Application of Synthetic Aperture Focusing Technique to visualize GPR data from reinforced concrete structures

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Abstract. Ground Penetrating Radar (GPR) has been proven to be the most effective technology for imaging and evaluating the condition of concrete structures. That said, this paper presents an algorithm to automatically visualize GPR data collected from reinforced concrete structures. Specifically, the algorithm is based on the synthetic aperture focusing technique (SAFT) and is executed with two GPR data sets collected in a perpendicular survey grid. In the first step, for each scan line in a data set, a B-scan is reconstructed from the corresponding raw data using the SAFT technique. In the second step, the linear interpolation is employed, for each data set, to generate missing information between B-scans and create a 3D image of the surveyed object. Finally, by retaining the maximum amplitude of each corresponding voxel in the two images obtained from the second step, a combined 3D model is created.

1. Introduction

GPR has emerged to be the most commonly used technology for inspecting concrete structures [1]. More specifically, the GPR can be utilized for pinpointing reinforcing steel bars in concrete, estimating concrete cover thickness and rebar diameter for construction quality assurance [2-9], or evaluating and monitoring the deterioration development within different concrete elements [10-13]. The GPR can also be employed as an alternative technique to substitute the destructive experimental technique in material and structural study [14-18]. In this paper, we will briefly explain how GPR technology works and then present a SAFT algorithm to visualize GPR data collected on reinforced concrete slabs.

2. How GPR works

GPR is a technology initially developed to explore subsurface soil structures. It operates based on the behavior of electromagnetic (EM) wave propagation. When a beam of EM energy encounters an interface between two media of different dielectric constants, a portion of the energy is reflected. The remainder penetrates the next medium. By recording and analyzing such reflections, we can identify within concrete the presence of buried objects, material layers, structural defects, or foreign inclusions.

To scan a concrete structure, an operator either pushes the GPR device (figure 1a) manually or attaches the GPR device to a vehicle. At each location, the transmitting element of the antenna emits a short pulse of the EM signal. Another element (bistatic mode) or the same one (monostatic mode) will...
monitor and record the energy reflected from various interfaces to its location. Such a recording occurs within a certain period of time to produce an A-scan signal. The entire process repeats for the next locations, as the antenna moves along the survey line.

When displaying the results for a location, a plot of amplitude data versus time is known as an A-scan. Furthermore, a stack of many A-scans collected from a scan line will create what is called a B-scan. An illustration is provided in figure 1b in which an A-scan right at the location of the top rebar is plotted on the right of the B-scan. The time on the vertical axis of the B-scan indicates how long it takes for a signal to travel from the transmitting element to a pixel and then back to the receiving element of the antenna.

![Commonly used GPR system](image1)

(a) Commonly used GPR system

![A-scan versus B-scan](image2)

(b) A-scan versus B-scan

**Figure 1.** GPR explanation

3. Visualization of GPR data based on SAFT algorithm

This section describes the essential steps to create a 3D reconstruction image of a reinforced concrete structure. In the first step, a focused B-scan will be reconstructed for each scan line in each data set using the SAFT algorithm [19-24]. In the second step, all the B-scans in each data set will be used to build the corresponding 3D image based on the linear interpolation method. Finally, the two 3D images obtained from the two data sets will be fused to create a single 3D model of the surveyed object. While the overall process is depicted in figure 2. The details of each step will be explained in the subsequent section.

![GPR raw data reconstruction with SAFT technique](image3)

2D image reconstruction with SAFT technique

***Figure 2.*** The entire process of 3D image reconstruction.

3.1. Two-dimensional (2D) image reconstruction

The SAFT technique was employed in this research. This algorithm consists of several steps when it is applied to reconstruct a B-scan from a raw GPR profile, as depicted in figure 3. Unlike the conventional methods of migration, the SAFT technique requires the reconstructed region to be input along with the raw B-scan. In the first step, the zero-time correction and background removal are
performed to specify the moment in time when the electromagnetic pulse is emitted and to remove the reflection at the concrete surface from the subsequent data analysis. In the second step, each A-scan in the time domain will be projected back to the reconstructed region based on the transmitter and receiver’s locations and an assumed velocity of the GPR signals. Finally, the reconstructed B-scan will be obtained by aggregating the amplitude data in the second step for all A-scans within the synthetic aperture.

For each A-scan

- Zero time correction and background removal
- Assign signal amplitude for each pixel
- Aggregate amplitudes from all A-scans
- Reconstructed B-scan

**Figure 3.** Process of 2D image reconstruction using the SAFT technique.

A schematic explanation provides a better understanding of the reconstruction process described above, as depicted in figure 4. As can be seen, based on the data acquisition parameters, it will be entirely possible to identify the locations of the transmitter and receiver corresponding to each A-scan (A-scan number \(i\)). To project that A-scan to a location (pixel) \(P\) in the reconstructed region, first, the length of the ray path corresponding to that pixel will be computed using equation 1. Next, based on the assumed signal velocity, the length obtained will be used to calculate the time when the signal reflected from that pixel was recorded in the A-scan. As explained in equation 2, the amplitude corresponding to that time point in the A-scan will be the projected amplitude. An example output of such a projection from one A-scan to the entire reconstructed region is depicted in figure 4b. The reconstruction will be completed when the same procedure has been done for all \((N)\) A-scans in the synthetic aperture, and the amplitudes have been summed up for each pixel, as explained in equation 3. Figure 4c illustrates an example of reconstructed B-scans from real GPR data collected on a section of a concrete slab.
Figure 4. Schematic explanation of B-scan image reconstruction using the SAFT technique.

\[ L_p^{th} = \sqrt{(X_p - X_T^{th})^2 + Z_p^2} + \sqrt{(X_p - X_R^{th})^2 + Z_p^2} \]  

(1)

Amplitude\(^{th}(P) = A_{scan}^{th} \text{ (at time } t = \frac{L_p^{th}}{signal \text{ velocity}}) \]  

(2)
3.2. Linear interpolation between 2D images

The objective of this step is to obtain the missing information/amplitudes for the voxels that lie in the spatial region between two consecutive reconstructed B-scans. It is achieved by using a technique known as interpolation. The interpolated amplitude at a query point in the reconstructed 3D space will be based on linear interpolation of the values at neighboring grid points in each respective dimension. It is noted again that the interpolation will be done separately for the two data sets corresponding to two polarization directions. Thus, two 3D images of the same 3D volume/space will be created at the end of this step.

\[
\text{Aggregated Amplitude}(P) = \sum_{i=1}^{N} \text{Amplitude}^{i\text{th}}(P)
\]

3.3. Three-dimensional image fusion

In this step, the two 3D images previously obtained will be combined to produce the final 3D representation of the structure being surveyed. It should have been mentioned before in the second step that, for them to be fused, they need to have the same size/resolution and the same coordinate system. Each voxel in one image should have the corresponding voxel in the other, which represents the same point in the 3D volume/space.

4. Algorithm implementation and results

A MATLAB program was developed to implement the proposed algorithm. The following presents the results obtained when the program was used to visualize GPR data collected for two slab sections. Specifically, the first section is small, only 1×1m, which aims to illustrate the 3D visualization. On the other hand, the second section is significantly larger (6.5×2.5m) to show the plan view of rebar locations.

As depicted in figure 5a, for each slab section, the data were collected in two perpendicular directions. The equipment used in these examinations was a hand-held C-thru system manufactured by IDS Georadar. It has two 2.0 GHz ground-coupled antennas oriented in perpendicular directions. The spacing between scan lines is 5 cm. The GPR signal velocity employed in the SAFT algorithm is 0.1m/ns. This value has been found applicable for most bare concrete bridge decks [2]. The 3D image obtained for the first slab section is shown in figure 5b. As can be seen, the image clearly displays the rebars within the tested volume. In addition to rebars, we can observe in the image the slab bottom, which also reflects GPR signals.

(a) Elevation view  
(b) 3D image developed by program

Figure 5. Three-dimensional visualization of the tested slab
Figure 6 depicts the plan view of the 3D image obtained for the second slab section with the proposed algorithm. As one can see, for most areas, it highlights clearly rebar locations. One thing that can also be noticed is that rebars are not obviously visible in some small regions. The reason is that the rebars in those areas are too close to the slab bottom, which leads to a mixture between rebar and slab bottom reflections. However, in general, based on the neighboring areas, we can still have some good ideas where on the image the rebars should be.

![Figure 6. Plan view obtained from 3D model](image)

5. Conclusions
This paper described in detail an algorithm to automatically visualize in 3D space the GPR data collected on a concrete structure. The algorithm is divided into three steps, namely B-scan reconstruction, interpolation, and 3D image fusion. In the first step, a B-scan is reconstructed for each scan line in each data set using the SAFT technique. In the second step, the linear interpolation is employed to interpolate missing data points between reconstructed B-scans and create a 3D model of the test object. Finally, the two 3D models obtained from the two data sets are merged using the maximum amplitude method to establish a comprehensive 3D visualization of the structure being tested. The implementation of the algorithm for two tested structures has shown excellent results. The rebars inside the structures have been successfully detected and clearly displayed in the obtained 3D and plan view images.

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