World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

Check for updates

Towards Accurate Underground Pipeline Visualization: Integrating Augmented Reality, Geospatial Databases, and Kilometer Markers

Wessam Mahmoud *

Technology and Innovation, Saudi Aramco, Dhahran, Saudi Arabia.

World Journal of Advanced Engineering Technology and Sciences, 2025, 17(03), 387-394

Publication history: Received 14 November 2025; revised on 23 December 2025; accepted on 25 December 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.3.1568

Abstract

Pipeline field operators traditionally rely on physical kilometer (KM) markers to locate and identify underground pipelines for inspection and maintenance activities. However, this approach is often inefficient due to marker degradation, limited size of marker plates, and the lack of precise spatial information about buried assets. Augmented Reality (AR) has emerged as a promising technology that enables the visualization of virtual objects onto real-world scenes using mobile devices equipped with Global Positioning System (GPS) sensors and cameras. This paper proposes an alternative approach that integrates AR technology with a geospatial database and existing KM markers to improve the visualization and localization of underground pipelines. The proposed method leverages KM markers as fiducial anchors within the AR environment, enhancing the positional accuracy of virtual pipeline overlays displayed on the live camera view. By using these physical reference points, the system mitigates inaccuracies associated with mobile GPS measurements and camera intrinsic parameters. Experimental results demonstrate that the proposed AR-based approach improves the accuracy of underground pipeline localization compared to conventional GIS-based visualization methods. The study concludes that the proposed method is an effective and practical solution for accurately identifying and locating hidden underground facilities and assets in field operations.

Keywords: Augmented Reality; Geographical Information Systems; Advanced Pipeline; Underground Pipelines; KM Markers

1. Introduction

1.1. Background and Motivation

Saudi Aramco has thousands of Kilometers of underground pipelines and utilities. Saudi Aramco pipeline operators use pipeline KM markers to get information about underground pipelines such as the pipeline name, type, and location [1]. This information is important when reporting emergencies and seeking assistance in determining the location of the buried pipelines. Relying only on physical KM markers has some limitations such as the small size of the marker plates restricting the amount of information that can be displayed. Also, some information becomes obscured or unreadable over time due to weather exposure [1].

During the last decade, many researchers and engineers have developed different solutions to overcome the limitations of the manual method for identifying and locating buried pipelines. These methods include integrating QR codes, utilizing Radio-Frequency Identification (RFID) technology, and employing magnetic locating technologies [2, 3]. Recently, Augmented Reality (AR) has been emerging as a new technology that uses AR software on mobile devices to superimpose buried or hidden objects on a real-world scene [4]. Also, the location-based services (LBS) have emerged

* Corresponding author: Wessam Mahmoud.

as an efficient technology that searches existing geospatial databases to identify and locate facilities by using mobile devices equipped with GPS [4, 5].

1.2. Problem Statement

Integration of AR technology and LBS can provides a promising solution for pipeline operators to retrieve the spatial information of the underground pipelines from an existing geographical information system (GIS) database and then use this information to superimpose a 3D model of the buried pipeline on a real-world scene [5]. However, this solution is not sufficiently reliable for practical use, as the accuracy of the superimposed pipeline is negatively affected by inaccuracies in the device's GPS and camera intrinsic parameters [6].

1.3. Purpose Statement

The proposed approach employs the pipeline KM marker plate as a fiducial marker (anchor) for the AR system of mobile devices to increase the accuracy of overlaying the buried pipeline on the captured scene. The main purpose of this research is to show how the integration of KM plates as fiducial markers with AR systems can improve the accuracy of identifying and locating underground pipelines by eliminate the inaccuracies of the device's GPS and camera intrinsic parameters.

1.4. Contributions

The contributions of this paper include:

- Innovation use of existing KM markers as fiducial anchors exploits already existing infrastructure without requiring additional hardware or marker installation.
- This approach presents a practical framework that integrates augmented reality with geospatial databases, enabling real-time visualization of underground pipelines in field environments using mobile devices.
- The paper addresses practical challenges faced by pipeline field operators, such as degraded or unreadable markers, by providing a digital, visually intuitive alternative.

2. Review of Literature

2.1. Traditional Marker Posts

Marking the position of buried utilities by using Kilometers (KM) marker posts is essential for safety, maintenance, and operational efficiency. Marker posts are warning signs that exist at frequent intervals along underground utilities rights-of-way (ROW) to indicate the presence of a pipeline [7]. Utility operators such as pipeline field personnel use KM marker posts to get primary information about specific segments of a buried pipeline including its name, type, size, and general location. This information is crucial during emergencies or initial inspection phases when a quick response assessment is required [7]. Despite the importance of the role of marker posts, relying solely on them for the precise identification and location of buried pipelines involves significant operational limitations [8]. These limitations include:

- Inaccurate location: Marker posts indicate the approximate position and direction of a pipeline route without providing sufficient information about its depth, alignment, and direction.
- Insufficient Information: The small size of a marker plate limits the amount of information that can be displayed [1].
- Degradation: Over time, some of the displayed information is prone to obscuration or loss due to exposure to weather or vandalism [1].
- Pipeline extension: Extending pipelines requires modifying information on marker posts to avoid adding negative kilometrage markers that would be confusing when reading location information of the extended segments [1].

To address the limitations of manual, visual location methods the industry require moving to more rigorous techniques for precise results. Many utility companies are using electronic marker systems (EMS) or radio-frequency identification (RFID) tags that can be buried alongside the pipeline or integrated into durable marker posts [9, 10]. These systems enable utility field operators to obtain accurate information about buried utilities such as transmission pipelines by using a special handheld receiver. The retrieved information may exist in the physical location of the pipeline, or it may exist in a geographical information system (GIS) database.

2.2. GIS and AR Integration

Many researchers highlighted that transition from physical markers to integrated geospatial systems is a critical advancement in utility management [11]. GIS offer a sophisticated alternative by providing a centralized, dynamic, and spatially-enabled database of underground assets [12]. GIS integrates multi-source data including ground penetrating radar (GPR) surveys, precise GPS coordinates, and existing geospatial records into a reliable, three-dimensional model of the underground network [13]. Unlike a static marker post, GIS provides comprehensive access to a wealth of associated data including operational status, maintenance history, installation date, material type, and pressure ratings. This comprehensive data access addresses the small size limitation of marker posts [14]. GIS offers highly accurate utility mapping, which provides a data-driven approach to risk assessment that physical signs can't provide [14].

Using AR for visualizing underground pipelines is an active area of academic research that focuses on improving safety, efficiency, and operational maintenance [15, 16]. These researches explore the integration of other technologies such as GIS, BIM, and GNSS to superimpose virtual 3D models into the real-world scene to enable field personnel to visualize buried assets [5, 11]. Many researchers have discussed employing mobile applications that use Augmented Reality (AR) to overlay precise 3D GIS data onto a field worker's live camera view of the ground [17]. Other researchers proposed different frameworks that combine GIS with Building Information Modeling (BIM) to offer comprehensive, real-time spatial information for managing earthwork operations [11, 18]. Li et al. [19] has explored a framework that fetches centralized geospatial databases and renders 3D models for underground utilities on mobile devices. Achieving accurate positioning of virtual models with the real world is a primary challenge for using AR to visualize underground pipelines. The limited accuracy of smartphones' GPS that ranged between 1-3 meters has a significant impact on the accuracy of the superimposed object [20]. The main challenges that prevent widespread deployment of using AR in this domain include data collection, modelling, hardware limitations, tracking, and alignment [19].

2.3. Markerless vs Marker-based AR

Researchers generally categorize AR technology into two primary types: markerless (location-based or natural feature tracking) and marker-based (fiducial) AR [21]. Despite the evolution of AR has shifted from relying on marker-based AR category to markerless AR [21], the marker-based systems still provide better accuracy, robustness, and low computational demands [22]. Marker-based AR has the highest priority in industrial context where precise overlay of information is crucial [23]. On the other hand, the markerless AR provides more freedom because it does not require fixed physical cues [24]. The markerless AR has two approaches: first, the natural feature tracking (NFT) that uses simultaneous localization and mapping (SLAM) algorithms to determine camera pose [25, 26]. The second approach is location-based AR which relies on device sensors such as GPS, camera, compass, and accelerometer to determine the user's location and orientation. Location-based AR is common with mobile navigation applications and assets visualization [27]. The choice between marker-based and markerless AR depends mainly on the use case [28]. Markerless AR is preferred for large-scale, and flexible environmental augmentation while marker-based AR is more suitable for high-precision tasks [28, 29].

3. Methodology

This section presents the methodology that was used to show how the accuracy of augmented underground pipelines of the AR system can be enhanced through the integration of geospatial data and by using KM marker plates as fiducial objects. The presented methodology includes data collection, developing AR system, and implementation. The main components of the framework for the presented approach includes: (1) a geospatial database that includes spatial data for pipeline segments and KM markers, (2) a mobile device equipped with GPS, camera, and AR system, (3) a pipeline segment, and (4) a KM marker plate. The main components are shown in Figure 1 as 104, 106, 102, and 114 consequently.

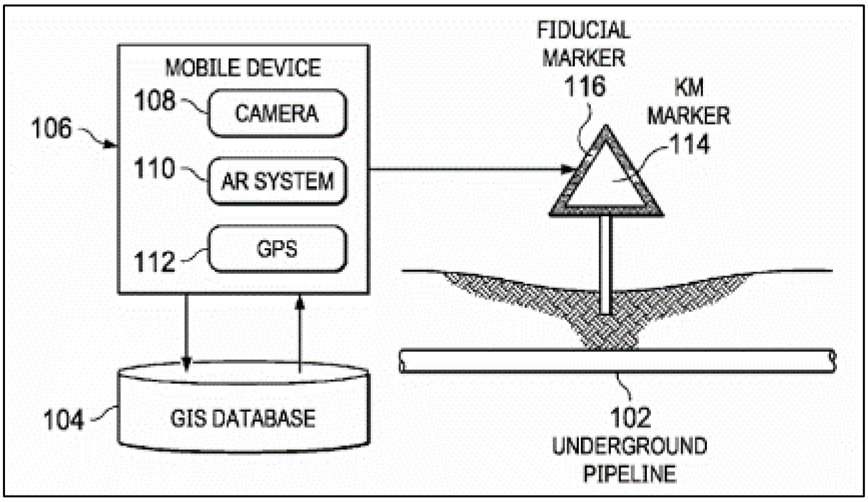

Figure 1 Main Components of the System

3.1. Data Collection

The collected data includes an underground pipeline segment, a KM marker, and 5 different locations for the mobile device observer. The coordinates and altitude of the start and end points of the selected pipeline segment were retrieved from the geospatial database. The coordinates of the nearest KM marker plate to the selected pipeline were retrieved from the geospatial database by using GIS software. The altitude of the KM marker was calculated based on Saudi Aramco standards for Oil & Gas KM markers. Five locations for the mobile device observer were selected where the mobile camera positions will ensure the presence of the selected pipeline segment and the km marker in the captured scene of the mobile device. All coordinates were retrieved in WGS84 (EPSG: 4326) coordinate system as shown in Table 1. The previous data collection steps are shown in Figure 2 as 201, 202, 203, and 204 consequently.

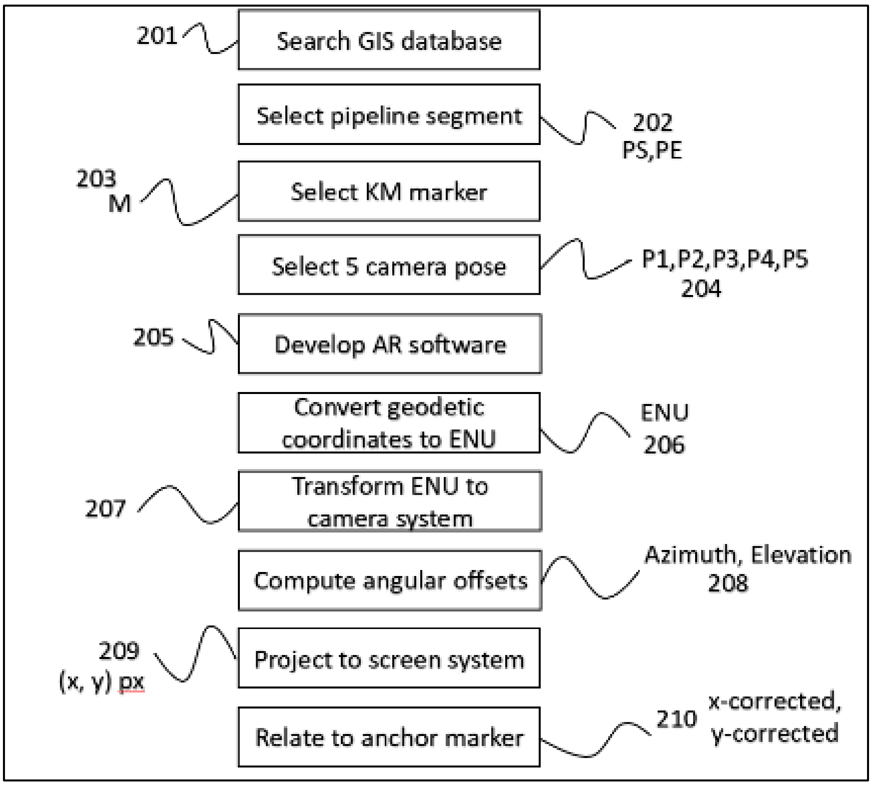

Figure 2 Data Collection Diagram

Table 1 WGS84 Coordinates for Pipeline Segment, Marker, and Camera Pose

Location ID	Description	Latitude (WGS84)	Longitude (WGS84)	Altitude (m)
PS	Start point of the pipeline segment	26.30814491	50.10925625	43.15
PE	End point of the pipeline segment	26.30808546	50.10926946	43.15
M	Marker location	26.30811645	50.10926258	45.35
P1	Camera Pose 1	26.30810074	50.10910625	45.75
P2	Camera Pose 2	26.30809005	50.10915781	45.75
P3	Camera Pose 3	26.30809164	50.10934419	45.75
P4	Camera Pose 4	26.30812052	50.10935825	45.75
P5	Camera Pose 5	26.30815052	50.1093387	45.75

3.2. AR System Development

The purpose of the developed system is to calculate the screen coordinates of the superimposed pipeline segment with and without using the selected KM marker as a fiducial marker. The change in the calculated position of the superimposed pipeline will indicate the enhancement in the accuracy after using KM marker as a fiducial marker. Unity AR foundation package version 6.4.0 was selected as the development framework. Apple ARKit XR Plug-in was used to enable deployment and implementation on iOS mobile devices.

3.3. Implementation

After deploying and testing the AR software on a mobile device, the input data that includes the start and end point of the selected pipeline segment, the KM marker location, and the camera position were applied. The input data was applied 5 times using a different camera position each time. The camera poses parameters; heading, pitch, and roll for each camera position were selected to ensure that the superimposed pipeline is shown with the KM marker at the same captured scene. The landscape mode was selected for the mobile device orientation to allow capturing a wider camera scene. Table 2 shows the camera parameters for the selected positions.

Table 2 Camera parameters for the selected positions

Pose ID	Heading	Pitch	Roll	Resolution	FOV	Sensor size	Near/far plane(m)
P1	85°	0°	0°	1920 × 1080	60°	6.4 mm × 3.6 mm	n = 0.1, f = 100
P2	70°	0°	0°	1920 × 1080	60°	6.4 mm × 3.6 mm	n = 0.1, f = 100
P3	300°	0°	0°	1920 × 1080	60°	6.4 mm × 3.6 mm	n = 0.1, f = 100
P4	270°	0°	0°	1920 × 1080	60°	6.4 mm × 3.6 mm	n = 0.1, f = 100
P5	240°	0°	0°	1920 × 1080	60°	6.4 mm × 3.6 mm	n = 0.1, f = 100

4. Results

4.1. Initial AR Projection Accuracy

Initial AR screen coordinates were computed by transforming WGS84 geodetic positions of the selected underground pipeline segment into a local Cartesian ENU reference frame centered at the camera position. The previous step was followed by orientation alignment using the smartphone's heading, pitch, and roll values. Next, the output coordinates were projected to normalized device coordinates (NDC). In the final step, the NDC coordinates were projected onto the 2D screen coordinate system of the smartphone under landscape orientation. The previous steps are shown in Figure 2 as 205, 206, 207, 208, and 209 consequently.

The results showed that the relative spatial relationship between superimposed pipeline and other objects was preserved. However, a noticeable pixel-level misalignment occurred between a projected virtual pipeline and its expected real-world position. The source of the attributed errors refers to smartphone magnetometer heading drift, approximate camera intrinsic parameters, and the GPS errors of the geodetic coordinates for camera pose and the target pipeline segment.

4.2. Anchor-Based Screen-Space Correction

To mitigate projection errors, geospatial a KM marker with known WGS84 coordinates and empirically observed screen position was introduced. The horizontal position and altitude of the KM marker was retrieved from the geospatial database. The screen position of the KM marker was used as an anchor to the superimposed pipeline segment. The anchor observations indicated that horizontal (x-axis) and vertical (y-axis) deviations between predicted and observed anchor position for each camera pose as shown in Table 3 as Δx, Δy. While these inaccuracies were moderate (few pixels from 0 to 11 pixels depending on distance), they are visually perceptible in close-range AR scenarios, particularly infrastructure visualization where alignment precision is critical.

4.3. Corrected AR Screen Coordinates

After applying anchor-based corrections, the target underground pipeline points were re-projected onto the screen. The corrected screen coordinates closely matched the visual alignment implied by the anchor KM marker. Compared to the uncorrected projection, the corrected output demonstrated consistent horizontal and vertical alignment and positioning accuracy and stable relative placement with respect to anchor KM marker. This confirms that using KM marker as anchor-based for underground pipeline significantly improves AR spatial accuracy, even when only minimal anchor data are available.

Table 3 Corrected Screen Coordinates

Point ID	Screen x	Screen y	Screen x Corrected	Screen y Corrected	Δx	Δy	Error
PS(P1)	601	742	607	743	6	1	6.08
PS(P2)	645	814	634	811	-11	-3	11.4
PS(P3)	1067	838	1068	842	1	4	4.12
PS(P4)	1369	840	1368	842	-1	2	2.24
PS(P5)	1665	918	1665	916	0	-2	2
PE(P6)	1261	734	1250	730	-11	-4	11.7
PE(P2)	1580	825	1584	820	4	-5	6.4
PE(P3)	-7	955	-5	956	2	1	2.24
PE(P4)	310	862	310	869	0	7	7
PE(P5)	513	855	505	854	-8	-1	8.06

5. Discussion

The results demonstrate that using AR with GIS spatial locations and smartphone orientation sensors and GPS is insufficient for precise underground pipeline visualization. However, the introduction of geo-referenced anchors such as KM marker plates enhances alignment quality.

Key findings include:

- Using KM markers as a geo-referenced anchor for AR visualization of underground pipelines is a practical solution that enhances the accuracy of superimposing buried objects on the screen of the device.
- A single anchor (KM marker) enables reliable translation correction but cannot address scale or angular distortion.
- The proposed method does not require using any artificial objects as geo-referenced anchors because the KM marker plates already existing and their spatial locations are available.
- The proposed method does not require an external tracking system or specialized hardware because it relies on mobile GIS workflow, which makes it suitable for field conditions.

6. Conclusion

This study presents a practical approach that uses existing KM markers to increase the accuracy of projecting geospatially referenced underground pipeline data into an augmented reality environment. The current approaches for using AR systems to visualize buried utilities rely on transforming geodetic coordinates of the buried utilities that can be retrieved from an existing geospatial database into a local reference frame and applying sensor-derived camera orientation. The initial results showed that the direct projection without using geo-referenced anchors preserves the relative spatial relationship, however, the absolute alignment accuracy requires corrections due to approximate camera intrinsic, sensor noise, and GPS accuracy. To address these limitations, an anchor-based correction was introduced by using the existing KM marker plates as geo-referenced anchors. The use of a geo-referenced anchor marker with known screen position enabled applying a translation correction for the projected coordinates, which resulted in increasing the accuracy of the superimposed objects.

Future work can focus on extending the solution to include multiple spatially distributed anchors to increase the accuracy of the projected coordinates. Despite that integrating real camera f calibration and using external, more accurate GPS will increase the accuracy of the projected coordinates, the practicality advantages of the solution will be impacted. Other researchers can focus on improving the reliability of AR-based geospatial visualization on mobile devices without sacrificing practicality.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Mahmoud W. (2021). Augmented reality visualization of underground pipelines using geospatial databases and km markers. U.S. Patent No. 16/840936

[2] Dziadak-Curtis, K., Kumar, B., & Sommerville, J. (2009). Model for the 3D location of buried assets based on RFID technology. Journal of Computing in Civil Engineering, 23(3), 148. https://doi.org/10.1061/(ASCE)0887-3801(2009)23:3(148)

[3] Esekhaigbe, E., Kazan, E. and Usmen, M. (2020). Integration of Digital Technologies into Underground Utility Asset Management. Open Journal of Civil Engineering, 10, 403-428. doi: 10.4236/ojce.2020.104030

[4] Talmaki, S. A., Dong, S., & Kamat, V. R. (2010). Geospatial databases and augmented reality visualization for improving safety in urban excavation operations. Construction Research Congress 2010. https://doi.org/10.1061/41109(373)10

[5] Fenais, A., Ariaratnam, S. T., Ayer, S. K., & Smilovsky, N. (2019). Integrating Geographic Information Systems and Augmented Reality for Mapping Underground Utilities. Infrastructures, 4(4), 60. https://doi.org/10.3390/infrastructures4040060

[6] El Barhoumi, N., Hajji, R., Bouali, Z., Ben Brahim, Y., & Kharroubi, A. (2022). Assessment of 3D Models Placement Methods in Augmented Reality. Applied Sciences, 12(20), 10620. https://doi.org/10.3390/app122010620

[7] American Petroleum Institute. (2018). Recommended Practice for Line Markers and Signage for Hazardous Liquid Pipelines and Facilities, Fifth Edition. American Petroleum Institute, Washington DC, U.S., 1-3.

[8] Adebiyi, J., Anspach, J. & Sturgill, R. (2025). Evaluating completeness and positional accuracy of traditional utility records compared to subsurface utility engineering: A comparative case study analysis. Transportation Research Interdisciplinary Perspectives, Volume 32, 101539. https://doi.org/10.1016/j.trip.2025.101539

[9] Uslu, B., Jung, Y. J., & Sinha, S. K. (2016). Underground Utility Locating Technologies for Condition Assessment and Renewal Engineering of Water Pipeline Infrastructure Systems. Journal of Pipeline Systems Engineering and Practice, 7(4)

[10] Dziadak, K., Sommerville, J., & Kumar, B. (2008). RFID-based 3D buried assets locating system. Journal of Information Technology in Construction, 13, 155-165.

[11] Sharafat, A., Khan, M. S., Latif, K., Tanoli, W. A., Park, W., & Seo, J. (2021). BIM-GIS-Based Integrated Framework for Underground Utility Management System for Earthwork Operations. Applied Sciences, 11(5721)

[12] sekhaigbe, E., Kazan, E., & Usmen, M. (2020). Integration of Digital Technologies into Underground Utility Asset Management. Open Journal of Civil Engineering, 10, 403–428

[13] Yan, J., Jaw, S. W., Soon, K. H., Wieser, A., & Schrotter, G. (2019). Towards an Underground Utilities 3D Data Model for Land Administration. Remote Sensing, 11(17), 1957. https://doi.org/10.3390/rs11171957

[14] Li, S., Cai, H., & Kamat, V. R. (2015). Uncertainty-aware geospatial system for mapping and visualizing underground utilities. Automation in Construction, 53, 105-119. https://doi.org/10.1016/j.autcon.2015.03.011

[15] Li, M., Feng, X., Han, Y., & Liu, X. (2023). Mobile augmented reality-based visualization framework for lifecycle O&M support of urban underground pipe networks. Tunnelling and Underground Space Technology, 136, 105069. https://doi.org/10.1016/j.tust.2023.105069

[16] Muthalif, M. Z., Shojaei, D., & Khoshelham, K. (2021). A review of AR visualization methods for subsurface utilities. Advanced Engineering Informatics. 18(4), 041008. doi:10.1115/1.4040460

[17] Huang, T., & Hong, J. (2024). Combination of Augmented Reality and 3D Geographic Information: A User perspective towards Feature-Based Augmented Reality. AGILE GIScience Series, 5, 1-9. doi:10.5194/agile-giss-5-29-2024

[18] Van Hoa, T., Nguyen, N. M., Van Phuc, L., & Phuong, N. C. (2025). Integration of BIM and GIS for managing infrastructure project: a case study of the 3/2 street in Kien Giang, Vietnam. Journal of Construction Informatics. Transportation Research Procedia, 85, 150-157. doi:10.1016/j.trpro.2025.03.145

[19] Li, R., Qu, K., Yan, Z., & Qian, J. (2018). Development of augmented reality pipeline visualiser (arpv) application for visualising underground water pipeline. IOP Conference Series: Earth and Environmental Science, 186(1), 012018. https://doi.org/10.5194/isprs-archives-XLII-4-W16-365-2019

[20] Zhou, Q. X., Chen, B. J., & Chen, H. (2022). An underground pipeline mapping method based on fusion of multi-source data. IEEE Transactions on Geoscience and Remote Sensing, 60, 1-11, 4511711. doi:10.1109/TGRS.2022.3200153

[21] Syed, T. A., Siddiqui, M. S., Abdullah, H. B., Jan, S., Namoun, A., Alzahrani, A., Nadeem, A., & Alkhodre, A. B. (2023). In-Depth Review of Augmented Reality: Tracking Technologies, Development Tools, AR Displays, Collaborative AR, and Security Concerns. Sensors, 23(1), 146. https://doi.org/10.3390/s23010146

[22] Saha, N., Gadow, V., & Harik, R. (2025). Emerging Technologies in Augmented Reality (AR) and Virtual Reality (VR) for Manufacturing Applications: A Comprehensive Review. Journal of Manufacturing and Materials Processing, 9(9), 297. https://doi.org/10.3390/jmmp9090297

[23] Kyaw, A. H., Xu, A., Zivkovic, S., Jahn, G., Newnham, C., & Van Den Berg, N. (2025). Accurate Augmented Reality Using Multiple Fiducial Markers for Glulam Fabrication. ArXiv Preprint, 2502.08566v2. https://doi.org/10.48550/arXiv.2502.08566

[24] Atkinson, M. (2024). The Learner's Experience Using Augmented Reality. Ph.D. thesis, Brigham Young University, UK, 10666.

[25] Sadeghi-Niaraki, A., & Choi, S. M. (2020). A Survey of Marker-Less Tracking and Registration Techniques for Health & Environmental Applications to Augmented Reality and Ubiquitous Geospatial Information Systems. Sensors (Basel, Switzerland), 20(10), 2997. https://doi.org/10.3390/s20102997

[26] Cao, J., Lam, K., Lee, L., Liu, X., Hui, P., & Su, X. (2021). Mobile Augmented Reality: User Interfaces, Frameworks, and Intelligence. arXiv:2106.08710. https://doi.org/10.48550/arXiv.2106.08710

[27] Schmidt, R., & Stumpe, B. (2025). Systematic review of mobile augmented reality applications in geography education. Review of Education, 13, e70042. https://doi.org/10.1002/rev3.70042

[28] Kim, J. Y., & Choi, J. K. (2025). Effects of AR on Cognitive Processes: An Experimental Study on Object Manipulation, Eye-Tracking, and Behavior Observation in Design Education. Sensors, 25(6), 1882. https://doi.org/10.3390/s25061882

[29] Sulistiyono, M., Hasyim, J. W., Bernadhed, B., Liantoni, F., & Sidauruk, A. (2024). Comparative study of marker-based and markerless tracking in augmented reality under variable environmental conditions. Journal of Soft Computing Exploration, 5(4), 413 - 422. https://doi.org/10.52465/joscex.v5i4.503