on top of the real environment regardless of their depth values. For example, when an underground pipe section is visualized in AR, the device will always draw the pipe above the ground. The resulting visualization is the underground pipe appears floating on top of the ground. Figure 3 illustrates how virtual models are visualized in an AR scene using an HMD when the occlusion function is disabled as it would hide the subsurface objects once the ground is mapped. As shown in Figure 3, Augmented Pit and the underground pipe appears in front of the bush (real world object) while both virtual models would look floating on the ground surface. Therefore, adding further depth cues to virtual subsurface objects is crucial for achieving better depth perception.

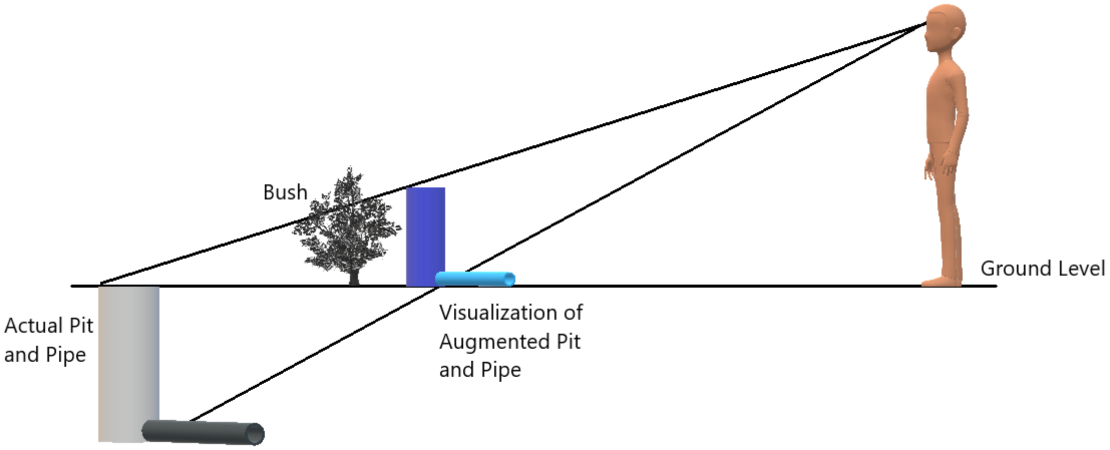


Figure 3. Subsurface utility visualization in AR

3.3 Parallax effect

The third challenge is the impact of the parallax effect on AR visualization of subsurface utilities during a dynamic situation. This occurs when the user continuously changes the location carrying AR device and visualize contents with depth such as underground utilities. Parallax effect will make subsurface 3D models to shift related to the real environment when the user moves. As shown in Figure 4, the parallax effect makes it challenging to locate the service under a horizontal surface. This is because the position of the virtual model on the real surface does not appear fixed and shifts with the user. Hence, when visualizing longer models such as longer underground pipes, far section of the underground pipe from user appears to have higher positional drifts than the closer. This can introduce poor alignment of longer virtual models with real environment when visualizing from different user point of views.

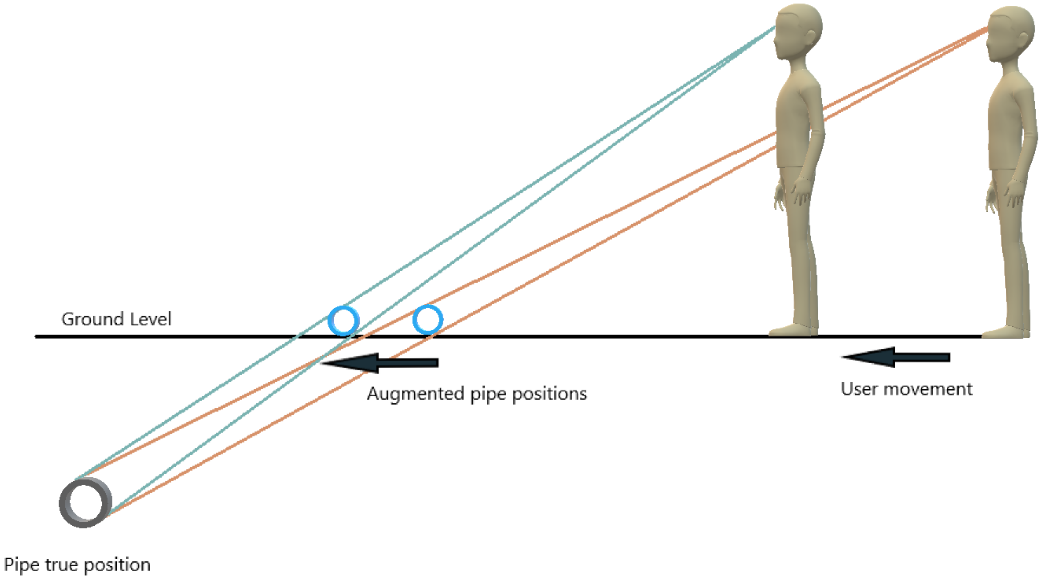


Figure 4. Parallax effect of virtual pipe with the user movement in AR

3.4 Positional accuracy of the AR devices and the virtual models

Accurate registration of virtual model with the real environment is key in effective AR visualization. Poor localization of AR device can lead to erroneous position of virtual contents in the real world. To correctly position the virtual model with the real environment, the projector of the AR application should be calibrated with the physical camera of the AR device. Accurate alignment of virtual and real worlds also requires pose estimation and tracking of the AR device [130]. Mobile phones and tablets are widely used for AR visualization, but these lack accurate tracking capabilities and are not capable of performing computationally expensive operations as compared to advance head mounted displays with environmental understanding sensors that are specially developed for immersive AR experience. However, presently available head mounted displays in the market are designed for indoor environments with adequate number of physical objects for mapping and localization [131,132]. The positional accuracy of virtual models in AR scene also depends on the anchoring methods used to superimpose the virtual model with real environment. Commercial AR visualization products like VGIS and Trimble SiteVision uses markerless anchoring methods which integrates survey based GNSS with mobile phones and tablets to achieve centimeter level positional accuracy in outdoor environments. However, it can be challenging to achieve such a positional accuracy in GNSS deprived area or in an indoor environment without physical markers on site.

4 AR visualization techniques for subsurface utilities

Application of AR for visualizing subsurface utilities has led to many studies over the past two decades, Yet there are still significant improvements have to be made before AR can practically be used in subsurface utility works. Different techniques introduced to enhance AR visualization of subsurface services so far, can be classified into six main categories even though they are referred to with slightly different names in the past studies. These include X-Ray view, Transparent view, Shadow view, Topo view, Image rendering, and Cross section view. In the following, we discuss the principles of the above AR visualization techniques.

4.1 *X-Ray View*

X-ray View is the most popular technique that has been examined in the past studies to visualize hidden objects/utilities [3,4,32,35,37,38,40,87,88,133-138]. It provides visualization of a hidden object inside another visible object (first order object). The same concept could be applied to the subsurface utilities imagining the utility is the hidden object and the first order object is the real world. Schall, et al. [4] referred the X-Ray View with an excavation tool, which creates a cavity in the ground (Figure 5). It represents the virtual utility model only inside an excavated pit with depths marked on the pit's walls to improve the depth perception in monocular displays. Schall, et al. [3] discussed similar representations of X-Ray view with virtual trench along the underground services (Figure 6 (a)) and an excavation box (Figure 6(b)).

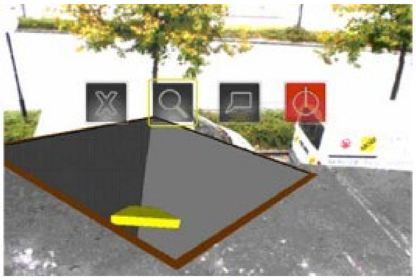


Figure 5. X-Ray View of underground utility. Underground utility (yellow) inside the Excavation tool (Grey box) [4].

(a) (b)

Figure 6. X-Ray view of an electricity line. Trench along the electricity line (a), Excavation Box (b) [3]

Behzadan, et al. [32] also analysed the excavation tool to visualize underground pipes in their research on utility collision avoidance to locate buried pipes without damaging them during the excavation. They integrated Real Time Kinematic Global Position System (RTK-GPS) with the available geospatial data to generate a 3D model and augmented it in real time using a display within the excavator's cabin. The study further improved the pose of the projected virtual model at each frame of the video by placing additional GPS antenna on the cabin to compute the directional vector of the excavator by applying a trigonometric 3D registration for a composite AR view. The research also reviewed the labelling, different colour coding of services and X-Ray vision/Excavation tool. Similar attempt was made in [135] to avoid collision during the excavation of underground pipe by augmenting live excavation work using a sandbox and a toy excavator. Kinect device was used to capture the dynamic terrain topography during the excavation. Côté, et al. [134] used X-Ray view in his experiment in increasing the level of accuracy of AR Utility virtual model visualization using robotic total station and a tablet. Feiner, *et al.* [139] discussed the X-Ray View but referred to it as "Cutaway effect". They illustrated how a hidden battery inside a radio can be visualized using X-Ray View (Figure 7). X-Ray view method can deliver additional depth cues by replacing a defined area of the first depth order object with the occluded object in AR visualization.

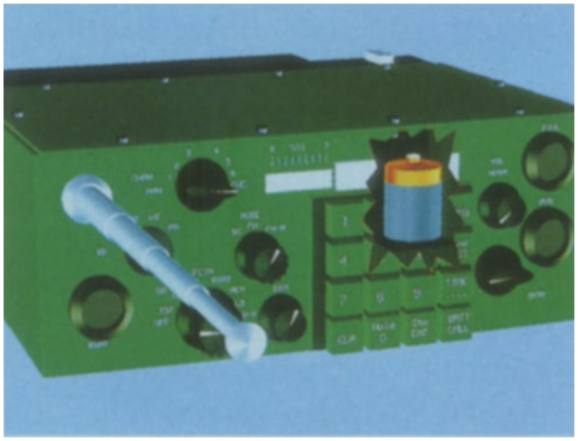


Figure 7. X-Ray view of a hidden battery inside a radio, The battery is rendered with cutaway effect [139].

Another form of X-Ray view is called Reality capture, where 3D models of actual utility excavation holes are captured as point clouds using various scanning methods and they can be visualized in AR later when needed. As shown in Figure 8 where the pre-captured point cloud of a utility pit is rendered on top of the footpath [137]. Similar representation of pre-captured point cloud embedded on the real world in AR is discussed in [140] as well for achieving a realistic view of the past. Since X-Ray view offers good quality depth perception, it has been discussed as one of the subsurface utilities' visualization methods in various aspects of research in AR for subsurface utilities [35,37,133,136].

Figure 8. X-Ray view of reality capture of utility Pit [137]

4.2 Transparent View

Transparent view provides a visualization of a virtual object rendered as transparent and overlaid on the real object. This method allows both the virtual and real objects to preserve only some of their information where they meet. The amount of the transparency is set by the user. Feiner, et al. [139] explained transparent view with hidden battery inside a radio by making the battery and the defined area of the radio transparent (Figure 9).

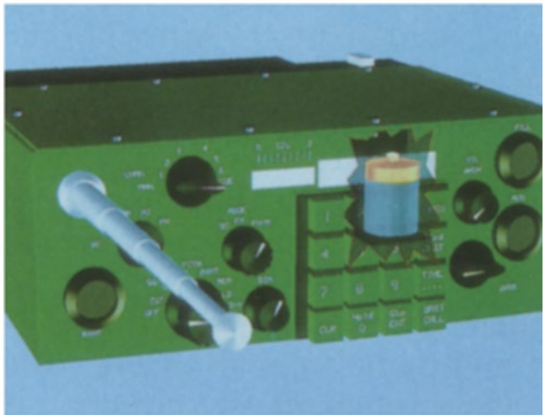


Figure 9. Transparent view of a hidden battery inside a radio. The battery and defined area of radio are rendered as transparent [139].

Zollmann, et al. [39] discussed another version of transparent view named alpha-blending, which uses half transparent objects preserving equal content of virtual and physical environments (Figure 10 (a)). Another form of transparency is called distance alpha-blending (Figure 10 (b)), in which the amount of the transparency is proportional to the distance of the virtual object from the user point of view. Thus, the far virtual objects would have more transparency compared to the closer virtual objects to minimize the complexity of the AR with many pipelines [35].

(a) (b)

Figure 10. Different Approaches of Transparent view. (a) Alpha-Blending [39] (b) distance alpha-blending [35]

4.3 *Topo view*

In Topo view the depth of the subsurface utility is not considered, and it is visualized using its surface-level position. Subsequently, the visualization does not suffer from the parallax effect. Stylianidis, et al. [34] called Topo view as a street level mode where all the pipes are projected on the street level regardless of their varying depths as illustrated in Figure 11. Topo view can represent the subsurface assets in a very simpler manner, which can be problematic when several subsurface assets are located at the same horizontal position but different depths.

Figure 11. Topo view. Street level mode [34]

Cote, *et al.* [141] also proposed to use Topo view in their research on visualizing underground utilities on to the roads surface and align the model with the real world utilizing a pre-captured 3D mesh of the real environment. They referred to Topo view as 2D pipe maps in their study. As shown in Figure 12, the pipes and pits are projected on to the ground level.

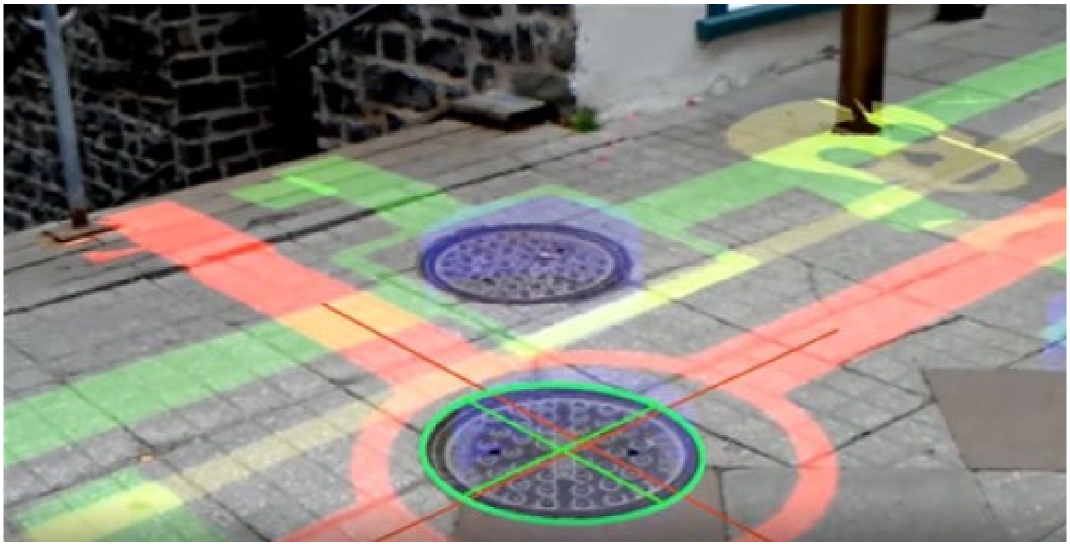


Figure 12. 2D pipe map [141]

Hansen, et al. [140] presented a new approach to replace physical spray marking by virtual spray marking which also a form of Topo view. As shown in Figure 13, the virtual utility representation replicates the actual ground marking. They utilized an iPad with built in Lidar sensor together with customized sensor box containing GPS-RTK, smart IMU and pressure sensor. Since real-time reconstruction of the real world is also performed in their approach, the virtual paint correctly aligns on the ground surface even during the excavation as well as the dynamic occlusion. Therefore, the virtual model will not be rendered on top of a moving object on top of the ground and correctly aligns on top of the changing ground surface during the excavation.

(a) (b)

Figure 13. (a) Physical marking on street surface (b) Virtual utility marking of similar information in AR [140]

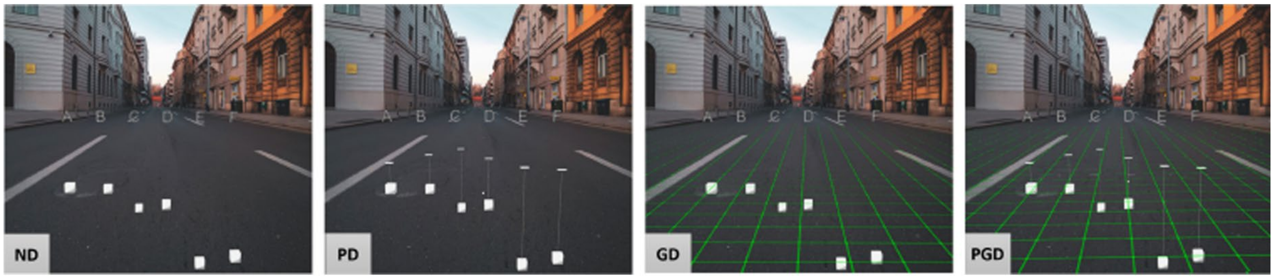
4.4 Shadow View

Shadow view is an attempt to provide depth perception of 3D utility (with depth) using its shadow cast on the surface. The shadow is essentially a Topo view. Consequently, the shadow on the ground surface does not shift with respect to the real environment when the user changes his/her point of view, but the apparent position of the 3D model itself might have horizontal movements. This technique consists of virtual 3D lines for each pipe and their consecutive shadows. Schall, et al. [3] applied this technique to visualize the underground electrical pipe (Figure 14 (a)) where the pipe is shown in red and the vertical projection (shadow) of the pipe is in grey and joining red lines between the pipe and the shadow. In another study, Stylianidis, et al. [34] tried the same method with slightly different representation as shown in Figure 14 (b) where a pipe and it's shadow are shown in the same colour but using different line styles. Liu, et al. [86] also attempted a similar way to visualize hidden pipes behind walls by projecting the shadow of a pipe on to the wall plane with different colours (Figure 14 (c))

(a) (b) (c)

Figure 14. Different visualizations of shadow view. (a) Virtual shadow cast on the ground plan [3], (b) shadows with different line styles [34], (c) shadow (yellow) and the pipe (green) in different colors [86]

Becher, et al. [33] evaluated the effectiveness of shadow view using virtual cubes which are in different depths from ground level. This method was referred to as Projection Display (PD) in the study. As shown in Figure 15 (b), the shadows of the cubes are projected on to the ground plane with connecting lines. Grid Display (GD) (Figure 15 (c)) and Projection Grid Display (PGD) (Figure 15 (d)) are rendered with additional ground plane grid to Naïve display (ND) (Figure 15 (a)) and PD respectively. ND is discussed in this experiment for the sake of comparing the quality of depth perception with other methods.



(a) (b) (c) (d)

Figure 15. (a) Naive Display (ND), (b) Projection Display (PD), (c) Grid Display (GD) , (d) Projection Grid Display (PGD*)* [33]

4.5 Image rendering

Image rendering method performs manipulations on of real-world phenomenon pixels in images or a video to enhance the depth perception of the subsurface utility in AR visualization. Chen*, et al.* [142] introduced a visualization technique on improving the depth perception of buried pipes on images and videos using a fixed camera. They divide the real scene into two parts, moving and static and segment the moving objects out from the rendering as they are above the ground. The objects depth order is enhanced by displaying the edges extracted from the image of the physical world over the virtual content as well as a smooth coloured mask around the virtual model with sharp edges at the intersections. In this method the virtual model can be occluded by moving objects on the ground level in the video as shown in Figure 16.

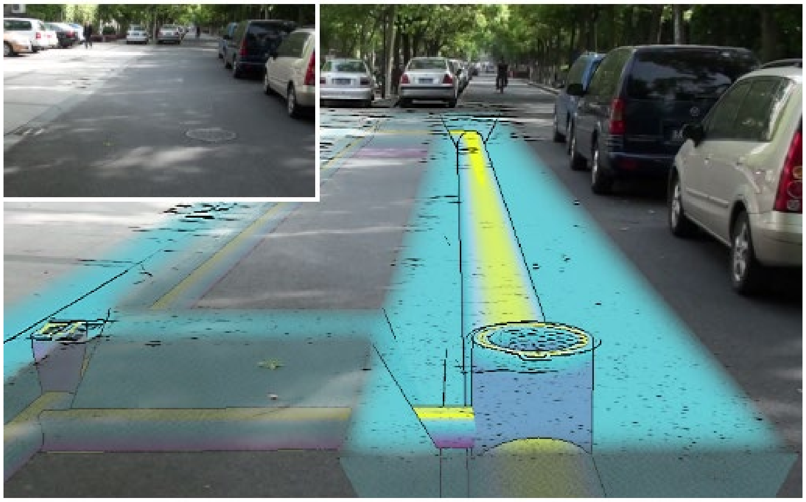


Figure 16. Image rendering method. Smooth colored mask and the edges of the physical world over the virtual objects [142]

Zollmann, et al. [39] analysed various image rendering methods to produce better AR for underground services, such as edge-based ghosting ((Figure 17 a)), image-based ghosting (Figure 17 (b)) on video images. The edge-based ghosting is a method in which edges of the real-world features replace the virtual models. The image-based ghosting method preserve only the important information from the image such as bright pixels and edges for rendering. According to the survey conducted in their studies, the image-ghosting method outperformed the other methods in terms providing better depth cues.

(a)

(b)

Figure 17. Image rendering (a) Edge-based ghosting (b) Image-based ghosting [39]

Eren, et al. [37] also investigated an image rendering method called edge overlay to increase the depth perception, where the sharp edges of the physical world replaced the virtual and the real contents. They tested this method by visualizing virtual pipes of a rectangle grated pit (Gray) (Figure 18). In this method the sharp edges extracted from the image of the real world are replaced with white bright pixels in the image. It adds a visual cue to assist the user to feel that the virtual model is under the physical environment.

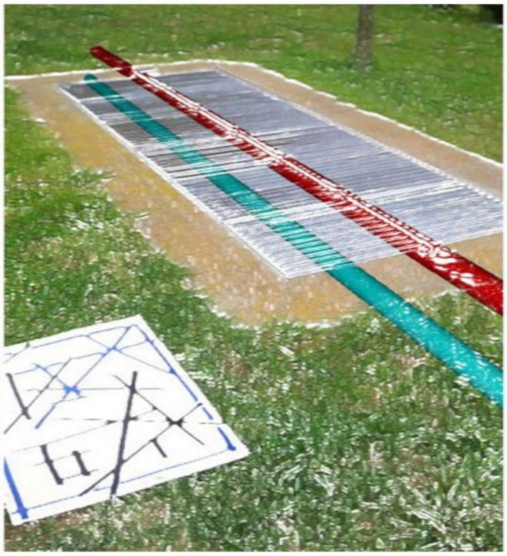
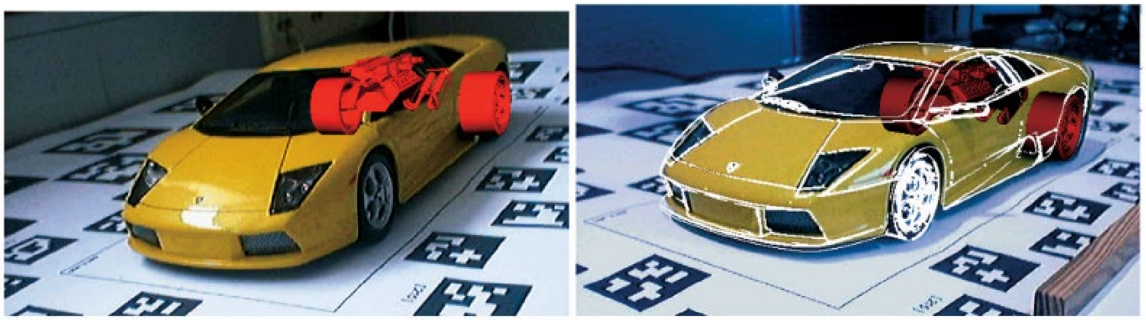


Figure 18. Image rendering. Edge overlay. Gray rectangle is the lid of the pit [37]

Kalkofen, *et al.* [143] analysed image rendering method by showing the edges of the real-world object with white pixels to add extra depth cues to the hidden object using a toy car (Figure 19). They referred to the method as Focus and Context where Focus is the important information, subsurface services, and the Context is visible to the bare eyes which is the real environment.

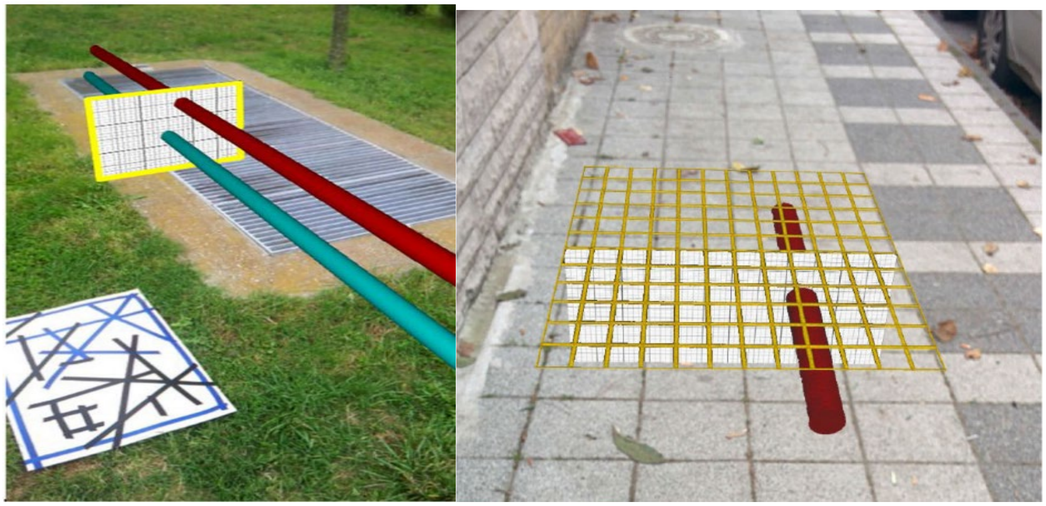


(a) (b)

Figure 19. (a) Careless overlay of virtual object (Red), which looks floating on the real environment. (b) After including edges of the actual car, it adds better depth perception of the virtual object (internal parts) [143]

4.6 Cross-section View

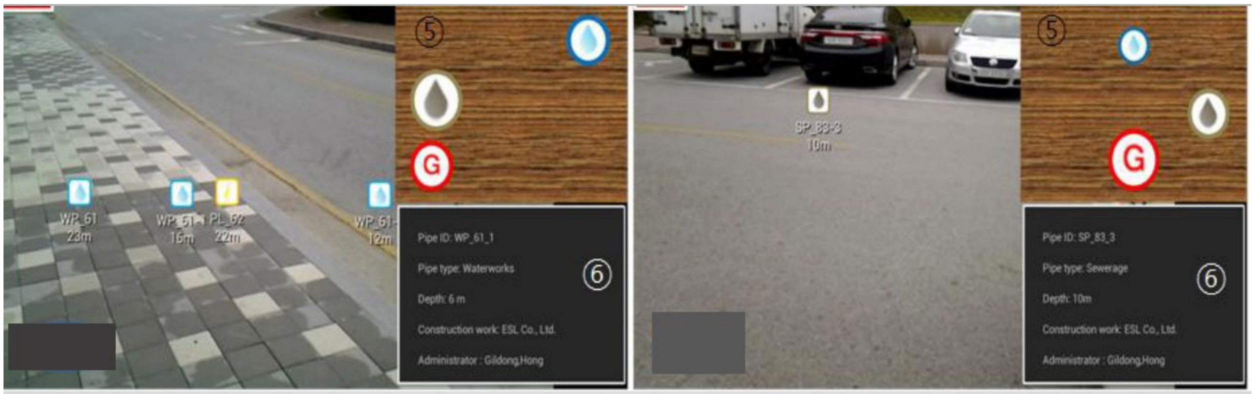
Cross-section view aims to enhance the depth perception by generating a virtual plane intersecting the virtual object where the top of the plane meets the ground level. (Figure 20). Eren, et al. [37] explored two distinct ways of using cross-section view, one based on an opaque cross section plane perpendicular to the pipes and the other using a grid overlay at the ground level with an opaque cross-section plane perpendicular to the grid as shown in Figure 20. The cross-section with a grid overlay is considered as a better approach in terms of providing more depth perception to the pipes.



(a) (b)

Figure 20. Different Cross-section view. (a) opaque cross section plane (b) ground plane grid [37]

AR visualization of multiple subsurface utilities at a user defined location in a single display can create confusion for the user at site. Baek, *et al.* [144] proposed a solution for this problem by developing a database of the marker location of the services and a system to automatically generate a cross section view where needed. The database also enables the user to make correction to the virtual contents. As shown in Figure 21, this provides a simplified and less cluttered way of displaying the location, depth, and materials of buried services.



Pipe ID: WP_61_1
Pipe type: Waterworks
Depth: 6 m
Construction work: ESL Co., Ltd.
Administrator : Gildong.Hong

Pipe ID: SP_83_3
Pipe type: Sewerage
Depth: 10m
Construction work: ESL Co., Ltd.
Administrator : Gildong.Hong

Figure 21. Visualization of marker locations of underground services, vertical arrangements, and attributes of pipes [144]

5 Comparison

The visualization techniques discussed above have advantages and drawbacks when applied in practice for visualizing subsurface utilities. It is important to determine the correct visualization method according to the requirements of the task. In this section we compare the AR visualization methods in terms of the quality of depth perception, the amount of occlusion of real world, the complexity of visualization and the parallax effect. Table 1 summarizes the comparison of AR visualization techniques in terms of the above criteria.

5.1 Quality of depth perception

Depth perception is important for an effective visualization of subsurface utilities to provide a visual cue about the depth of buried utilities from surface. Incorrect overlay of the virtual content over the real-world would create depth perception issues, which will lead to unnatural visualization or wrong perception of the objects order [32]. When the quality of depth perception is poor, the augmented subsurface model would appear floating on top of the real environment rather than under the surface. AR methods discussed in section 4 provide different depth perceptions of different quality. X-Ray view and Cross-section view provide better depth perception as compared to the other methods. Baek, et al. [144] compared the X-Ray view with few other methods and conducted a survey to find the most effective method. Their results show that Excavation box which is a form of X-Ray view outperformed the other methods. Moreover, the survey conducted in [37] revealed that the Excavation Box (X-Ray view) and the Cross-section techniques provided a similar quality of depth perception. Reality capture form of X-Ray view is also a great way of achieving a better depth cues, but it requires pre-captured data which is a major limitation of the method.

Transparent view, shadow view and image rendering methods provide moderate quality of depth perception. The depth perception achieved in transparent view is less effective than the X-Ray view. This can be examined by comparing the visualization shown in Figure 7 and Figure 9 where the cutaway method (form of X-Ray view) shown in Figure 7 provides better depth cues than transparent view shown in Figure 9. Similarly, comparing the visualization in Figure 6 (a) and Figure 14 (a) reveals that shadow view is less effective in providing depth perception than the X-Ray. The survey conducted in [3] with expert end users from utility companies shows that the virtual trench along the subsurface utility pipes gives better depth cues as compared to shadow view of the pipe on the ground. Experiment performed in [33] compares shadow view (Projection display) with Naïve Display (ND), Grid Display (GP) and Projection Grid Display (PGD) (Figure 15). Even though the result of the experiment reveals that PGD which is a shadow view combined with a grid on ground plane outperformed other methods, it is difficult to compare PGD with other visualization methods reviewed in this paper. Various image rendering methods used in the past studies such as edge-based, image-based, and predefined mask approaches do assist in accomplishing better depth cues [39,142]. From the result of the user survey conducted in [39], the image-based ghosting method (Figure 17 (b)) outperformed the edge-based ghosting method (Figure 17 (a)). The survey conducted in [37] found that Edge overlay technique (Figure 18) is less effective than the other methods in terms of depth perception. Comparing Figure 6 and Figure 17 also shows that X-Ray view provides a higher quality of depth than image rendering.

Topo view simply ignores the depth data and, therefore, it does not give any depth perception of buried utilities. Topo view may not be the suitable for users who require 3D visualization of the subsurface utilities, which is necessary when exposing and pin the preliminary planning stage of construction. Even if the depth information could be retrieved at user selected locations, it might not be the most user-friendly method as the user has to select multiple locations when necessary.

5.2 Occlusion of real world

The amount of occlusion of real world by the virtual models during the AR visualization is a critical criterion when comparing different visualization methods. The more occlusion means less knowledge about the real environment which can prevent the user from identifying potential hazards or useful information of the real world. For an effective AR visualization preserving both the virtual and the real content to the furthest extent is important. Transparent view can be considered as the best visualization method in terms of occlusion of real world depending on the transparency level of the virtual model. Past studies have tried various methods of transparent views, but the real challenge is to determine the amount of the virtual and the physical contents to be visible, while preserving the important information of virtual and physical contents [39]. X-Ray view can occlude a large part of the real site depending on the size of the excavation box or area of the reality capture (Figure 6 and Figure 8).

Topo view and shadow view partly occlude the real environment, but they are more effective that X-Ray view as they occlude a small area. Cross-section view also provides a moderate level of occlusion, but excessive use of cross sections can occlude more real environment (Figure 20). Comparing image rendering methods with other AR visualization methods in terms of occlusion of real world is not straightforward as the result highly depends on the algorithm used to determine the amount of the occlusion of the real environment.

5.3 Complexity of visualization

The AR visualization for subsurface utilities can be complex when there are multiple virtual models in the scene. Consequently, the scene may become too crowded and confuse the user. Topo view provides the least complex visualization as it provides a simple view of subsurface utilities. An exception is the situation when there are multiple utilities located in the same horizontal position but at different depths. In this situation only one of those utilities could be visualized at a time. Similarly, X-Ray view is also capable of providing a simple view when only the utilities inside the excavation box/Trench is visualized (Figure 5 and Figure 6 (a)). However, it is more complex than the Topo view as there are more virtual contents visualized in X-Ray view than Topo view.

Transparent view can create a moderate level of complexity based on the transparency level used in the visualization as it preserves information of both virtual and real worlds (Figure 9). Similarly, Cross-section view can add complexity to the scene depending on the number of the cross-section planes used for the visualization (Figure 20 (a)). Image rendering methods cannot be compared in terms of complexity as the complexity depends on the pixel processing algorithms used. When the algorithm tries to preserve more information of the virtual and real worlds, it can be complex, but simple image rendering is also possible. As shown in Figure 17, image-based ghosting method occludes the entire section of the virtual model by bright pixels in the image whereas edge-based ghosting method occludes the virtual model only where the sharp edges of the real worlds are. Shadow view could be considered as the most complex method among the other methods as it visualizes two lines for each utility and make the scene crowded (Figure 14(b)).

5.4 Parallax effect

Parallax effect makes it difficult for the user to locate 3D subsurface utilities on a horizontal surface when the user moves (Figure 4). To achieve an effective visualization, it is very important to mitigate the effect of parallax in AR visualization for subsurface utilities. Parallax would persist to affect every time when a 3D virtual subsurface object with depth is visualized. Parallax effect is controlled to a certain extent in X-Ray view even though the utility model is visualized in 3D. When the utility model is visualized inside a virtual trench or virtual pit the shift of the virtual utility model relative to real world will be negligible as the model is shown at its true depth. The remainder of the 3D virtual model, however, would suffer from parallax in X-Ray view. The only method which would not be affected by parallax is the Topo view as it does not contain depth information. As shown in Figure 11, the pipes are visualized on the ground level, and when the user moves with the AR device, the shift of the subsurface utility relative to the ground would be zero. Shadow view is the second-best AR visualization method in terms of parallax. Since the shadow of the subsurface utilities is like Topo view, the parallax effect is handled to some extent as the shadow of the subsurface utility would be stable when the user moves. But the subsurface utility has the parallax effect unlike its shadow (Figure 14(b)). Cross-section method also suffers from parallax except for top of the cross-section plan and the grid in Figure 20 (b)). The other AR visualization methods suffer from parallax effects as 3D objects with depth are shifted on the ground surface.

Table 1. Comparison of AR visualization methods.

Methods	Quality of Depth Perception	Occlusion of Real World	Complexity of visualization	Parallax Effect
X-Ray View	High	High	Low	Partial
Transparent View	Moderate	Low	Moderate	Yes
Topo View	-	Moderate	Low	No
Shadow View	Moderate	Moderate	High	Yes, for utility, No for its shadow
Image rendering	Moderate	Variable	Variable	Yes, for 3D models with depth
Cross Section View	High	Moderate	Moderate	Yes

6 Discussion

To achieve an effective AR visualization of subsurface utilities indoor/outdoor, a suitable visualization method that allows the user to achieve correct depth perception with low occlusion of real world, low complexity and minimized parallax effect is crucial. None of the above discussed AR visualization methods meets all these requirements when they are implemented alone. Figure 22 and Figure 23 show two examples of visualization methods used by commercial products from VGIS and Trimble. As depicted in the figures, the above discussed drawbacks apply for these two visualization methods as well. Figure 22 illustrates a form of shadow view where the virtual underground pipe models (solid blue, red and green lines) appear floating on top of the road providing poor depth perception. Figure 23 shows an X-Ray view with a yellow opaque Pit where the underground pipes and pits (blue/red horizontal and vertical models respectively) are rendered within. Almost half of the real environment information is occluded in the mobile display from the current point of view which will prevent the user from identifying potential hazards in the real environment.

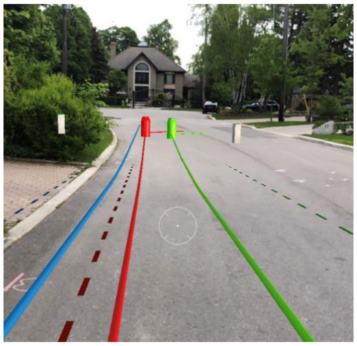


Figure 22. VGIS Shadow View "with permission" [1]

Figure 23. Trimble SiteVision Pit View (X-Ray View) "with permission" [2]

Another issue in visualizing 3D subsurface utilities that requires further investigation is the parallax effect caused by the user movement with the AR device. Liu, et al. [86] tested an approach with laser-based target designation which extrapolates the location of a hidden pipe (behind a wall) on the surface of the wall to counteract the parallax issue. This method is like projecting the shadow of the subsurface pipes on to the surface to provide a better depth perception. User studies conducted in that research, found that, even though the user is provided with visual cues for understanding the depth, the spatial assessment of the target position is untrustworthy when the offset between the user and the virtual object increases. In such a situation the parallax effect cannot be eliminated and as the distance between the virtual model and the user increases the parallax effect becomes more significant.

An effective AR visualization is achieved when both the real and the virtual models are accurately registered with each other in real-time, or else the projected virtual model would look out of the true position or floating on the real scene creating an unnatural experience as shown in Figure 7 and Figure 5 respectively. Accurate registration of virtual content to the real world requires, accurate localization of the AR device as well as proper understanding of the real-world by the AR application. This problem could be resolved by seamless registration of the virtual model with an image of the real world in real time. This approach is called model-based tracking [93,140] and can potentially minimize the misalignment between the virtual and the real worlds. However, model-based tracking is computationally complex, and its feasibility depends on the processing power of the AR device [101]. Moreover, it requires pre-captured 3D model of the real environment which is a major limitation [141].

Another major limitation of AR visualization of subsurface utilities is the low accuracy of the virtual model. Currently the majority of available outdoor utility datasets are still based on paper plans and do not comprise of accurate horizontal/vertical locations for every situation which is a significant challenge in outdoor AR visualization of subsurface utilities [15]. In some instances, utilities buried long time ago may not have any information about their location or depths. On such occasions, the first step is capturing underground utilities using locating techniques. Once the utilities are located, they could be used to create virtual models to be used in AR visualization. Alternatively, geo-referenced digital data captured by utility locating devices can also be used in AR visualization [145]. Ayala Cabrera*, et al.* [146] developed a method to fuse AR with underground utility information captured by locating devices such as GPR for Water Supply System (WSS). Their system enables elements of WSS to be explored and updated which would help for a dynamic management of WSS.

7 Conclusion and Future Work

This paper reviewed AR visualization methods for subsurface utilities and hidden objects from journals, conference papers, books, commercial products guides, and magazines published from 1992 to 2021. We describe the principles of different AR methods and discussed the advantages and drawback of each method when used individually. Our comparison of the different methods in terms of quality of depth perception, occlusion, complexity, and parallax revealed that no single method provides the best visualization in all application scenarios and the choice of a suitable method depends on application and user requirements.

Further research is needed to develop more effective visualization techniques to overcome the drawbacks of the current methods for achieving better depth perception when a 3D virtual model with depth is visualized. Existing AR methods are more focused on improving the quality of the virtual model and not considering the real world. When AR has spatial awareness, it is possible to achieve a better visualization allowing the virtual contents to interact with the real world [58]. Therefore, taking the topology of the real world into account can potentially improve the AR visualization of subsurface utilities [135,140]. Moreover, a combination of different visualization methods might accomplish an effective AR visualization depending on the site condition. Future directions for developing more effective AR visualization include:

1. With recent development in AR devices, interaction with the real environment can be more practical. This brings a new source of information in addition to the virtual contents to provide a better visualization and perception to users in an AR scene. This needs to be explored further.
2. Developing better depth perception cues such as contour lines and meshes representing the depth of excavation and topography of the ground surface respectively.
3. Machine Learning (ML) methods could be developed to automatically learn the site condition and propose a suitable visualization method to the user, or automatically apply a suitable visualization method in real time.
4. To tackle the localization problems in indoor or GNSS deprived area, further research needs to be done on performing real-time registration of the virtual model and the real world.
5. New approaches are needed to overcome the parallax effect and avoid confusion in the AR visualization when multiple utilities with depth are visualized in a dynamic situation.

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Figures