DEVELOPMENT OF AN INTEGRATED GPR-BIM FRAMEWORK FOR MODELING UNDERGROUND SPACES

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by

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Submitted

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Dedicated to my

Parents, wife, teachers and friends

CERTIFICATE

This is to certify that the thesis entitled **"Development of an Integrated GPR-BIM Framework for Modeling Underground Spaces"**, submitted by Mr. Anikesh Paul (Entry No. 2020CEZ8406) to the Department of Civil and Environmental Engineering, Indian Institute of Technology Delhi for the fulfilment of the requirements of the award of the degree of Doctor of Philosophy is a bonafide record of the research work carried out by him. He has worked under my supervision and guidance and has fulfilled the requirements for the submission of this thesis, which, to my knowledge, has reached the requisite standard. The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

With the global rise in urban sprawl and subsequent land scarcity, efficient underground space utilization has become critical. This is particularly true for developing nations witnessing rapid underground infrastructure growth, driven by flagship initiatives and substantial public investment. However, underground infrastructure development faces persistent challenges from unpredictable subsurface conditions and undocumented underground utilities, often worsened by outdated records and fragmented spatial databases. Even where records exist, it becomes difficult to visualize the 3D details from the 2D maps. Conventional investigation methods like borehole drilling are also often inadequate for large-scale projects.

This study advocates for the use of non-destructive geophysical techniques, particularly Ground Penetrating Radar (GPR) to enhance subsurface diagnostics. While GPR is well-established for non-invasive utility detection and soil stratification, its standalone capabilities in 3D spatial modeling, data integration and decision support hinder its broader application. To address these gaps, the objective of this study is to develop an integrated framework combining GPR with Building Information Modeling (BIM) and Global Positioning System (GPS) technologies to enhance underground diagnostics and digital utility management through experimental case study approach. This integration supports geo-visualization-based planning, early clash detection, confident execution of earthwork activities, and the creation of a long-term digital repository to inform future infrastructure development.

The research begins with a systematic review of last 25 years of literature, identifying key challenges in GPR-based subsurface investigations for underground utility detection and subsurface profiling. Based on these findings, a GPR implementation challenge–solution taxonomy is proposed to address key technical and operational barriers.

Building on this, the study further develops an integrated GPR–BIM framework through experimental studies. The framework is automated using Dynamo scripts within Autodesk Civil 3D for incorporation of GPR data into BIM, and LLM-enhanced machine learning algorithms for the automatic identification and classification of utilities, thus minimizing manual errors and improving scalability. From analysis, the LLM-based model yields a high F1-score of 78.39% for hyperbola identification, and average accuracy close to 75% for hyperbola classification based on utility material.

The framework's performance is further evaluated through four case studies with varied geotechnical conditions and utility complexities. Results show a maximum data acquisition error of 7%, demonstrating a high reliability in utility detection and geospatial accuracy. A qualitative sensitivity analysis further assesses the impact of site-specific variables and modeling parameters on detection accuracy, integration efficiency, and decision-making effectiveness.

The study concludes with a future roadmap, emphasizing opportunities in multi-sensor data fusion, advanced machine learning, IoT integration, and trade-off strategies. These insights aim to guide the evolution of a holistic and scalable approach to underground space diagnostics and planning. By presenting a robust digital framework for underground investigation and planning, this research contributes to the domains of geotechnical engineering and digital construction, supporting improved visualization, documentation, and execution of complex urban infrastructure projects.

Keywords: *Ground Penetrating Radar (GPR), Building Information Modeling (BIM), 3D Underground modeling, Integrated GPR-BIM Framework, underground utility mapping, subsurface profiling, Geotechnical BIM, Digital Automation.*

सार

शहरी फैलाव में वैश्विक वृद्धि और उसके बाद भूमि की कमी के साथ, कुशल भूमिगत स्थान का उपयोग महत्वपूर्ण हो गया है। यह विशेष रूप से विकासशील देशों के लिए सच है जो तेजी से भूमिगत बुनियादी ढांचे के विकास को देख रहे हैं, जो प्रमुख पहलों और पर्याप्त सार्वजनिक निवेश द्वारा संचालित है। हालांकि, भूमिगत बुनियादी ढांचे के विकास को अप्रत्याशित उपसतह स्थितियों और अनिर्दिष्ट भूमिगत उपयोगिताओं से लगातार चुनौतियों का सामना करना पड़ता है, जो अक्सर पुराने रिकॉर्ड और खंडित स्थानिक डेटाबेस से खराब हो जाते हैं। यहां तक कि जहां अभिलेख मौजूद हैं, वहां भी 2-डी मानचित्रों से 3-डी विवरणों की कल्पना करना मुश्किल हो जाता है। बोरहोल ड्रिलिंग जैसे पारंपरिक जांच तरीके भी अक्सर बड़े पैमाने पर परियोजनाओं के लिए अपर्याप्त होते हैं।

यह अध्ययन गैर-विनाशकारी भूभौतिकीय तकनीकों, विशेष रूप से ग्राउंड पेनेट्रेटिंग रडार (जी. पी. आर.) के उपयोग की वकालत करता है ताकि उपसतह निदान को बढ़ाया जा सके। जबकि जीपीआर गैर-आक्रामक उपयोगिता का पता लगाने और मिट्टी के स्तरीकरण के लिए अच्छी तरह से स्थापित है, 3डी स्थानिक मॉडलिंग, डेटा एकीकरण और निर्णय समर्थन में इसकी स्वतंत्र क्षमताएं इसके व्यापक अनुप्रयोग में बाधा डालती हैं। इन कमियों को दूर करने के लिए, इस अध्ययन का उद्देश्य प्रायोगिक केस स्टडी दृष्टिकोण के माध्यम से भूमिगत निदान और डिजिटल उपयोगिता प्रबंधन को बढ़ाने के लिए बिल्डिंग इंफॉर्मेशन मॉडलिंग (बीआईएम) और ग्लोबल पोजिशनिंग सिस्टम (जीपीएस) प्रौद्योगिकियों के साथ जीपीआर को मिलाकर एक एकीकृत ढांचा विकसित करना है। यह एकीकरण भू-दृश्य-आधारित योजना, जल्दी टकराव का पता लगाने, मिट्टी की गतिविधियों के आत्मविश्वास निष्पादन और भविष्य के बुनियादी ढांचे के विकास को सूचित करने के लिए एक दीर्घकालिक डिजिटल भंडार के निर्माण का समर्थन करता है।

अनुसंधान पिछले 25 वर्षों के साहित्य की एक व्यवस्थित समीक्षा के साथ शुरू होता है, जिसमें भूमिगत उपयोगिता का पता लगाने और उपसतह प्रोफाइलिंग के लिए जीपीआर-आधारित उपसतह जांच में प्रमुख चुनौतियों की पहचान की जाती है। इन निष्कर्षों के आधार पर, प्रमुख तकनीकी और परिचालन बाधाओं को दूर करने के लिए एक जीपीआर कार्यान्वयन चुनौती-समाधान वर्गीकरण का प्रस्ताव किया

गया है। इसके आधार पर, अध्ययन आगे प्रयोगात्मक अध्ययनों के माध्यम से एक एकीकृत जीपीआर-बीआईएम ढांचा विकसित करता है। बीआईएम में जीपीआर डेटा को शामिल करने के लिए ऑटोडेस्क सिविल 3-डी के भीतर डायनेमो स्क्रिप्ट का उपयोग करके फ्रेमवर्क को स्वचालित किया जाता है, और उपयोगिताओं की स्वचालित पहचान और वर्गीकरण के लिए एलएलएम-वर्धित मशीन लर्निंग एल्गोरिदम, इस प्रकार मैनुअल त्रुटियों को कम करता है और मापनीयता में सुधार करता है। विश्लेषण से, LLM-आधारित मॉडल हाइपरबोला पहचान के लिए 78.39% का उच्च F1-स्कोर देता है, और उपयोगिता सामग्री के आधार पर हाइपरबोला वर्गीकरण के लिए औसत सटीकता 75% के करीब है।

विभिन्न भू-तकनीकी स्थितियों और उपयोगिता जटिलताओं के साथ चार मामलों के अध्ययन के माध्यम से ढांचे के प्रदर्शन का मूल्यांकन किया जाता है। परिणाम 7% की अधिकतम डेटा अधिग्रहण त्रुटि दिखाते हैं, उपयोगिता का पता लगाने और भू-स्थानिक सटीकता में उच्च विश्वसनीयता का प्रदर्शन करते हैं। एक गुणात्मक संवेदनशीलता विश्लेषण आगे पता लगाने की सटीकता, एकीकरण दक्षता और निर्णय लेने की प्रभावशीलता पर साइट-विशिष्ट चर और मॉडलिंग मापदंडों के प्रभाव का आकलन करता है।

अध्ययन भविष्य के रोडमैप के साथ समाप्त होता है, जिसमें मल्टी-सेंसर डेटा फ्यूजन, उन्नत मशीन लर्निंग, आईओटी एकीकरण और ट्रेड-ऑफ रणनीतियों में अवसरों पर जोर दिया जाता है। इन अंतर्दृष्टि का उद्देश्य भूमिगत अंतरिक्ष निदान और योजना के लिए एक समग्र और स्केलेबल दृष्टिकोण के विकास का मार्गदर्शन करना है। भूमिगत जांच और योजना के लिए एक मजबूत डिजिटल ढांचा प्रस्तुत करके, यह शोध भू-तकनीकी इंजीनियरिंग और डिजिटल निर्माण के क्षेत्र में योगदान देता है, जो जटिल शहरी बुनियादी ढांचा परियोजनाओं के बेहतर दृश्य, प्रलेखन और निष्पादन का समर्थन करता है।

मुख्य शब्दः ग्राउंड पेनेट्रेटिंग रडार (जीपीआर), बिल्डिंग इंफॉर्मेशन मॉडलिंग (बीआईएम), 3-डी अंडरग्राउंड मॉडलिंग, इंटीग्रेटेड जीपीआर-बीआईएम फ्रेमवर्क, अंडरग्राउंड यूटिलिटी मैपिंग, सबसर्फेस प्रोफाइलिंग, जियोटेक्निकल बीआईएम, डिजिटल ऑटोमेशन।

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LIST OF ABBREVIATIONS

GDP	Gross Domestic Product
UU	Underground Utilities
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
ASCE	American Society of Civil Engineers
SLA	Singapore Land Authority
CSA	Canadian Standards Association
NUAR	National Underground Asset Register
GPR	Ground Penetrating Radar
LiDAR	Light Detection and Ranging
BIM	Building Information Modeling
GIS	Geographic Information System
NSDI	National Spatial Data Infrastructure
NGDI	National Geospatial Data Infrastructure
MRTS	Mass Rapid Transit System
IoT	Internet of Things
RFID	Radio Frequency Identification
EMI	Electromagnetic Induction
MASW	Multichannel Analysis of Surface Waves
NBIMS	National Building Information Modelling Standard
BDS	Building Description System
O&M	Operations and Maintenance
CAD	Computer-Aided Design
AEC	Architecture, Engineering and Construction
RTK	Reak Time Kinematic
GPS	Global Positioning System
DXF	Drawing eXchange Format
IGES	Initial Graphics Exchange Specification

IFC	Industry Foundation Class
LoD	Level of Development
NDT	Non-Destructive Testing
R-CNN	Region-based Convolutional Neural Network
SS	Subsurface
MTU	Mapping the Underworld
AI	Artificial Intelligence
ML	Machine Learning
UUL	Underground Utility Locating
CSV	Comma Separated Variable
VBA	Visual Basic Application
HOG	Histogram of Oriented Gradients
SVM	Support vector Machine
SLR	Systematic Literature Review
DNN	Deep Neural Network
DC	Direct Current
ASCII	American Standard Code for Information Interchange
S/N	Signal to Noise ratio
SPT	Standard Penetration Test
COGO	Co-ordinate Geometry
NNI	Natural Neighbour Interpolation
API	Application Programming Interface
ANN	Artificial Neural Network
ICT	Information and Communication Technology
MS	Mild Steel
DI	Ductile Iron
EML	Electromagnetic Cable Locator
MHz	Megahertz
GHz	Gigahertz