MAPPING UNDERGROUND UTILITIES WITH COMPLEX SPATIAL CONFIGURATION USING GROUND PENETRATING RADAR

by

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ABSTRACT

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Records of the locations, measures, and properties of vast underground utility networks are incomplete, inaccurate, and many times unavailable. This lack of information of underground pipes and cables is a primary reason for over six million of utility interruptions every year that cause injuries, fatalities, property damages, and environmental pollutions, amounting to billions of dollars in loss. It also poses a critical challenge to maintaining and upgrading underground infrastructure. Therefore, methods must be devised to accurately map and label underground utilities.

Ground Penetrating Radar (GPR) has shown its promise in detecting and locating buried objects. It sends electromagnetic (EM) pulses via a transmit antenna to the underground and collects part of the reflected EM wave via the receiver antenna. The control unit measures the EM wave properties, which will be altered when it encounters changes in subsurface layers and buried anomalies. This process produces a two-dimensional data matrix with columns containing the reflected amplitudes at certain times for each measurement position along each trace. Since GPR shows the patterns related to the location of underground utilities, an interpretation process is needed to restore spatial information from patterns. Various signal-processing or pattern recognition algorithms have been created to automatically or semi-automatically interpret the reflected signals or patterns from GPR radargrams. However, it is still constraint to apply current approaches to the utility-congested urban environment because of the complex spatial configurations of underground utilities and its interfered signal reflection in the resulting GPR scan, which are very difficult to interpret. Two main reasons are: (1) the oblique pipe orientation

produces irregular GPR patterns, and (2) adjacent pipes generate coupled or occluded GPR patterns.

There is a research need to design a novel approach to automate the process of mapping underground utilities with complex spatial configurations from multiple transformed signatures using GPR system. In this study, I identify four knowledge gaps in the perspective of the system development. The first knowledge gap is the lack of a practical algorithm to automatically extract hyperbolas and segment them into legs, and peaks, which is the essential step for analyzing the patterns of GPR signatures from the scan images. For example, the peak of the hyperbola indicates the closest point to the GPR survey trajectory. The intersecting point between the right trailing leg and the left rising leg indicates there may exist two pipelines close to each other. By analyzing the decomposed segments of the hyperbola shapes, the possible spatial configuration of the buried pipes can be estimated, providing an "educated" guess for estimating the spatial configuration, size, and location of underground utilities from GPR scan images in congested urban areas.

The second knowledge gap is that the causality between the complex spatial configuration of underground utilities and resulting patterns in GPR scan images has not been thoroughly investigated and established, which makes the inverse estimation from decomposed transformed GPR signatures to complex spatial configurations of buried utilities impossible. Therefore, in order to interpret the GPR data and map the underground utilities in an automatic manner, it's essential to investigate the rationale that: (1) how the spatial configurations affect the transformation and occlusion of generating GPR signatures? and (2) how can we inversely estimate the spatial configurations from the transformed, occluded GPR signatures?

The third knowledge gap is the lack of an intelligent GPR survey trajectory planning approach, in which GPR data are processed and interpreted in real-time and the trajectory is automatically adjusted correspondingly. The rationale is as follows. Ideally, the perpendicular-to-pipe scanning yields highest detectability, and along-pipe scanning yields highest planimetric and depth accuracy. However, it is quite challenging for field operators to maintain the ideal angels, i.e., "perpendicular-to-pipe" and "along-pipe", in the survey grid while not knowing the exact orientation of the pipes. The deviation between pipeline's orientation and GPR moving trajectory will pose ill-shaped or incomplete signatures in GPR scan images, which brings great challenges in the following signal/images processing and utilities attribute estimation from the collected field data. If we can detect the ill-shaped or incomplete signature early while they are still under developing and adjust the trajectory correspondingly and continuously, we could guarantee a good angle and a reasonable accuracy.

The fourth knowledge gap is the lack of an illusion-free visualization platform for information sharing and communication of buried infrastructure. Current AR platform is limited to visualize multiform information of buried utilities retrieved from GPR data, i.e., (1) the unstable dynamic tracking of pipes in markerless environment causes visual fatigue; (2) the missing depth cues (e.g., relative size, occlusion, shadows) affect the quality of visual integration of the physical objects and virtual pipes underneath; and (3) the indirect way to differentiate materials of pipes in either color-labeled or rendering mode. With these limitations, the data sharing and communication efficiency are still underestimated in the current visualization platform.

Four solutions are proposed in this research to fill the aforementioned four knowledge gaps. First, I develop an effective algorithm to automate the detection and decomposition of GPR signatures into feature components in two-dimensional scans, i.e., hyperbola apex, rising legs, trailing legs and junction points of intersecting hyperbolas, which forms the base for estimating the spatial configuration, size, and location of underground pipes. By commencing at a strip of pixels from the top of the edge of the scan image, the algorithm mimics the motion of a "raindrop" falling or flowing as it touches the edge pixels of the image. The movement of the "raindrop" completes the decomposition of the GPR signature when it touches the "ground", i.e., the bottom of the edge image. Chapter Two of this dissertation is devoted to solving this problem.

In Chapter Three of this dissertation, the causality is investigated extracted from the synthetic GPR data generated from parametric modeling and simulation. On one side, the complex spatial configurations of buried pipes are represented by four geometric parameters for individual pipes and three spatial relationships between two pipes. On the other side, the resulting GPR scan images are interpreted by four shape features and three interfering relationships. By investigating the changing patterns of the GPR signatures owing to the change of spatial configuration of buried pipes, the causality is established as the "spatial patterns" between the parameters above on both sides. Such patterns serve as the "expert" knowledge in understanding spatial pattern and estimating spatial configuration.

In Chapter Four, I propose an automated adaptive trajectory planning approach to help adjust the GPR survey trajectory during the field survey in an automated and adaptive manner. A prototype of automated GPR trajectory planning cart is developed, which can adjust GPR survey trajectory in real-time based on the decomposed GPR signatures and the intrinsic relationship between the GPR signatures in scanned images and the angles between GPR trajectory and pipe orientations.

In Chapter Five, I propose an AR platform on mobile devices to represent the multi-dimensional information (e.g., geo-location, spatial configuration, material types of buried pipes) retrieved from GPR survey and other sources for mapping underground utilities. Specifically, I address the limitations in three modules to enhance observers' location perception, depth perception and material perception. A complete geo-locating and rendering process is proposed in this chapter. Moreover, all of the information is rooted in a uniform geo-spatial database.

The research contribution is significant. It automates and streamlines the analysis of GPR raw data, revolutionizes the use of "spatial patterns" related to complex spatial configurations of the congested urban underground world to map and label underground utilities. Four specific outcomes are summarized.

- First, a new algorithm is developed to detect and decompose GPR signatures in 2D profiles of GPR scans (e.g., occluded or intersecting hyperbolas). The algorithm exhibits the ability to provide all the essential information needed for determining the complex spatial configuration of pipes in a congested area. Specifically, it has at least two outstanding merits: (1) there is no need for an initial guess of the number of hyperbolas, and (2) it is capable of not only detecting the number of hyperbolas, but also decomposing individual hyperbolas into rising leg, apex, and trailing leg, as well as the intersections between neighboring connected hyperbolas.
- Second, the causal relationship is established between congested underground utilities and their interfered GPR signatures in the scan images. "Spatial patterns" are extracted in the forms of eight characteristic parameters, four of which can determine the spatial configuration of

underground utilities, and the other four of which can represent the geometrical of the GPR signatures in scan images. The causal relationship serves as the "expert" knowledge in understanding spatial pattern and estimating spatial configuration.

- Third, an intellectual GPR survey framework is proposed to automate the process of GPR trajectory planning and data collection. A prototype of automated GPR survey cart is developed, which can adjust GPR survey trajectory in real-time based on the collected field data and the intrinsic causal relationship between underground utilities and their GPR signatures in the scan images. This intelligent survey framework enables the systematic integration of the research outcomes from the previous two tasks as well as the existing GPR data processing achievements from other researchers, which has great potential to automate the entire process of GPR field survey design and data collection, GPR signal pre-processing, GPR signature extraction, and attribute estimation of buried objects in real practice in an efficient and intelligent manner.
- Fourth, a visualization platform is developed to represent the multi-dimensional information retrieved from GPR for mapping underground utilities in an illusion-free manner, which improve the data communication efficiency and easiness with engineers, designers and stakeholders.

The importance of fulfilling these objectives is acknowledged in a wide range of fields, including the Mapping the Underworld initiative in the United Kingdom and the Subsurface Utility Engineering practice in the United States. With accurate utility locations and dimensions, 22% of the excavation-related incidents and a significant number of dry holes (i.e., excavations failed to find utilities) could be avoided. It helps realize enormous cost savings, reduce potential hazards to citizens, improve the sustainability of urban communities, and reduce life-cycle costs of underground infrastructure. By engaging the general public with the devised technologies, this application will raise awareness of underground utility infrastructure that has long been neglected due to their invisibility, and improve public scientific literacy that in turn, can help to engage the public in all life cycle stages of underground utility infrastructure. Thus, the proposed research is not only expected to vertically drive the field of underground mapping and labeling, but also to have broad and highly positive societal impacts.