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Object Detection and Localization in GPR B- Scan images using Hyperbola Fitting Algorithm

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Abstract

Ground-penetrating radar [GPR] is a non-invasive method, that generates an electromagnetic wave to map a subsurface object. It finds applications in various fields such as civil / structural engineering, environmental, Geotechnical and Military applications. This research is conducted at the Civil Engineering laboratory, IISc, Bangalore to collect the experimental data, using the Mala Pro-ex ground-coupled antenna GPR system from Mala Geoscience. GPR technology emits electromagnetic pulses into the ground and captures the reflected echoes from the target,enabling a detailed visualization of the subsurface targets.This paper presents the Hyperbola fitting algorithm for accurate detection and localization of the underground objects such as metallic and nonmetallic. It involves several steps, including preprocessing, identifying hyperbolas, fitting hyperbolas, determining target locations and depths, and validating the results. Following the fitting of the hyperbola, the algorithm proceeds to estimate the target's position and depth using the hyperbola's parameters. These estimated values for the target location and depth are subsequently validated through a model generated using the gprMax numerical modeling tool and is also tested on experimental data. There are numerous iterations of hyperbola fitting algorithms, and their implementation varies according to the attributes of the GPR data and the subject of interest. This method provides significant advantages for engineers before excavation of the ground. The algorithm has been developed and implemented using MATLAB. It has been rigorously tested using both experimental data and simulated data generated through gprMax Numerical modeling tool. The algorithm achieves a minimum error of 0.02 in the lateral position (x) and 0.01 in the depth (Y) direction. These results demonstrate the algorithm's accuracy and reliability in identifying and locating buried objects.

Keywords: *GPR, Hyperbola Fitting, gprMax, B-Scan, Paraview*

1.Introduction

GPR technique is a most effective method to identify and locate the different objects like metal and non-metal, that are buried beneath the ground surface. In recent years, ground-penetrating radar (GPR) has found extensive applications in the detection of landmines, archaeological research, and geological surveys [1]. Its rapid data acquisition and non-invasive nature have made it a popular non-destructive testing (NDT) tool in the field of civil engineering. An electromagnetic pulse of high frequency is transmitted by ground-penetrating radar system to capture the images of underground objects like metallic and nonmetallic pipes. It records an electromagnetic signal in the radio spectrum's microwave band, and recognize the signals returned from the underground objects. GPR employs a frequency range between 10MHz to 2.6GHz. The antenna frequency selection is vital for accurately detecting the target position. Due to the varying dielectric properties of subsurface materials, interpreting GPR images can be challenging, particularly when attempting to differentiate targets from other materials. So, it is required to form a suitable algorithm which is very critical and complex for the accurate identification and localization of the target [2]

Hyperbola fitting algorithm is used to accurately detect the position of an object. Manual detection and localization of the target can be a time-consuming and intricate task, making it challenging to achieve accurate results. When radar signals interact with objects buried in the ground, they undergo reflection and scattering due to differences in material permittivity. As the GPR antenna scans from left to right on the surface, the presence of underground targets gives rise to the formation of hyperbolic shapes. The scattering behavior of these underground targets is significantly influenced by the polarization of the radar's electromagnetic wave and the size of the target relative to the incident wavelength. The GPR system can operate over a broad frequency range, and it determines the depth to which a signal penetrates the ground. High frequency antenna produces better resolution while lower frequencies enable deeper penetration, making target detection easier.

2.Literature Survey

Qingxu Dou et al.,[3] presents an innovative approach for automated interpretation of Ground-Penetrating Radar (GPR) images, particularly for detecting buried objects and obtaining hyperbola parameters. It introduces the C3 algorithm, which can segment hyperbolic signatures, including intersected ones, by connecting adjacent image elements. A neural network classification method efficiently identifies hyperbolic signatures with just two features and minimal training data. The orthogonal distance hyperbola fitting algorithm is robust and efficient for specific hyperbolic shapes. Experimental results demonstrate the method's superior performance in noise resilience, efficiency, and accuracy, making it suitable for real-time on-site applications.

K. Rajiv et al.,[4] proposed a hyperbola fitting technique that effectively extracts shapes and features from both synthetic and real GPR data objects. This method has demonstrated its superiority in feature extraction across various GPR data sets and holds promise for applications like underground pipe identification.

Shape and feature extraction from Ground Penetrating Radar (GPR) data is a critical aspect of current underground object identification methods. The primary challenge involves automatically identifying and fitting hyperbolic features within GPR data objects.

Giannopoulos [5] presents a gprMax software for numerical simulations in Ground Penetrating Radar (GPR). It is highly beneficial for deepening our comprehension of how GPR functions in detection. The GprMax software suite enables the emulation of real-world scenarios encountered in routine GPR usage. With the ongoing advancements in computer capabilities, GPR modeling is poised to play a crucial role in educating new GPR users and enhancing the interpretation of intricate GPR data. Continuous efforts are directed towards incorporating more advanced attributes into modeling software, particularly to achieve highly realistic representations of actual GPR transducers.

Simone Meschino et al.,[6] proposed a method known as SPOT-GPR a freeware tool is usedfor analysis of GPR data to detect and localizing the targets. This simulation tool is implemented in MATLAB R2017b. A Radargram (B-Scan) is given as a input to the software. In this work a two-way travel time of the electromagnetic field is calculated for each trace. Then it is filtered to remove any noise present in the signal and finally, the targets are detected accurately. MUSIC algorithm and matched filter technique is employed for estimation of DoA. This software is tested by creating a dataset from gprMax which gives a better result.

Based on the previously mentioned studies, this paper has developed a dataset of field GPR B-scan images using gprMax Numerical Modeling simulation tool and Paraview visualization software. This paper has presented a Hyperbola fitting approach for the automatic identification and localization of buried metallic and non-metallic objects.

3. Data Collection

The acquisition of GPR data is obtained using two methods: simulation data and experimental data. Simulation data is generated using the gprMax software simulation tool. gprMax software is used to design the numerical modelling of the GPR. Experimental data is acquired using MALA GPR machine at IISc, Bengaluru, of different antenna frequency for the detection of the underground objects.

3.1 Gpr Modeling Using Gprmax

The primary use of Ground Penetrating Radar (GPR) is to identify the underground objects through a non-destructive testing approach. GPR possesses rapid data acquisition capabilities and effectively detects both metallic and non-metallic targets. gprMax is a Finite Difference Time Domain (FDTD) technique used for modeling GPR, as it offers advantages over other electromagnetic methods like integral techniques and finite element methods. The gprMax software tool is used for creating numerical models of GPR systems. Another software known as Paraview V4.3 is used to view the geometry created by gprMax. Users can create targets of varying shapes and sizes within the software. It also includes essential features like absorbing boundary conditions and precise discretization in both temporal and spatial dimensions. The software's core C programming code has been completely rewritten in Python and Cython languages. gprMax comprises two distinct simulators: GprMax2D for two-dimensional modeling and gprMax3D for three-dimensional representation of Ground Penetrating Radar (GPR) images generated through numerical modeling techniques. In this work a couple of experiments were conducted to select a suitable antenna frequency and depth of the target. The processing steps employed in gprMax is depicted in Figure 1.

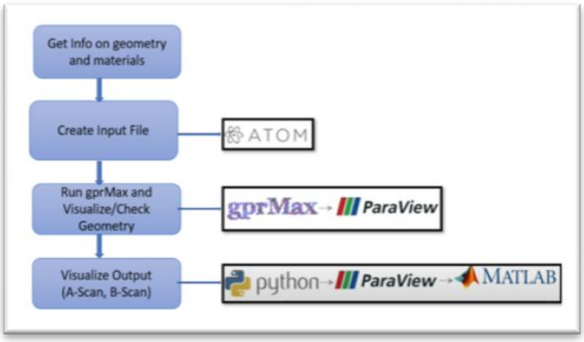

Figure 1.Processing Steps of gprMax

A text file is created in a text editor to serve as an input for gprMax. This file contains essential data such as domain dimensions, trace spacing, trace window settings, central frequency, relative permittivity, conductivity, and the specific target to be used in the GPR model simulation. To activate an antenna, a Ricker waveform with a central frequency of 1.5 GHz is applied. Several models have been generated, each with varying domain sizes and distinct targets, including metal, metal with free space, PVC, and PVC with free space. The gprMax-generated model is visualized using Paraview software, and the data obtained from Paraview is subsequently imported into Matlab software for additional analysis and processing. Model has been developed in the gprMax software to simulate two distinct scenarios.

Scenario 1 involves five distinct metal objects, each serving as a perfectly conductive conductor and positioned at varying depths, as illustrated in Table 1. and Figure 2.

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Table 1: Design Parameters of Different size

Scenario # 1			
Domain Size : 0.66 x 0.28 m^2 No. of A-Scans in the radargram : 100			
Object	**Center Position (m)**	**Radius (m)**	**Material**
No.1	(0.18,0.17)	0.01	Metal
No.2	(0.28,0.14)	0.01	Metal
No.3	(0.38,0.11)	0.01	Metal
No.4	(0.48.0.14)	0.005	Metal
No.5	(0.58,0.14)	0.005	Metal

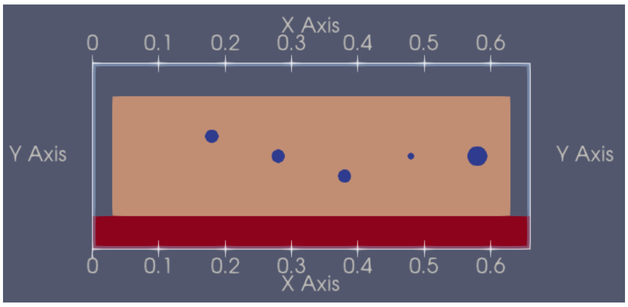

Figure 2. Geometric model- Metal of different size

Scenario 2 involves a PVC with free space, as indicated in Table 2. The object is positioned within a domain size of 0.66 x 0.28 m2. Figure 3 depicts the geometry generated by gprMax, and the visualization using Paraview software.

Table 2: Design Parameters of Different Targets

Scenario # 2			
Domain Size : 0.66 x 0.28 m^2 No. of A-Scans in the radargram : 100			
Object	**Center Position (m)**	**Radius (m)**	**Material**
No.2	(0.3,0.14)	0.002	PVC

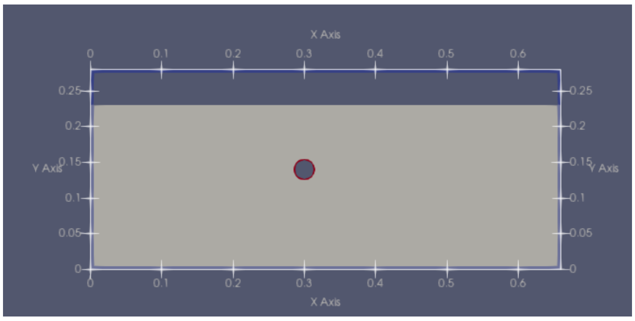

Figure 3. Geometric model- PVC

3.2 Experimental Data

Mala Pro-Ex ground-coupled antenna GPR System is used at IISc Bangalore to generate real-time data, as illustrated in Figure 4. A model track is constructed which includes the underground objects such as a metal track as shown in Figure 5. Low frequency antenna penetrates deeper in to the ground but provides a less resolution in comparison with high frequency antennas. Figure 6. and Figure 7. shows the GPR antenna and model constructed at IISc to detect the underground objects.

Figure 4. Mala GPR System

Figure 5. Metal Object

Figure 6. Experimental Data -Model Track

Figure.7 Model constructed at IISc

4. Proposed Methodology - Hyperbola Fitting Algorithm

An algorithm is proposed in ground-penetrating radar (GPR) data to fit hyperbolic signatures of subsurface objects, allowing for the estimation of their depth beneath the surface. This approach uses the minimum mean square error technique for hyperbolic functions, which are derived from the standard equation of a hyperbola. Within this approach, it identifies the most optimal fitting parameters by minimizing the sum of squared error function to subsequently determine both the radar velocity and the radius of the subsurface object. To assess the efficiency of the proposed algorithm, this technique undergoes testing with both simulated and experimental data. The algorithm for fitting a hyperbola involves a series of steps.

Data Acquisition: The first stage is to use a radar system to acquire GPR data over the area of interest to identify the underground objects.

Preprocessing: Prior to further analysis, it is important to perform preprocessing on the GPR data, which includes tasks like noise and artifact removal, as well as improving the signal-to-noise ratio. This involves such as filtering, eliminating background interference, and adjusting gain.

Data analysis: In the data analysis stage, the GPR data needs to be examined to detect the existence of the target and determine its depth. This involves choosing a portion of the data containing the target and conducting hyperbola fitting as a method of estimation.

Hyperbola fitting: Hyperbola fitting is a process that entails using a nonlinear least-squares algorithm to match a hyperbolic curve with GPR (Ground Penetrating Radar) data. This curve models the reflection originating from a buried target, and its various attributes (such as focal length, vertex depth, and vertical offset) can be employed to make estimations about the target's depth below the surface.

Depth estimation: By measuring the distance between the surface and the hyperbola's vertex after the hyperbolic curve has been fitted to the GPR data, the depth of the target may then be inferred. The target's depth is represented by this distance.

4.1 Mathematical Analysis

Consider an ideal vertical transverse axis hyperbola of coefficient a and b centered at the origin of a Cartesian reference system as shown in Figure 8. and Figure 9.

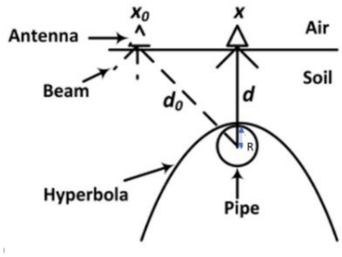

Figure 8. Hyperbolic Signature Spread due to buried target

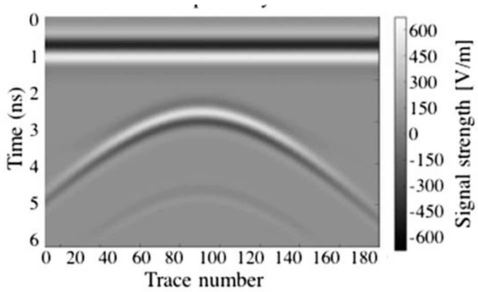

Figure 9. GPR Radargram

The equation for the hyperbola is given by,

$$\frac{yi^2}{a^2} - \frac{xi^2}{b^2} = 1 \quad (1)$$

where (x_i, y_i), i =1, 2, 3…... n are the n-point-coordinates of the points along the curve. If the curve is a perfect hyperbola, then all the points (xi, yi) satisfy the above equation and thus the error due to fitting of the hyperbola is zero.

For real field, hyperbolic patterns in a radargram, the curve may not lie on the fitting hyperbola. So, the error generated 'e' is given by the difference between the left and the right-hand sides of equation 1.

$$1- \frac{yi^2}{a^2} - \frac{xi^2}{b^2} \quad (2)$$

The error is therefore the sum of all n point errors given by

$$e = \sum_{i=1}^{n} 1- \frac{yi^2}{a^2} - \frac{xi^2}{b^2} (3)$$

Thus, square error is given by

$$e^2 = \sum_{i=1}^{n} \left(1- \frac{yi^2}{a^2} + \frac{xi^2}{b^2}\right)^2 (4)$$

Equation 4 is a function of the parameters a and b. These parameters are to be determined such that the square error e^2 is minimized. The optimal values of a and b are obtainable by differentiating e^2 with respect to the parameters and by equating the differentials to zero. That is by solving the equation

$$\frac{\partial e^2}{\partial a} = 0 \quad (5)$$

leads to

$$\sum_i X_i^2 - \sum_i \frac{X_i^2}{a^2} + \sum_i \frac{X_i^2 Y_i^2}{b^2} \quad (6)$$

and

$$\frac{\partial e^2}{\partial b} = 0 \quad (7)$$

Which leads to,

$$\sum_i Y_i^2 + \sum_i \frac{y_i^2}{b^2} - \sum_i \frac{X_i^2 Y_i^2}{a^2} \quad (8)$$

To calculate the parameters 'a' and 'b' the equations 6 and 8 has to be solved , which is given by,

$$a^2 = \frac{\sum_i Y_i^4 \sum_i X_i^4 - \left(\sum_i X_i^2 Y_i^2\right)^2}{\sum_i Y_i^4 \sum_i X_i^4 - \left(\sum_i X_i^2 Y_i^2\right)^2 \sum_i Y_i^2} \quad (9)$$

and

$$b^2 = \frac{(\sum_i X_i^2 Y_i^2)\sum_i Y_i^4 - (\sum_i X_i^2 Y_i^2)^2}{(\sum_i X_i^2 Y_i^2)\sum_i X_i^2 - \sum_i Y_i^2 \sum_i X_i^4} \quad (10)$$

The depth to the top of the target d is given by

$$d = \frac{vt0}{2} \quad (11)$$

The hyperbola parameters 'a' and 'b' equations are given by

$$a = t_0 + \frac{2R}{v} \quad \text{and} \quad b = \frac{vt_0}{2} + R \quad (12)$$

4.2 ALGORITHM STEPS

Step 1: Collect the parameter values of Speed of EM wave in space, Dielectric permittivity of sand medium, velocity of EM wave, time window tw and center frequency.

- Total number of traces of field E (x, z = 0, t)
- Obtain Mx N matrix by discretizing E (x, z =0, t).

Step 2: Preprocessing to eliminate the noise

Step 3: Select the B-scan region containing only hyperbolas by selecting the minimum and maximum value of time window.

Step 4: Hyperbola fitting: Fit a hyperbolic curve to the GPR data using a minimum least-squares error technique.

Step 5: Define the hyperbolic curve as:

y = a * sqrt ((x – h) ^2 + b^2) + c

Step 4: Select a section of the GPR data that contains the target.

Step 5: Use a nonlinear least-squares algorithm to fit the hyperbolic curve to the selected data. The algorithm should minimize the sum of the squared residuals between the hyperbola and the data points

Step 6: Find the maximum peak point in each hyperbola.

Step 7: Obtain the parameters of the hyperbolic curve and use them to estimate the depth of the target.

Step 8: Obtain the depth by calculating major axis and minor axis of each hyperbola.

Step 9: Depth estimation: Estimate the depth of the target by calculating the distance between the surface and the vertex of the hyperbola. This distance represents the depth of the target.

5.Results And Discussion

The results of the hyperbola fitting algorithm for object localization in GPR data can provide accurate and precise results for well-defined hyperbolic curves. To validate this algorithm both experimental and simulation data are considered.

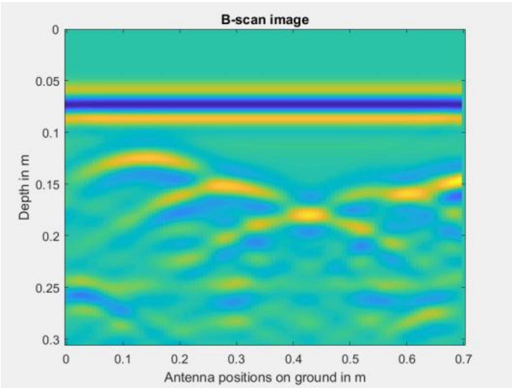

Figure 10. B-Scan (Metal)

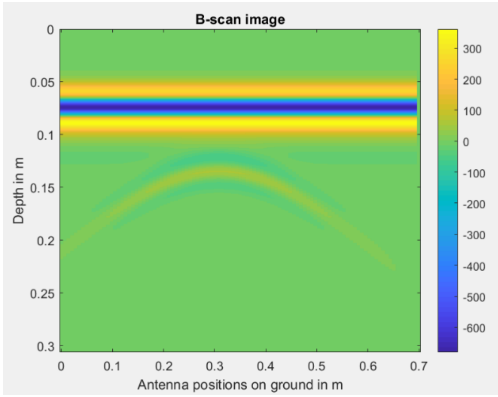

Figure 11. B-Scan (PVC Pipe)

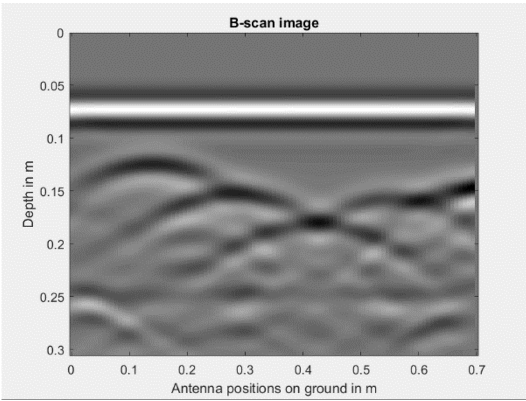

Figure 12. Processed Image (Metal)

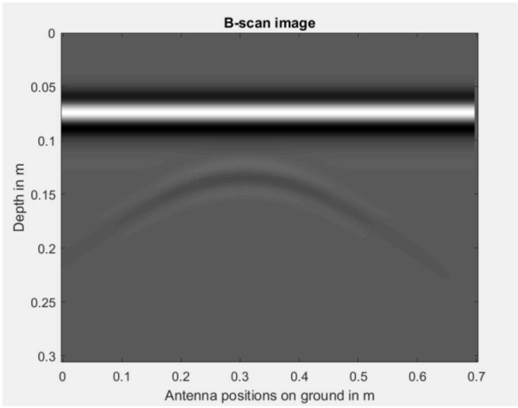

Figure 13. Processed Image (PVC pipe)

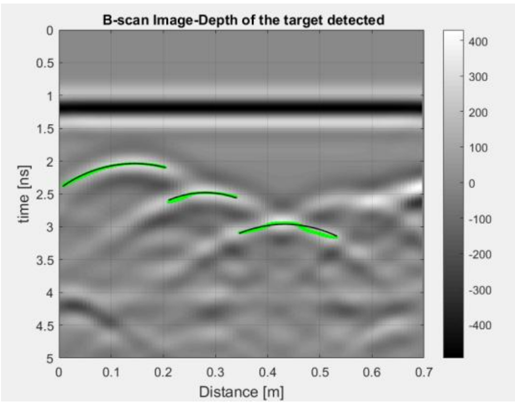

Figure 14. Hyperbola Detection (metal)

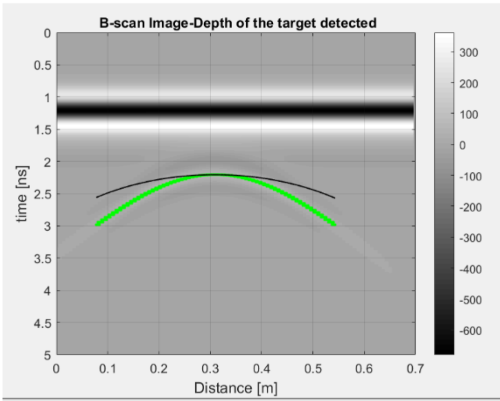

Figure 15. Hyperbola Detection

In simulation method, gprMax software is used to create a dataset. Paraview software is used to visualize the model generated through gprMax. The data generated from the gprMax is in HDF5 format. To read the data in Matlab, h5read function is used. Figure 10.and Figure 11. shows the B-scan of the processed image in Matlab and applied as an input to Hyperbola fitting algorithm. Figure 10. Contains of five metal objects while Figure 11. Contains only one object i.e., PVC. After applying the Hyperbola fitting algorithm to the processed image (metal) depicts in Figure 12 shows a hyperbola signature for the detected target. The migrated depth (y) for metal 1 is determined to be 0.14 meters and the lateral position (x) is 0.16 meters. For metal 2, the migrated depth is determined to be 0.16 meters and the lateral position is 0.27 meters. For metal 3, the migrated depth determined to be 0.12 meters and the lateral position is 0.40 meters These migrated depths and lateral positions for metal 4 and metal 5 are shown in Figure 14. The processed image of PVC object shown in Figure 13. is applied as input for the Hyperbola fitting algorithm. The migrated depth (y) is 0.15m and lateral position (x) is 0.29 as shown in Figure 15.

Metal object has a stronger reflection due to high conductive nature while PVC, being a non-conductive plastic has comparatively weaker reflective characteristics. The proposed hyperbola fitting algorithm is compared with the ground truth data and verified the results by calculating the error as shown in Table 3. The detection and localization of the target is accurately identified by implementation of this algorithm. The target depth i.e., X and Y location is identified with less error.

Comparing the results of hyperbola fitting algorithm for detecting the depth of a target with real-time data requires collecting GPR data over a known target, processing the data, and estimating the depth using hyperbola fitting. The estimated depth can then be compared to the actual depth of the target as measured by excavation.

Table 3. Comparison of Results

Sl No	Target	True Target location in meters		Radius (m) of the target	Hyperbola fitting algorithm		Error in (m)	
		X true location	Y true location		X (m) Location	Y(m) Location	X	Y
1	Metal	0.39	0.25	0.24	0.35	0.23	0.04	0.02
2	PVC	0.3	0.14	0.02	0.29	0.15	0.01	0.01
3	Metal 1	0.18	0.17	0.01	0.16	0.14	0.02	0.03
4	Metal 2	0.28	0.14	0.01	0.27	0.16	0.01	0.02
5	Metal 3	0.38	0.13	0.005	0.40	0.12	0.02	0.01
6	Metal 4	0.48	0.14	0.005	0.46	0.16	0.02	0.02
7	Metal 5	0.58	0.14	0.015	0.54	0.15	0.04	0.01

6.Conclusion

In this work, datasets are generated using gprMax simulation software with different targets and real time datasets are collected by constructing a model at IISc. The Hyperbola fitting algorithm is implemented on both simulation and experimental data. The hyperbola fitting method is a technique used to detect the depth of a different objects like metal and PVC, using Ground Penetrating Radar (GPR). GPR is a non-destructive geophysical method that uses electromagnetic waves to image the subsurface. The hyperbola fitting method works by analyzing the reflections of electromagnetic waves from the subsurface. When the waves encounter a target, they are reflected to the GPR antenna. The time taken for the wave to travel to the target and back is measured, and this information is used to estimate the distance to the target.Metal objects typically produce strong and well-defined reflections in GPR data.Plastic objects, such as PVC pipes, tend to produce weaker and more diffuse reflections in GPR data. This is because plastics are generally less conductive than metals, so they do not reflect as much of the radar signal. The hyperbola fitting method involves analyzing the reflections from multiple points around the target to determine the location and size of the target. This is done by fitting a hyperbola to the reflections and using the parameters of the hyperbola to estimate the target's location and size.

Overall, the hyperbola fitting method is a powerful tool for detecting the size and location of targets using GPR. Its accuracy and effectiveness depend on a range of factors, including the quality of the GPR equipment, the soil and subsurface conditions, and the expertise of the operator. By implementing this algorithm, the calculated depth of the target value is very close to the actual value with minimum error.

Statements & Declarations

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