Automated Underground Mapping of Buried Utilities: A Review of Robotic Solutions and Sensor Technologies

Mohit Vohra*
4IR-Robotics
Dubai Electricity and Water Authority
Dubai, UAE
mohit.vohra@dewa.gov.ae

Ayush Gupta*
School of Mechanical and Materials Engineering
Indian Institute of Technology Mandi
Mandi, India
gupta.ayush2587@gmail.com

Mian Muhammad Umair
4IR-Robotics
Dubai Electricity and Water Authority
Dubai, UAE
mian.muhammad@dewa.gov.ae

Aditi Gupta
Centre for Artificial Intelligence and Robotics
Indian Institute Of Technology Mandi
Mandi, India
dd23015@students.iitmandi.ac.in

Amit Shukla
Centre for Artificial Intelligence and Robotics
Indian Institute Of Technology Mandi
Mandi, India
amitshukla@iitmandi.ac.in

Jayakumar Vandavasi Karunamurthy
4IR-Robotics
Dubai Electricity and Water Authority
Dubai, UAE
jayakumar.vandavasi@dewa.gov.ae

***Abstract*—In smart cities, utility infrastructures are strategically placed underground for convenience, safety, and aesthetics. The aging of these underground utilities emphasizes the importance of accurate mapping for inspections and maintenance. This survey paper extensively explores a range of sensors specifically designed to detect underground utilities. The manual operation of these sensors, requiring skilled personnel, is characterized by their slow pace, susceptibility to human errors, and safety concerns in potentially hazardous environments. To overcome these challenges, researchers are developing robots to achieve rapid and accurate underground mapping. The paper offers a comprehensive overview of existing methods, sensors, and robotic solutions, emphasizing their integration with diverse sensors to enable autonomous and efficient mapping of underground utilities. The shift toward automated solutions is deemed crucial to meet the growing survey demands in rapidly developing urban environments, ensuring safety, accuracy, and speed in modern underground utility mapping practices.**

***Index Terms*—Underground utility mapping, non-invasive cable detection, GPR, robotic system for power cable tracing, Autonomous subsurface mapping.**

I. Introduction

In this age of fast-paced urbanization and cutting-edge technology, the adoption of robotic solutions is on the rise. These innovative technologies are proving instrumental in diverse fields, including site inspection, construction automation [1], warehouse automation [2], autonomous goods transportation [3], and object manipulation [4], [5]. A key attribute of these robotic systems lies in their ability to perceive and adapt to their surroundings by fusing data from various sensors, such as cameras and LIDARs. It enables them to navigate and prevent collisions and empowers them to make intelligent decisions tailored to specific tasks.

While robotic solutions for surface-level environmental sensing are increasingly prevalent across industries, the significance of subsurface mapping cannot be overstated. Beyond the visible landscape, the need for understanding and mapping what lies beneath the surface has emerged as a critical component in addressing the challenges posed by modern urban development and infrastructure expansion [6]. Traditional excavation remains the most widely used method for subsurface investigation, but it is time-consuming and costly [7]. A recent study reveals that accidental utility strikes cost the United States approximately $30 billion in damages in 2020 alone [8]. As a result, non-invasive sensors and techniques have been adopted to analyze the subsurface.

One of the most frequently used non-invasive sensors for subsurface mapping is Ground Penetrating Radar (GPR), which emits electromagnetic waves into the ground and analyzes the reflected waves to gather information about subsurface utilities [9]. In addition to GPR, various other non-invasive sensors are available to enhance subsurface mapping capabilities. Magnetometer sensors, for example, offer a method for detecting the presence of underground utilities by measuring the change in magnetic field. This technology is particularly effective in identifying ferromagnetic materials or power cables (carrying currents). On the other hand, transmitter-receiver-based sensors operate by having a transmitter produce a signal through a utility, such as an underground power cable. The receiver then senses the signal and locates the power cables based on signal strength and direction. These diverse sensor technologies contribute to a comprehensive toolkit for subsurface mapping, offering

*Corresponding author

flexibility and adaptability in addressing specific mapping requirements.

Recognizing the limitations of manual sensor handling for surveying large areas, integrated robotic solutions have become indispensable for conducting fast and error-free surveys. Hence, our focus is on developing a fully autonomous robotic system integrated with multiple sensors and advanced technologies to automate subsurface mapping. As a primary step towards realizing this goal, this survey paper provides a concise overview of various sensors used for subsurface utility detection, along with insights into state-of-the-art robotic solutions based on these sensors for rapid and autonomous subsurface mapping. Furthermore, we outline some of the key challenges that must be addressed to develop a fully autonomous robotic system for underground utility mapping.

The remainder of this survey paper is structured as follows. Section II provides an overview of various sensors for underground utility detection. Section III delves into the state-of-the-art methods for subsurface mapping. In Section IV, we shed light on some of the crucial challenges that need to be resolved to develop robotic-based solutions. Finally, Section V presents the conclusion of this survey paper.

II. Type of Sensors

1) Radio Frequency Identification (RFID) Marker: RFID markers were a popular solution for locating power cables and transmission cables. These markers are buried with the cable and pipelines and activated when they get a specific frequency signal. [10] The underground utilities are tracked by localizing these RFIDs. The cost of these markers depends on the required step size (the distance between two consecutive markers) and the total length of the utility. Later, industries started burying an extra cable alongside the utility to locate and geotag the buried utility. Injects a signal into the cable using the transmitter, and a receiver catches this signal and positions the underground buried utility. However, such methods also depend on the humidity and conductivity of the soil. This cable localization works on electromagnetic induction.

2) Pipe and Cable Locator: [11] This method of locating buried pipes, cables, and sewers has become almost universal. Its main shortcoming is that it will not locate non-metallic lines like plastic pipes. This method works on Faraday's law of electromagnetic induction. [12] According to this, a changing magnetic field induces an electric current in the conductor. Hence, this sensor has two major parts: one is a transmitter that uses an AC signal of a specific frequency. This injected current will induce a magnetic field of a specific frequency around the cable and pipe. A locator, carried by an operator, moves over the surface to locate and detect the signal while navigating over the utility. This technique, where the operator has to inject the signal into the underground utility, is known as the active technique. The power cables that carry electricity also generate a magnetic field. Locating cables from their naturally induced magnetic field is known as passive localization. The only disadvantage of this technique is that it can work only with conducted material but cannot be implemented for non-metallic pipelines.

3) Acoustic Sensor: This method involves using sound-based technology to identify and locate buried utilities. [13] These methods rely on listening for acoustic signals produced by utilities or equipment underground. This method is based on the principle that various underground utilities, such as water pipes, gas lines, and air leaks, emit sound or vibration. These sounds and vibrations can be detected and analyzed to determine the presence, localization, and characteristics of the utilities. Some utilities emit sound naturally due to flowing fluids that produce vibration due to pressure changes. Similar high-voltage wires also emit sound because of energy discharge. In some cases, a sound source, such as a transmitter, is introduced to emit sound waves or vibrations. An acoustic utility locator equipped with a sensitive sensor or microphone that picks up sound is then converted into audio or displayed on a screen for the operator to interpret. This is a non-intrusive technique and is used for leak detection, identifying blockages, and tracing utilities. However, this sensor is limited to utilities that emit sound or vibration, and external noise and interference can make it challenging to distinguish.

4) Sonde-based underground utility locator: This method for underground utility localization is similar to an electromagnetic pipe locator sensor. Here, a sonde, which is a small self-contained transmitter that emits a specific radio frequency signal, is attached to a wire that is inserted into the pipelines that need to be located. A hand-held receiver or mobile unit is used to pick up the radio frequency signal transmitted by the sonde. These locators provide high-precision localization information, including depth, and can be used with a variety of utilities, including water and sewer pipes, in various soil and ground conditions. It is an intrusive technique for utility localization and affects by signal interference from nearby utilities.

5) Infrared Thermography: [14] IR thermography uses an imaging system to measure the electromagnetic energy, also known as thermal radiation, emitted from a surface in the IR radiation band. Here, IR data (images) are used to detect the presence of possibly buried objects and characterize them based on the estimation of their thermal as well as geometrical properties. This method cannot be used for the localization of deep-buried pipelines and cables. For humanitarian landmine detection, IR techniques can help reduce the number of false alarms. These techniques are still in the early stages of development, and their practical application is still limited due to the limitations of data processing techniques.

6) Continuous wave Doppler sensing technique: It involves the dispersion of radio waves into the ground continuously and monitoring for changes in frequency in the reflected waves brought on by moving things, including underground utilities [15]. The underlying premise is based on the Doppler effect, which explains a change in the frequency or wavelength of a wave in proportion to an observer moving relative to the source of the waves. The CW Doppler sensing method is used to map and identify buried utilities by recognizing the frequency

S No.	Sensor Technology	Working Principle	Remarks (Use cases or limitations)
1	Radio Frequency Identification (RFID) Marker	Electromagnetic Induction	Very accurate but need to be buried along with the target utilities.
2	Pipe and Cable Locator	Electromagnetic induction	Can not be used for non-metallic pipe and cables.
3	Acoustic Sensor	Acoustics signals to localize the utilities	Limited to the sound emitting utilities.
4	Sonde-based underground utility locator	Sonde act as a transmitter, is used to detect the utilities	Very accurate, but manual insertion of sonde is required.
5	Infrared Thermography	Localize the utility by estimating the emitted thermal energy	Could not detect deep buried and insulated objects.
6	Continuous wave Doppler sensing technique	Can accurately map the utilities by measuring the frequency change.	Requires significant prior information about the target utilities makes this technique less favourable.
7	Magnetometer	Detect the utilities by measuring the emitted magnetic field	External Interference makes this technique less favorable.
8	Ground Penetrating Radar	Works by emitting a pulse into the ground and recording the echoes that result from subsurface object	Non destructive method to localize the underground utilities. But its accuracy highly depends the soil conditions.
9	Sensor Fusion	Data integration from multiple sensors to detect various utilities and enhance accuracy	Researchers are addressing key challenges in data fusion, such as integrating diverse data types, ensuring accuracy, and ensuring sensor compatibility.
10	Robotic Based Solutions	Multiple sensors integrated on a robotic system	In addition to sensor fusion challenges, managing power consumption, ensuring real-time processing, and optimizing system efficiency are crucial aspects researchers are tackling for integrating multiple sensors on robots

TABLE I
OVERVIEW OF ALL SENSOR AND ROBOTIC TECHNOLOGY FOR UTILITY DETECTION

changes brought on by the facilities' movement. It can accurately detect the movement of underground utilities, providing real-time information about their presence and location, and can operate in various environmental conditions and terrain types. Signal interference from other objects or materials in the vicinity can affect the accuracy; reading Doppler sensing can be complex, requiring specialized knowledge. Implementing Doppler sensing technology for underground utility detection can involve significant costs, including equipment expenses and the need for skilled personnel.

7) Magnetometer: Metallic objects generate a magnetic field that disrupts the Earth's magnetic field. These sensors measure the intensity of the magnetic field at different points on the ground's surface. Anomalies or deviations from the expected magnetic field strength indicate the presence of subsurface metallic objects. [16] Flux gate magnetometers are common in utility detection due to their sensitivity and ability to detect subtle changes in the magnetic field. Magnetometer sensors offer a non-destructive and efficient means of locating buried utilities but are also affected by factors such as soil composition, interference from nearby metallic objects, and the depth of the buried utilities.

8) Ground Penetrating Radar: Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. It is a non-invasive method of surveying the sub-surface to investigate underground utilities such as concrete, asphalt, metals, pipes, cables, or masonry. This nondestructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum and detects the reflected signals from subsurface structures. GPR can have applications in a variety of media, including rock, soil, ice, fresh water, pavements, and structures. In the right conditions, practitioners can use GPR to detect subsurface objects, changes in material properties, and voids and cracks.

III. THE CURRENT TREND IN SUBSURFACE MAPPING

The mentioned sensors are presently operated manually, with an operator consistently monitoring the sensor output displayed on a screen. The operator relies on visualizing sensor data and personal experience to identify the presence of underground utilities. To ensure accuracy, the operator repeatedly maneuvers the sensor over the region of interest, confirming and precisely detecting buried utility presence through multiple assessments. However, this manual approach is vulnerable to human errors and is often time-consuming. In the following section, we provide a brief overview of the research efforts undertaken by industry professionals and researchers to address these challenges.

A. Enhancing Subsurface Utility Mapping

Ongoing research initiatives, driven by collaboration between academic researchers and industry professionals, aim to explore innovative methods and technologies for enhancing subsurface utility mapping accuracy. It involves integrating data from multiple sensors and developing technology capable of interpreting complex sensor data into a simple, human-readable form to mitigate human errors. Notable projects like "Mapping the Underworld" in the United Kingdom [17] and specific studies, such as the one conducted in Slovenia [18], focus on achieving precise localization, mapping, and documentation of buried utilities by integrating data from multiple sensors.

GPR is a commonly used sensor for subsurface detection. However, analyzing GPR B-Scan images, which depict reflected waves, requires significant effort to estimate the locations of subsurface targets. Recent studies [19]–[21] propose methods for automatic analysis of GPR B-Scan images to localize and estimate underground utilities. Efforts are also made to interpolate sampled locations for a smoother representation of underground utilities [22], [23].

To create 3D maps of underground utilities, it is crucial to transform local GPR locations into the global frame. Research [24] integrates GPR data with GPS data for this purpose. In GPS-deprived areas, another approach [25] fuses GPR data with encoder readings and Visual Simultaneous Localization and Mapping (vSLAM) readings. Expanding the sensor suite to include cameras, LIDAR, and magnetic sensors further enhances the system's performance. Combining GPR with cameras and LIDAR allows for both subsurface and surface inspection [26]. Magnetic sensors, such as magnetometers, are effective for detecting power cables, with research [27], [28] proposing methods for tracing and estimating the spatial information of buried power cables through magnetic field measurements.

B. Robotic-based subsurface utility mapping

Manual surveys often face challenges due to their slow pace, and the manual handling of sensors limits the frequency of surveys. To overcome these constraints and enhance survey efficiency, researchers are actively working on integrating sensors, including multiple sensors, with advanced solutions into robotic systems. The robots with navigation, localization, and inspection sensors hold significant potential for improving these operations. Such robots can execute tasks in challenging environments and adverse conditions, demonstrating heightened endurance without being affected by external factors. Additionally, the substantial data acquired by the robotic system can be efficiently managed, processed, and analyzed in real time using AI-ML algorithms. This section will explore robots specially designed for underground utility mapping, inspection, and geo-positioning.

1) Unmanned Ground Vehicle (UAV): UGVs are one of the most popular wheeled robots due to their wide range of variety, high payload capacity, and endurance. The integration of sensors such as LIDAR, cameras, stereo cameras, and GPS makes them intelligent. These robots can make decisions and navigate [38] in a complex environment with obstacles. For underground utility mapping in 2012, [29] NASA integrated a GPR sensor with the all-wheel steering robot and tested it in the Haughton Crater on Devon Island for underground utility mapping. A similar robotic platform with an omnidirectional robot with GPR was presented in [30]. Later on, [31] used a robot to tow the GPR trolley for underground utility mapping and data collection. They have also developed a machine-learning model to detect the different kinds of buried utilities in the B-scan images. Robots such as AUSMOS [32] by SENSYS, RUMI [33] by Blue Halo, and GuideLine Sensor manufacturers have developed wheeled robots integrated with the GPR for autonomous subsurface mapping. All of these robotic platforms equipped with autonomous navigation and obstacle avoidance capabilities, are used to carry the GPR sensor. These robots are either operated by a human operator from a distance or will work on way-point and hot-point navigation. These robots are used to collect the GPR data and process the data on the ground vehicles for data analysis. Later in [34], an electromagnetic sensor, also known as a pipe and cable locator, was used for accurate tracking of underground pipelines, and a magnetic tomography sensor was used for anomaly detection on the oil and gas pipeline and accurate geo-positioning of the utility. This robotic platform can also operate in GPS-denied environments, such as mines and tunnels.

2) Unmanned Aerial vehicles (UAVs): In the last few years, UAVs have become popular among industrialists and researchers. Due to their agile flight and sufficient endurance, drones are also being used for high-rise industrial utility inspection, health monitoring, visual surveillance, forest area mapping, surveillance and security, traffic management, precision agriculture, emergency response, delivery services, and 3D mapping and modeling of infrastructure. These aerial vehicles generally operate at a higher altitude and collect the required data quickly. Due to their agile flight mechanism, sufficient flight time, and payload capacity, researchers are working on the low-altitude flight of the drone for the inspection of close-to-ground or buried utility infrastructure and tracking. In [35], a hexacopter drone is equipped with a radar antenna and receiver to perform subsurface mapping, and [36] has employed a magnetometer sensor to collect data on magnetic fields due to buried metallic objects. These drones are used as carrying vehicles to collect the data. The drone loaded with the sensor will move along a predefined path and map the collected data according to the flight path for visualization. On the other hand, a locator and inspection sensors with real-time data streaming can enhance the capability of the vehicles to track the object accurately. It will also improve the collected data quality and will be able to perform the task in a short time.

IV. Observations

Ground Penetrating Radar (GPR) offers significant advantages in underground utility mapping due to its non-destructive nature, which minimizes disruption and cost compared to traditional excavation methods. Researchers are actively engaged in developing methods for the automated analysis of GPR data to facilitate the creation of 3D subsurface maps for providing the valuable spatial information for utility localization. However, these maps are typically in a local frame, necessitating integration with Real-Time Kinematic Global Positioning System (RTK-GPS) for accurate georeferencing in a global frame. By combining GPR with RTK-GPS, precise georeferencing of the mapped utilities is achieved, enabling seamless integration with existing geographical information systems (GIS) and facilitating accurate utility management and planning.

Despite its strengths in utility localization, GPR has limitations in utility classification. While it can identify the presence and location of buried objects, it cannot differentiate between different types of utilities. This is because the current methodologies primarily focus on extracting the apex

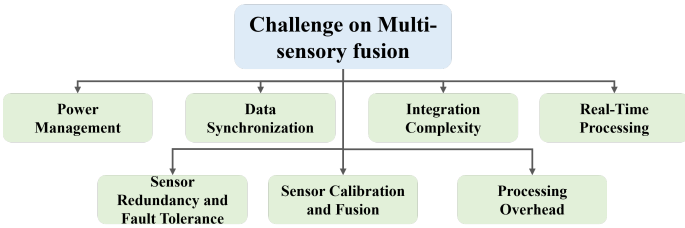

Fig. 1. Challenges with Multi sensor Fusion

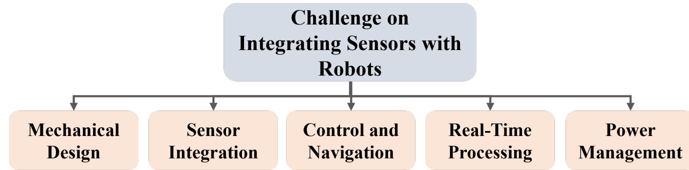

Fig. 2. Challenges on integrating Sensors with the Robot

of hyperbolic signatures, providing only the location of the utility. To achieve utility classification, a more sophisticated approach is required, involving advanced image processing and computer vision modules that aims at analyzing the multiple properties of hyperbolas, which can be useful to classify the underground utility [37]. Integration with other sensors presents an alternative solution for utility classification. For example, integrating GPR with a magnetometer enhances utility classification by identifying ferromagnetic materials or magnetic flux-emitting objects within the 3D maps generated by GPR. This multi-sensor approach provides a more comprehensive understanding of subsurface conditions, aiding in utility classification. However, the fusion of multiple sensors presents several technical challenges shown in Fig. 1.

Integrating multiple sensors into a single platform for mobile or remote sensing applications demands careful power management to extend operational duration and minimize battery replacements. Challenges arise in synchronizing data acquisition due to varying frequencies and sampling rates across different sensors, necessitating accurate temporal alignment for meaningful data fusion. Real-time processing of diverse sensor streams, especially in high-resolution applications like GPR, presents computational hurdles that efficient fusion algorithms must overcome to minimize latency. Calibration techniques and fusion algorithms must address sensor-specific biases for reliable results, particularly when integrating sensors from different manufacturers or employing diverse technologies. Standardizing communication protocols and data formats can mitigate compatibility issues while incorporating redundancy and fault-tolerant mechanisms ensures system reliability in the face of sensor failures. Optimizing data fusion algorithms and leveraging distributed processing architectures can alleviate computational strain, particularly in resource-constrained environments.

Moreover, to expedite the utility inspection process and enhance efficiency, there is a growing trend towards integrating these sensors into robotic systems. Robotic solutions offer improved mobility and accessibility, allowing for more efficient data collection in challenging environments. By deploying robotic platforms equipped with a suite of sensors, operators can remotely navigate and explore underground areas, reducing the need for manual labor and minimizing human exposure to hazardous conditions.

However, the integration of multiple sensors into robotic systems introduces a host of technical challenges (Shown in Fig. 2) that must be addressed. For example, designing robotic platforms capable of accommodating multiple sensors while maintaining stability and maneuverability is a challenging task in terms of mechanical design. Proper sensor placement and orientation are crucial for optimizing data collection, necessitating careful consideration of mechanical design constraints. Integrating diverse sensors into a unified platform requires robust interfaces and communication protocols to enable seamless data exchange and coordination, adding complexity to the integration process. Real-time processing of sensor data demands efficient computational resources and algorithms to minimize latency and resource consumption while ensuring accuracy and reliability. Efficient power management strategies are essential to extend operational duration and reduce reliance on external power sources, particularly in remote or resource-constrained environments where balancing power consumption with performance requirements is critical. Developing control algorithms for autonomous navigation while coordinating sensor operations presents complex engineering challenges, requiring robust sensing, perception, and decision-making capabilities to ensure smooth and efficient navigation while avoiding obstacles and hazards.

Addressing these technical challenges requires a multi-disciplinary approach, encompassing robotics, sensor technology, control systems engineering, and data science. By overcoming these obstacles, robotic systems equipped with integrated sensor suites can revolutionize underground utility mapping and inspection, enabling safer, more efficient, and more comprehensive infrastructure management.

V. Conclusion

This paper highlights the evolving landscape of subsurface utility mapping, driven by the critical need for accurate localization and assessment of underground infrastructure. The challenges inherent in manual operations underscore the importance of adopting automated solutions. The exploration of diverse sensors, including ground-penetrating radar (GPR), electromagnetic sensors, acoustic sensors, and infrared thermography, showcases the versatility of subsurface mapping. The current shift towards robotic-based solutions, armed with multiple sensors and advanced machine learning, is crucial to meeting the growing demands of subsurface mapping. Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) demonstrate the trend towards autonomous systems capable of navigating complex environments for efficient surveys. The paper acknowledges challenges in integrating multiple sensor types into a robotic system. In summary, the integration of robots with diverse sensors offers a promising path for subsurface utility mapping, ensuring safety, accuracy, and efficiency amid urbanization and infrastructure expansion. Ongoing collaboration between academia and industry is essential for innovation, overcoming current challenges, and refining automated solutions for the future of subsurface mapping.

REFERENCES

[1] Vohra, M., Kumar, A., Prakash, R. and Behera, L., 2021, October. End-To-End Real-Time Visual Perception Framework for Construction Automation. In 2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC) (pp. 3485-3490). IEEE.

[2] Vohra, M., Prakash, R. and Behera, L., 2019, October. Real-time grasp pose estimation for novel objects in densely cluttered environments. In 2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN) (pp. 1-6). IEEE.

[3] Vohra, M. and Behera, L., 2022, October. Visually Guided UGV for Autonomous Mobile Manipulation in Dynamic and Unstructured GPS-Denied Environments. In Proceedings of International Conference on Computational Intelligence: ICCI 2021 (pp. 1-13). Singapore: Springer Nature Singapore.

[4] Vohra, M., Prakash, R. and Behera, L., 2021. Edge and corner detection in unorganized point clouds for robotic pick and place applications. arXiv preprint arXiv:2104.09099.

[5] Vohra, M. and Behera, L., 2022, July. Robot learning by Single Shot Imitation for Manipulation Tasks. In 2022 International Joint Conference on Neural Networks (IJCNN) (pp. 01-07). IEEE.

[6] Jaw, S.W., Van Son, R., Soon, V.K.H., Schrotter, G., Kiah, R.L.W., Ni, S.T.S. and Yan, J., 2018, June. The need for a reliable map of utility networks for planning underground spaces. In 2018 17th International Conference on Ground Penetrating Radar (GPR) (pp. 1-6). IEEE.

[7] Merkle, D., Frey, C. and Reiterer, A., 2021. Fusion of ground penetrating radar and laser scanning for infrastructure mapping. Journal of Applied Geodesy, 15(1), pp.31-45.

[8] Oguntoye, K.S., Laflamme, S., Sturgill, R. and Eisenmann, D.J., 2023. Review of Artificial Intelligence Applications for Virtual Sensing of Underground Utilities. Sensors, 23(9), p.4367.

[9] Baker, G.S., Jordan, T.E. and Pardy, J., 2007. An introduction to ground penetrating radar (GPR).

[10] Sen P, Sen D. RFID (Radio Frequency Identification) Applications in Utilities for Underground and Other Fixed Asset Detection and Management. InTechnology Conference 2005 2005 Jan 1 (pp. 988-997). Water Environment Federation.

[11] Darilek GT, Cooper Jr EH, inventors; Texas Gas Development Corp, CORROSION LOGGING SERVICE INTERNATIONAL, assignee. Detecting buried pipeline depth and location with electromagnetic triangulation. United States patent US 4,542,344. 1985 Sep 17.

[12] https://www.radiodetection.com/en/cable-and-pipe-location-theory

[13] Liu Y, Habibi D, Chai D, Wang X, Chen H, Gao Y, Li S. A comprehensive review of acoustic methods for locating underground pipelines. Applied sciences. 2020 Feb 4;10(3):1031.

[14] Azmat Z, Turner DJ. Infrared thermography and its role in rural utility environment. InRural Electric Power Conference, 2005 2005 May 8 (pp. B2-1). IEEE.

[15] Tauqeer T, Islam M, Aziz AK. Short range continuous wave radar for target detection in various mediums. Microwave and Optical Technology Letters. 2014 Nov;56(11):2484-9.

[16] Vo CK, Staples SG, Cowell DM, Varcoe BT, Freear S. Determining the depth and location of buried pipeline by magnetometer survey. Journal of Pipeline Systems Engineering and Practice. 2020 May 1;11(2):04020001.

[17] Rogers, C.D., 2011. Site Assessment of Multiple-Sensor Approaches for Buried Utility Detection.

[18] Šarlah, N., Podobnikar, T., Ambrožič, T. and Mušič, B., 2020. Application of Kinematic GPR-TPS model with high 3D georeference accuracy for underground utility infrastructure mapping: A case study from urban sites in Celje, Slovenia. Remote Sensing, 12(8), p.1228.

[19] Zhou, X., Chen, H. and Li, J., 2018. An automatic GPR B-scan image interpreting model. IEEE Transactions on Geoscience and Remote Sensing, 56(6), pp.3398-3412.

[20] Zhou, X., Chen, H. and Hao, T., 2019. Efficient detection of buried plastic pipes by combining GPR and electric field methods. IEEE Transactions on Geoscience and Remote Sensing, 57(6), pp.3967-3979.

[21] Liu, H., Yue, Y., Liu, C., Spencer Jr, B.F. and Cui, J., 2023. Automatic recognition and localization of underground pipelines in GPR B-scans using a deep learning model. Tunnelling and Underground Space Technology, 134, p.104861.

[22] Jiang, G., Zhou, X., Li, J. and Chen, H., 2019. A cable-mapping algorithm based on ground-penetrating radar. IEEE Geoscience and Remote Sensing Letters, 16(10), pp.1630-1634.

[23] Zhou, X., Chen, Q., Lyu, S. and Chen, H., 2022. Mapping the buried cable by ground penetrating radar and gaussian-process regression. IEEE Transactions on Geoscience and Remote Sensing, 60, pp.1-12.

[24] Li, S., Cai, H., Abraham, D.M. and Mao, P., 2016. Estimating features of underground utilities: Hybrid GPR/GPS approach. Journal of Computing in Civil Engineering, 30(1), p.04014108.

[25] Li, H., Chou, C., Fan, L., Li, B., Wang, D. and Song, D., 2019. Toward automatic subsurface pipeline mapping by fusing a ground-penetrating radar and a camera. IEEE Transactions on Automation Science and Engineering, 17(2), pp.722-734.

[26] Chou, C., Kingery, A., Wang, D., Li, H. and Song, D., 2018, May. Encoder-camera-ground penetrating radar tri-sensor mapping for surface and subsurface transportation infrastructure inspection. In 2018 IEEE International Conference on Robotics and Automation (ICRA) (pp. 1452-1457). IEEE.

[27] Jahromy, M.F., Ostovarzadeh, M.H. and Davarani, R.Z., 2017, December. Detection of underground power cable route using magnetic field. In 2017 IEEE 4th International Conference on Knowledge-Based Engineering and Innovation (KBEI) (pp. 0533-0538). IEEE.

[28] Sun, X., Lee, W.K., Hou, Y. and Pong, P.W., 2014. Underground power cable detection and inspection technology based on magnetic field sensing at ground surface level. IEEE transactions on magnetics, 50(7), pp.1-5.

[29] Horz F, Heggy E, Fong T, Kring D, Deans M, Anglade A, Mahiouz K, Bualat M, Lee P, Bluethmann W. Potential of probing the lunar regolith using rover-mounted ground penetrating radar: Moses Lake dune field analog study. In40th Lunar and Planetary Science Conference 2009 Mar 23 (No. JSC-18026).

[30] Feng J, Yang L, Hoxha E, Jiang B, Xiao J. Robotic inspection of underground Utilities for Construction Survey Using a ground penetrating radar. Journal of Computing in Civil Engineering. 2023 Jan 1;37(1):04022049.

[31] Kouros G, Kotavelis I, Skartados E, Giakoumis D, Tzovaras D, Simi A, Manacorda G. 3d underground mapping with a mobile robot and a gpr antenna. In2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2018 Oct 1 (pp. 3218-3224). IEEE.

[32] https://ulctechnologies.com/robotic-system-for-underground-utility-damage-prevention/

[33] https://www.volpe.dot.gov/sbir-success-stories/robotic-utility-mapper

[34] Sudevan V, Shukla A, Karki H. Autonomous tracking and tagging of buried pipelines based on Pipe-Locator data. In Proceedings of the International Conference on Diagnostics of Structures and Components using Metal Magnetic Memory Method 2019 Jun (pp. 1-8). Prague, Czech Republic: Ether NDE.

[35] Dill S, Schreiber E, Engel M, Heinzel A, Peichl M. A drone carried multichannel Synthetic Aperture Radar for advanced buried object detection. In2019 IEEE Radar Conference (RadarConf) 2019 Apr 22 (pp. 1-6). IEEE.

[36] Mu Y, Zhang X, Xie W, Zheng Y. Automatic detection of near-surface targets for unmanned aerial vehicle (UAV) magnetic survey. Remote Sensing. 2020 Feb 1;12(3):452.

[37] Pasolli, E., Melgani, F. and Donelli, M., 2009. Automatic analysis of GPR images: A pattern-recognition approach. IEEE Transactions on Geoscience and Remote Sensing, 47(7), pp.2206-2217.

[38] An, Zhen, et al. "Development of mobile robot SLAM based on ROS." International Journal of Mechanical Engineering and Robotics Research 5.1 (2016): 47-51.