RESOLVING PERCEPTUAL CHALLENGES OF VISUALIZING UNDERGROUND UTILITIES IN MIXED REALITY

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ABSTRACT:

Augmented reality (AR) is intensely explored due to its wide range of potential applications, from education and engineering to medicine and defense. Nevertheless, utilizing AR for visualizing underground utilities still faces a number of challenges, including the unavailability of reliable, readily accessible digital information about underground utilities, localization of AR devices in a GNSS-deprived environment, and visual perceptual challenges. This paper discusses the utilization of Mixed reality (MR) to address the visual perceptual challenges, which can provide a realistic visualization and convenient user experience compared to AR. Six MR visualization prototypes have been developed, namely, "General view", "General + Range view", "General + Elevator view", "X-Ray box view", "X-Ray box + Depthslider view", and "X-Ray + box + Clipping view", and they are deployed to Microsoft HoloLens 2 for testing purposes. These new MR visualization methods can potentially resolve AR's visual perceptual challenges for visualizing underground utilities.

1. INTRODUCTION

With the rise of industry 4.0 and the arrival of affordable and advanced devices, many industries, including Architecture Engineering and Construction (AEC), began exploring reality technologies such as Virtual Reality (VR), AR, and MR as tools for visualizing digital information and remote collaboration. VR delivers an entirely virtual world around the user with a VR headset. VR is more suitable in a closed environment due to its inability to interact with the physical world. In contrast, AR enables digital content such as images, texts, and 3D models to be superimposed over the real environment to build a hybrid world. However, AR's interaction between the virtual and the physical world is significantly limited. MR solves this by allowing the virtual content, the so-called Holograms, to seamlessly blend with the virtual build of the physical environment enabling interactions between the virtual and the physical worlds (Rokhsaritalemi et al., 2020). MR can be achieved using head-mounted displays (HMD), which are comparatively expensive but possess high computational capabilities for real-time mapping of its surrounding for a more immersive experience than AR.

AR is widely explored in many industries, from education to defense, because of its potential to be implemented using low-cost and commonly public-owned devices like smartphones and tablets. However, AR for underground utilities still suffers from many challenges, including the availability of accurate utility location information for generating virtual content, AR device positioning in a GNSS-deprived/limited environment, and visual-perceptual issues. Poor depth perception of the underground utilities, parallax effect on the utilities due to the utilities' depth while the user moves, scene complexity caused by an excessive number of virtual contents when there are many utilities to be visualized, and the amount of the occlusion of the physical environment by the virtual content for safety concerns are few of the primary visual perceptual issues in an underground utilities AR scene (Muthalif et al., 2022).

Since MR can deliver more immersive visualization than AR, it has the potential to overcome the visual-perceptual challenges of visualizing underground utilities. This paper presents six new MR visualization methods to minimize the visual-perceptual challenges of AR. These MR methods are categorized into two scenarios that can be implemented in two situations: 1) General visualization purposes such as preliminary site inspection in the planning stage of construction works. 2) Excavation-related works. To the best of our knowledge, this is the first study that analyses multiple MR visualization methods for visualizing underground utilities

The remainder of this paper is structured as follows; Section 2 discusses the practical challenges in implementing AR for underground utilities. Section 3 provides a brief of past related works. New MR prototypes have been explained in Section 4, followed by a discussion of these methods in Section 5. Section 6 provides a conclusion and the future aspects of this research.

2. BACKGROUND

In the last two decades, AR has been a widely researched topic due to several challenges in the current practice of locating and visualizing underground utilities. For instance, utility locating contractors in Australia utilize PDF plans obtained via an online platform called Dial Before You Dig (DBYD). Then the utility locating process is started using various kinds of locating devices depending on the utility's types. The located utilities are then marked on the ground before the excavation. The key drawback is that the ground marking is usually done with spray paint and will disappear once the excavation starts.

Consequently, the excavating personnel might have to refer back to the PDF plans to verify the utility locations or repeat the locating process. Else, a surveyor can be employed to record the marking before the excavation begins to assist with staking out the location when needed. This process can be time-consuming and expensive. Moreover, ground markings can also be complex when several utilities are buried in a small area. Thus, it may lead the excavating personnel to misread the markings. As a result, utility strikes or damage to utilities may occur, costing a lot of repair works and project delays and posing a risk to the safety of the workers (Fenais et al., 2020).

2.1 Challenges in AR for underground utilities

AR can resolve the traditional marking method's challenges when used effectively. However, several other limitations still need to be addressed to realize its full potential.

2.1.1 Availability of utility location information: AR for visualizing underground utilities is still far from practical due to several data issues. The most critical one is the unavailability of accurate and reliable underground utility information for generating a virtual model to be displayed. For instance, DBYD has four categories of plans, Level A to Level D. Level A plans provide the highest location accuracy of ±50mm and are very limited in numbers. Level D provides the least accurate location information indicating only the presence of the utility at the site. More importantly, DBYD does not hold plans for all the underground utilities in Australia (Dig, 2021). Furthermore, existing location information of the underground utilities may be associated with human errors such as plan errors during drafting and surveying. These are almost impossible to verify at the site before locating them using locating devices.

In the absence of reliable location information for generating a virtual model to be visualized in any reality technology, a conventional locating process must be performed. Later the information from utility locating devices can be used for creating the appropriate virtual content. This can also limit the use of AR as it can be time-consuming and not practical. Therefore, the availability of accurate, reliable, and accessible digital location information for underground utilities plays a vital role in AR visualization.

2.1.2 AR device localization in GNSS-deprived environment: Pose estimation (positioning and orientation) of the AR devices with Six Degree of Freedom (DOF) throughout the user experience is critical in AR visualization. Most AR commercial products for visualizing underground utilities integrate survey-grade GNSS with the AR device for accurate positioning and built-in sensors such as the Inertial Measurement Unit (IMU) for orientation (Trimble, 2021). In an environment like an urban canyon or heavily vegetated area, the GNSS signal can be weak or unavailable. Consequently, the AR visualization will be erroneous even if the utilities' accurate location information is available.

Finding the pose of a person in an unknown environment is a well-known issue, and various solutions have been proposed. They can be divided into infrastructure-based and infrastructure-free methods. Infrastructure-based methods use sensors like Radio Frequency Identification (RFID), Bluetooth, and WIFI (Gu et al., 2019) for positioning and the device's internal sensors like IMU for rotation. This method can be expensive to implement. Moreover, the positioning accuracy can vary up to a few meters and is considered unsuitable, especially for subsurface utilities AR applications.

Alternatively, the infrastructure-free methods and, in particular, the visual positioning of AR devices is an extensively researched topic in GNSS-deprived environments such as indoor and underground constructions (Acharya et al., 2020; Acharya et al., 2019). The popular technique in this method is called Simultaneous Localization And Mapping (SLAM) (Jinyu et al., 2019). This method does not need any pre-installed sensors. It depends entirely on the real-time construction of the physical environment and localizing using the built 3D map. However, the process is computationally expensive and requires high processing capacities. Additionally, it suffers from accumulating errors when applied in large environments.

2.1.3 Visual perceptual issues in AR: AR suffers from many visual perceptual issues as it superimposes the virtual content over the physical environment. The most significant issue is the quality of the depth perception of the utilities. Poor depth perception in AR visualization of underground utilities will make them float on top of the physical world (Figure 1). Consequently, the underground utilities will appear in front of above-ground objects (Figure 2). Additionally, the underground utilities can look misaligned/misplaced when viewed from different directions.

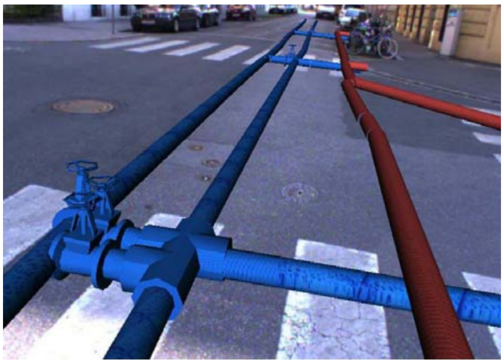

Figure 1. The virtual model appears floating (Schall et al., 2010)

Figure 2. Underground utility visualization in AR

The parallax effect of the subsurface virtual objects is another issue, making them drift in relation to the real world when the user moves (Figure 3). It can make it difficult for the user to estimate the actual location of the subsurface virtual object on the surface. Therefore, visualizing underground utilities in AR without additional visual cues can confuse the user in estimating their horizontal location on the ground.

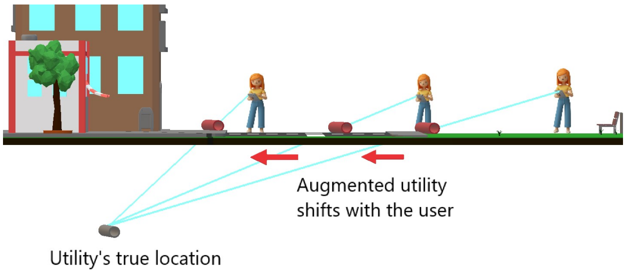

Figure 3. Parallax effect of virtual pipe with the user movement.

Moreover, visualizing several virtual objects can make the AR scene complex and cause inconvenience to the user. When several underground utilities are buried in a small area (Figure 4), AR visualization should effectively reduce the scene complexity for the user.

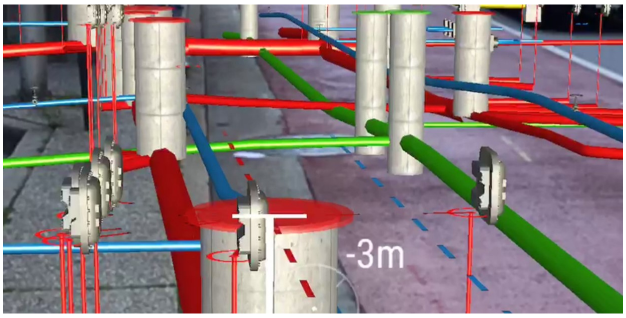

Figure 4. Crowded AR scene (Kci, 2022)

Visualizing large virtual objects in AR can occlude a significant amount of the physical world. This is a critical aspect when designing an AR visualization for underground utilities at a construction site or busy environment, as it can be challenging for the users to spot any potential hazards at the site. A sizeable virtual model does not necessarily have to complicate the AR visualization. However, it can significantly obscure the physical world (Figure 5). Therefore, a suitable approach must be utilized when visualizing larger virtual models.

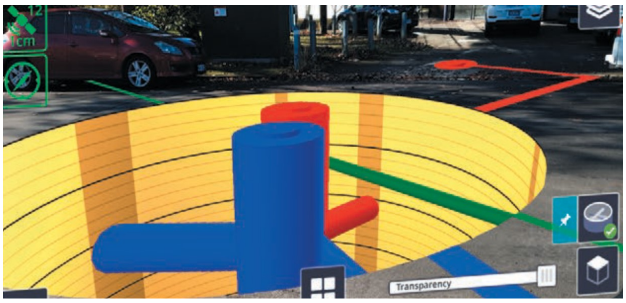

Figure 5. Large virtual model in AR (Trimble, 2021)

2.2 Mixed Reality

Due to the limited interaction between the virtual content and the physical world in AR, the need for MR emerged. MR provides an immersive experience using MR head-mounted devices by blending the virtual content in the form of holograms with the virtual construction of the user environment, providing real-time interaction between holograms and the physical environment. Consequently, MR holds much potential to address AR's visual-perceptual challenges when visualizing underground utilities.

MR experience is practically achievable using HMDs as it involves constructing the user's surroundings and is computationally heavy for Hand-Held Devices (HHDs). MR attained interest from several industries, including academia, with the arrival of Microsoft HoloLens in 2016, followed by its much improved second generation in 2019 (Figure 6).

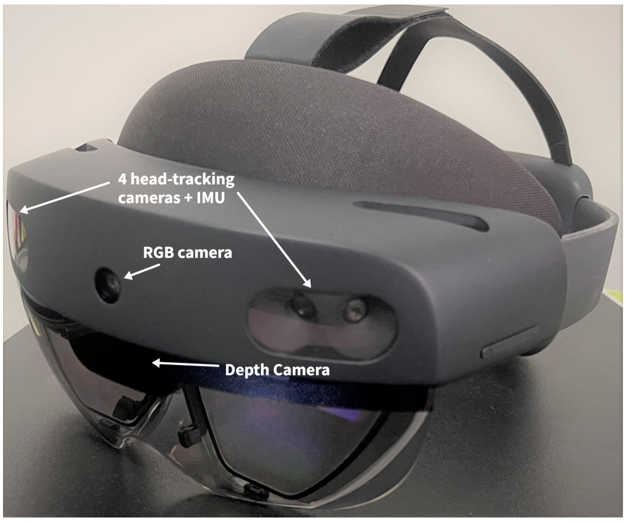

Figure 6. Microsoft HoloLens Gen 2

HoloLens is an Optical-See Through Head-Mounted Display (OST HMD) that uses optical lenses to reflect the virtual contents into the users' eyes while allowing them to see through it. HoloLens consists of several sensors, including four head-tracking cameras for real-time 3D virtual environment construction, Time of Flight (ToF) depth sensor, IMU, hand-tracking, and eye-tracking sensors. Moreover, It comprises a powerful Central Processing Unit (CPU), Holographic Processing Unit (HPU), and an in-built power supply for wireless MR (Microsoft, 2022a).

Moreover, it provides unique ways of interacting with virtual objects because it can track the user's both hands and eye movements. Because it has see-through displays, it provides a wide FOV of the real world, and the occlusion by the virtual content is managed to some extent compared to HHDs. Additionally, it provides a hands-free experience. Users can use their hands to perform other tasks, whereas using HHDs will always require the users to hold them

3. RELATED WORKS

Numerous studies developed visual cues to improve depth perception of subsurface utilities in AR. One of the most common approaches was applying transparency to the virtual utilities to make them look like they were underground. Ortega et al. (2019) explored different transparency methods called alpha-blending that vary the transparency level by seven distance-based (from the utilities to the viewer) functions: fixed, linear, smoothstep, logistic, tanh, arctan, and softsign. These functions can return the transparency level within the range of 0-1 for any given distance. Zollmann et al. (2014) also used alpha-blending with fixed 50% transparency of the virtual content along with other image analysis methods: edge-based and image-based ghosting. These methods take the real-world features like edges and objects to overlay virtual objects in an image frame of an AR scene to improve depth perception of the underground utilities. Another common method to visualize underground utilities at a particular place is the pit view. This method visualizes a virtual object similar to an excavated pit or trench, where only the utilities within the virtual pit will be visualized (Schall et al., 2010; Hansen et al., 2020). Many past studies have demonstrated that the virtual pit method can provide higher depth perception than other AR visualization methods (Eren and Balcisoy, 2017; Ortega et al., 2019).

Muthalif et al. (2022) reviewed the existing AR visualization methods for subsurface utilities and classified them into six groups.

X-Ray view: Subsurface utilities are visualized inside a virtual pit or trench.
Transparent view: Subsurface utilities are set with different transparency levels to make them look under the surface.
Topo view: Subsurface utilities are vertically projected to the surface plane. This method does not visualize utilities with depths.
Shadow view: Subsurface utilities are visualized with both depths and vertical projections (shadows).
Image rendering: Subsurface utilities are rendered as images where image analysis such as edge detection and overwriting virtual content can be performed in the image frames.
Cross-section view: Subsurface utilities are visualized on a plane intersecting the utilities.

The study further performed a visual comparison of these six types of visualization methods in terms of four criteria that are the quality of depth perceptions of the subsurface utilities, scene complexity with the amount of virtual content in the AR scene, occlusion of the physical world behind the virtual content, and the confusion due to parallax effect on the subsurface utilities when the user moves (Table 1). According to this review, all the existing AR visualization methods suffer from these perceptual aspects.

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

Table 1. Comparison of AR visualization methods for subsurface utilities (Muthalif et al., 2022).

Moreover, most of the existing visualization methods have been tested using Hand-Held Devices (HHD), such as smartphones or tablets (Muthalif et al., 2022), and they are limited in providing a visually convenient user experience. Notably, the Field of View (FOV) of the physical world is restricted to the size of the display and the camera's FOV. In addition, the displays may get the user's full attention, and it can be hazardous when the user moves to get a visualization from a different angle. It is almost comparable to playing games on a smartphone while walking, depending on the occlusion of the physical world by virtual content.

4. MR VISUALIZATION CONCEPTS

To overcome the perceptual challenges of AR when visualizing underground utilities, we propose six MR visualization methods and deployed them to Microsoft HoloLens. These visualization methods are developed to minimize at least one of the visual perceptual challenges: depth perception, scene complexity, parallax effect, and the occlusion of the real world by the virtual content. For a simple demonstration, the utilities visualized in these methods are assumed to be parallel to each other with constant depth values. These visualization methods are divided into two scenarios (three visualizations each): overall views and specific views.

4.1 Overall views (Scenario 1)

Visualization methods in overall views or Scenario one are more suitable for visualizing all the underground utilities during any construction's preliminary inspections or any other general reasons at the planning stage of construction. It provides an overall understanding of the existing underground utility network on the site. Overall views consist of three visualizations methods: "General view", "General + Range view", and "General + Elevator view".

4.1.1 General view: "General view" initially shows only the utilities' shadows. Shadows are the vertical projections of the utilities to the ground plane (Figure 7).

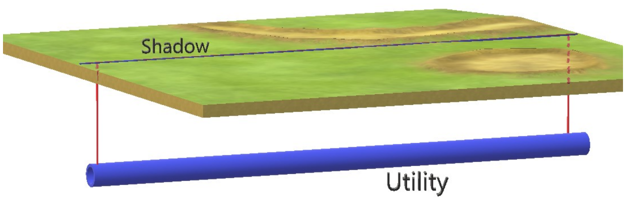

Figure 7. Shadow of a utility

One of the utilities can be selected using the HoloLens ray-cast, a virtual line extending from the user's pointing finger to facilitate the manipulation of virtual contents out of the hand's reach.

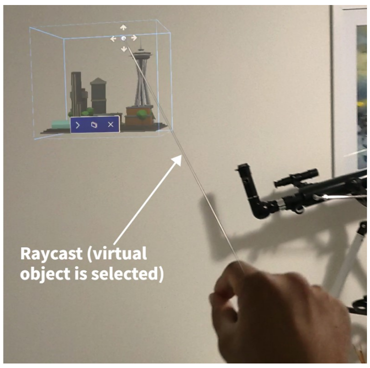

Figure 8. HoloLens Raycast

Once the ray-cast hits the shadow of the particular utility that needs to be visualized, the user simply has to use a pinching hand gesture (Figure 8) to select the shadow

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Once the selection has been made, the underground utility and the "connecting lines" between the utility and its shadow

(Figure 9) will be visualized. Connecting lines provide additional visual cues to improve the depth perception of the underground utility. In addition to that, the selected shadow will be highlighted. A window showing the selected utility's attributes will also be visualized. This window will be tracked to the user's head to travel with the user for convenience.

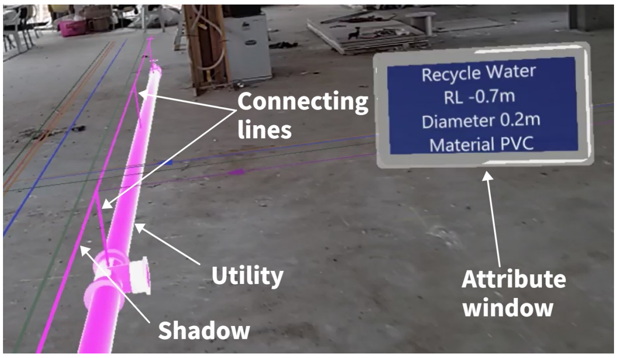


Figure 9. General View

4.1.2 General + Range View: The "General + Range View" method can reduce the scene complexity compared to the "General view" by initially visualizing only the specific range of the shadows of all the utilities. Similar to the "General view", this method allows selecting a specific utility for visualization with "connecting lines". Once a selection is made, the entire pipe section and its complete shadow will be visualized and highlighted (Figure 10). Moreover, the attribute window of the selected utility, which is tracked to the user's head and travels with the user, is also visualized
This method assumes that the scene complexity can be lessened by reducing the amount of virtual content in the AR scene at a time. This method makes the transparency of the shadows (unselected utilities) 100% at a specific range from the user's current location.

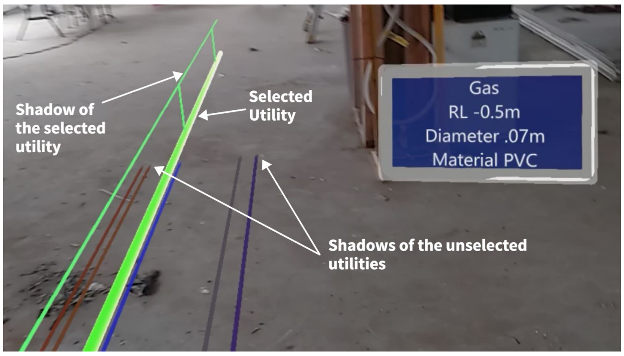
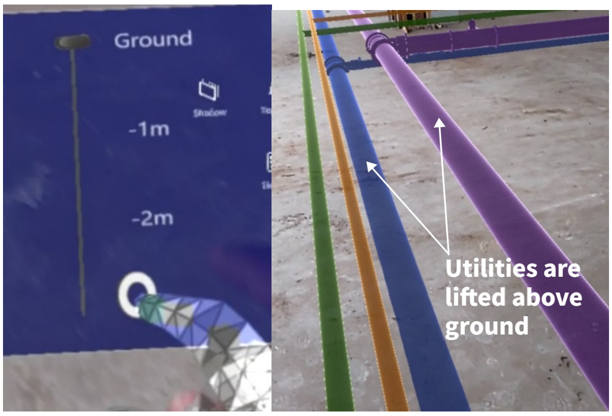


Figure 10. General + Range View

4.1.3 General + Elevator View: Since the HoloLens construct the real-time 3D map of the physical world, the "General + Elevator View" method utilizes it to occlude the underground utilities beneath it. Consequently, no underground utility is visualized in the initial stage as they are underground and occluded behind the virtual construction of the ground.

The slider provided in the holographic user menu lets the user change the heights of the whole underground utility network (Figure 11 (a)). i.e., it is possible to bring the underground utilities above ground (Figure 11 (a)). Since it is the user's choice to visualize the utilities within a specific range, the other utilities deeper than the user's preference can remain hidden under the ground.



(a) (b)

Figure 11. General + Elevator View (a) Slider (b) Utilities are lifted above ground

It is similar to sliding down underground to a certain depth like an elevator. Moreover, "General + Elevator View" enables the user to select one of the utilities brought above ground so that all the other utilities are disappeared to reduce the scene crowdedness. The selected utility is accompanied by the "connecting lines" to the ground for estimating the horizontal location (Figure 12). Moreover, the dynamic attribute window of the selected utility is also visualized.

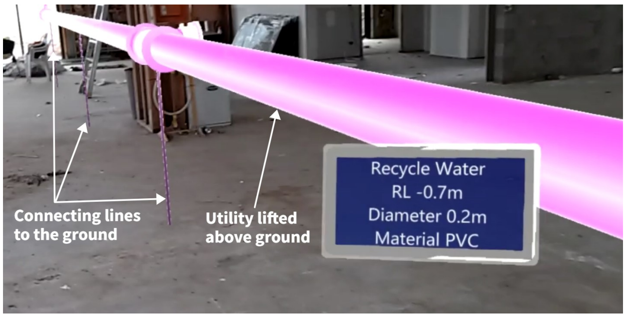


Figure 12. Selected utility in "General + Elevator View"

4.2 Specific Views (Scenario 2)

Visualization methods in specific views or scenario two are designed for situations where a detailed visualization of underground utilities at a specific location is required, for instance, excavation works. While it is important to minimize all the visual perceptual challenges at this location, this may not be achieved by a single visualization technique. Therefore, it is assumed that the most critical visualization aspect during exposing underground utilities is the improved depth perception. According to (Muthalif et al., 2022), the best-proven method for good quality depth perception is visualizing utilities only within a virtual pit (Figure 5). The three visualization methods in specific views attempt to reduce the other perceptual challenges; scene complexity, parallax effect, and occlusion of the real world while maintaining a similar level of depth perception.

4.2.1 X-Ray box View: "X-Ray Box View" visualizes a virtual pit and depth contours on the internal pit walls to quickly estimate the utility depth within the pit. Additionally, to estimate the horizontal location of the utilities, connecting lines from the utility to the top of the pit along the pit walls are also visualized. Shadows of all the utilities are shown outside the pit for the user to understand the distribution of the utility network at the site (Figure 13).

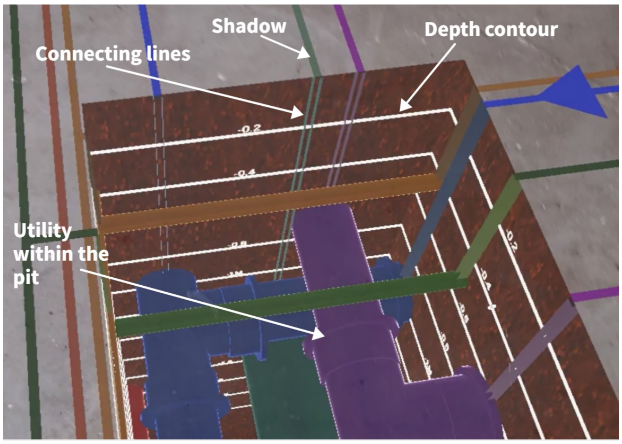


Figure 13. X-Ray Box View

The user can highlight a specific utility and get its properties by selecting its shadow (Figure 14). This method allows the user to move the pit to the user's preferred destination and manually change the pit's area according to the user's needs using the HoloLens ray-cast. Since the HoloLens can track both hands, two ray-casts can be used simultaneously to scale the virtual objects conveniently.

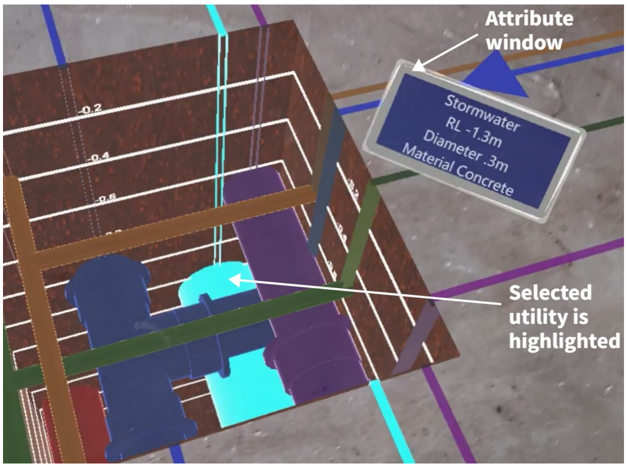


Figure 14. Selected utility in "X-Ray Box View"

4.2.2 X-Ray + Depthslider View: "X-Ray Box + Depthslider View" consists of the virtual pit with the contour lines and connecting lines as in "X-Ray box view". Since the virtual pit can occlude a large area of the physical world within the user's field of view at a time, this method attempts to increase the visibility of the physical world by automatically letting the pit move along the ground plane with the user by enabling it to be tracked with the user's head. This allows the user to identify and avoid potential hazards at the site while walking compared to having the pit static at a specific place. This method provides a button in the user menu to turn the pit tracking function off whenever needed (Figure 15).

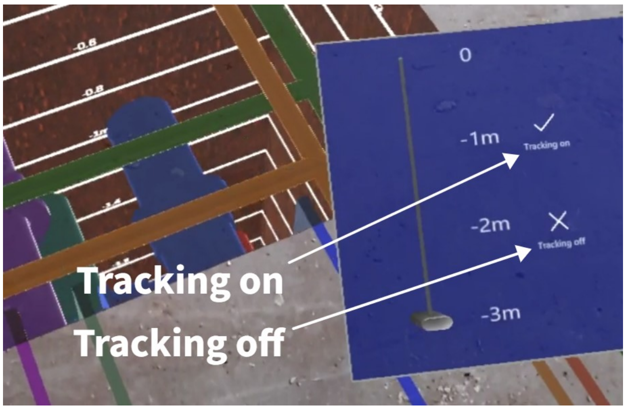


Figure 15. Tracking buttons to turn on-off in "X-Ray Box + Depthslider View"

Moreover, a slider in the menu lets the user change the pit's depth by sliding up/down the pit's base. i.e., it is possible to reduce the scene complexity within the pit by reducing its depth so that only the utilities within the required depth range are visualized. The other deeper utilities than the user-chosen depth are not visualized (Figure 16). This method allows selecting a specific utility to highlight, visualize its attribute window, and scale the pit size.

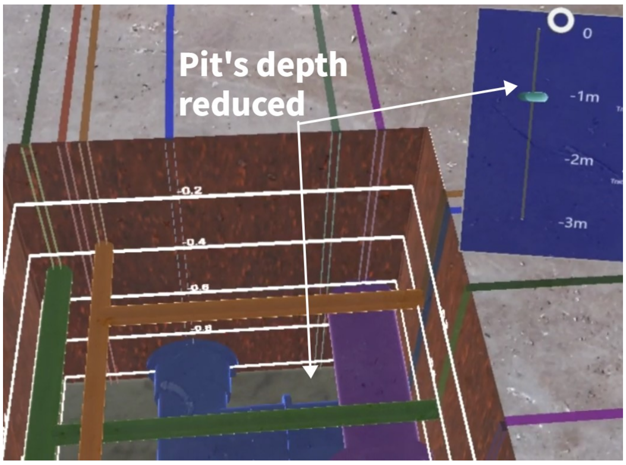


Figure 16. Slider in the "X-Ray Box + Depthslider View"

4.2.3 X-Ray Box + Clipping View: "X-Ray Box + Clipping View" is similar to the previous method of visualizing a virtual pit with depth contour lines, connecting lines between the shadows and the utilities, shadows of the utilities outside the pit, and the pit tracking function. The key difference is that the utilities within the pit are clipped along the pit's wall except for a small portion. The user can visualize the complete utility (inside and outside the pit) by selecting its shadow. This method shows the selected utility without letting the other utilities partially occlude it regardless of its depth value (Figure 17). In addition, once a utility is selected, its shadow and connecting lines are highlighted. Moreover, the head-tracked attribute window is also visualized.

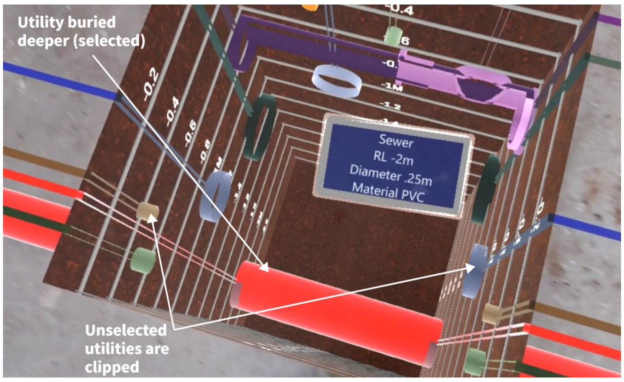


Figure 17. "X-Ray Box + Clipping View"

5. DISCUSSION

The unavailability of readily accessible and digital location information of the underground utilities to visualize in AR/MR techniques is the most critical dilemma that prevents the industry from leveraging AR/MR. Even though the initial intention was to use actual data from DBYD plans, extracting the accurate 3D position of all the utilities at a particular location was challenging due to missing information in the plans. Even if the 3D position of the utilities is available in the plans, they might still contain uncertainties that are almost impossible to discover without locating techniques or performing an excavation. i.e., MR visualization methods discussed in this article use synthetically generated utilities parallel to each other with a uniform depth for a simple demonstration focussing on different visualization approaches considering the visual perceptual challenges. Even though AR/MR visualization is currently challenged by data unavailability and inaccuracy, it is expected that more accurate data will be available in the near future as more research is performed on the concept of the Digital Twin (DT) of underground (Fernandes et al., 2022; Van Son et al., 2019).

The MR methods discussed in this article were tested in an indoor environment due to the limitation of HoloLens's localization in an open outdoor environment. HoloLens tracking works best when real-world features are in close vicinity since the depth camera used for SLAM has a limited range of approximately 3 meters. In addition, the efficiency of HoloLense positioning and orientation varies significantly depending on the lighting condition of the environment, the number of the features and their stability in the environment, and how far they are from the user (Microsoft, 2022b, c). Leveraging MR in an outdoor environment is still challenging due to the technological limitations of MR devices, even though they can provide a hands-free experience with a wide-angle view of the physical world.

Visualization methods in scenario one are assumed to provide an overall understanding of the utility network at the site. However, it is arguable that the "General +_Range view" does not offer the complete conception of all the utilities due to not displaying the shadows outside the specified range. This method could be effective for users who do not prefer a crowded scene with too much virtual content. Similarly, the "General + Elevator view" may solve the confusion due to the parallax effect on underground utilities by lifting them above ground. Nevertheless, it might eventually increase the real-world occlusion by the utility as the size of the utility will increase because it gets closer to the user. The "General + Elevator view" can be helpful when a close look at complicated areas is required, such as many utility fittings crowded in an area.

The" X-Ray box + Depthslider view" and "X-Ray box + Clipping view" can be more efficient compared to the "X-Ray box view" as they provide a simple user-preferred visualization within the virtual pit. The tracking function frees the user from manually moving the virtual pit using HoloLens ray-cast. Since HoloLens virtually builds the physical ground while the user walks, the virtual pit can be stuck to it even if the user needs to look around to be cautious at the site. In contrast, in the "X-Ray box view" the user may be more concentrated on moving the virtual pit manually and distracted from the actual world events.

6. CONCLUSION AND FUTURE WORK

This article discusses the existing challenges in AR visualization for underground utilities, including the unavailability of readily accessible and reliable digital information about underground utilities, the localization of AR devices in a GNSS-deprived environment, and the visual perceptual challenges of AR. The most critical visual perceptual challenges are the poor depth perception of underground utilities, scene complexity when an excessive number of virtual components are displayed, the occlusion of the physical environment when large virtual objects are visualized, and the parallax effect on the underground utilities. This paper propose six MR visualization methods namely "General view", "General + Range view", "General + Elevator view", "X-Ray box view", "X-Ray box + Depthslider view", and "X-Ray + box + Clipping" that have the potential to minimize the visual perceptual challenges in AR.

A user survey is being finalized by involving industry professionals to evaluate the effectiveness of these MR visualization methods. In the future, a comprehensive analysis will be conducted, discussing each method's performance compared to each other in scenarios one and two.

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