

# Article GPR Virtual Guidance System for Subsurface 3D Imaging

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**Abstract:** Three-dimensional GPR imaging requires evenly and densely distributed measurements, ideally collected without the need for ground surface markings, which is difficult to achieve in large-scale surveys. In this study, a guidance system was developed to guide the GPR operator to walk along a predesigned traverse, analogous to the flight path design of an airborne drone. The guidance system integrates an auto-track total station unit (ATTS), and by estimating the real-time offset angle and distance, guidance corrections can be provided to the operator in real time. There are two advantages: (1) reduced survey time as grid marking on the ground is no longer needed and (2) accurate positioning of each traverse. Lab and field experiments were conducted in order to validate the guidance system. The results show that with the guidance system, the survey paths were better defined and followed in terms of feature connectivity and resolution of images, and the C-scans generated were closer to the real subsurface world.

Keywords: ground penetrating radar; virtual guidance system; 3D GPR image



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# 1. Introduction

Ground penetrating radar (GPR) is one of the most effective and efficient geophysical techniques for imaging the subsurface [1,2]. Three-dimensional (3D) GPR imaging (Cscan) is becoming increasingly popular because it reveals the subsurface environment [3] as slices that are readily understandable. The denser the grid spacing, the higher the accuracy of the survey result [4–6]. However, traverses cannot be infinitely dense because of limitations such as work time and data storage, and areas not covered by traverses are therefore estimated by interpolation of the signals obtained. In this way, a full-covered image can be reconstructed for the whole survey area using an efficient means of data collection. Such a full-covered image requires precise positioning of each A-scan using either (1) global or (2) local positioning networks. For (1), one relies on synchronizing the positioning and GPR data with the global navigation satellite system (GNSS). Examples include America's Global positioning system (GPS), Europe's Galilieo, Russia's GLONASS, and China's BeiDou. The GNSS system requires an open-sky area for positioning, and centimeter-level accuracy requirements may not be satisfied in cloudy weather, in city centers, or under tree areas. For (2) however, using the auto-track total station with a local positioning network, the system is able to operate above GNSS-constrained areas or even indoors. However, positioning with the GNSS system is more convenient, as it does not require extra setup of the total station or the local referencing network, though the precision may be inconsistent throughout different parts of survey areas and, in general, may be less accurate. Currently, the mainstream GPR systems have widely adopted and integrated GNSS positioning [4-6]. However, as most of the underground surveys in Hong Kong are carried out in urban areas due to tall buildings and cloudy weather, the GPS signal would be unstable if using the GPS real-time kinematic (RTK) method for real-time positioning. Studies have improved the positioning performance by combining

GNSS and the inertial measurement unit (IMU) [7–9]. However, the size and cost of an IMU system is comparatively large, so it is less flexible for surveys in dense urban areas. Therefore, navigating with an auto-track total station would be more suitable, especially in urban areas.

For GPR traverses in a grid-free survey guided by either GPS or an auto-track total station unit (ATTS), GPR scans are often unevenly distributed within the survey area. This affects the accuracy of C-scans caused by buried objects, because the interpolation search radius is always the same throughout the whole survey area. If a smaller search radius is used, there will be more blanks in areas with unevenly distributed scans. In contrast, if the search radius used is larger, then more data will be considered during the interpolation process, which may also decrease the accuracy as the calculations may be affected by a strong but irrelevant signal from far away. There is therefore an expectation that GPR scans will be evenly distributed so that an appropriate search radius for interpolation can be defined [10–12].

In terms of pre-designed gridded surveys, it is still difficult for operators to walk precisely along a grid. Moreover, marking the grid on the ground area is tedious work, especially for large-scale surveys. In this case, the actual scan position may not coincide with the recorded position, thus degrading the accuracy of the imaging. Recently, many local and non-GNSS auto-positioning GPR survey methods have been developed. Le et al. [13] developed a robotic GPR system for bridge deck inspections. Boniger and Tronicke [14] explored the feasibility of guiding GPR using an auto-track total station, and identified the potential problem of latency. Chang [15] developed a piece of software for recording real-time GPR antenna positions. Kouros et al. [16] developed a mobile robot with a GPR antenna to conduct a 3D subsurface survey. However, the influence of GPR scan distribution on 3D images has not yet been considered. Slob et al. [17] developed an automatic indoor GPR data-acquisition system for slab imaging. BETOSCAN [18] combines different non-destructive sensors on a mobile robot system for large-area reinforced concrete floor diagnoses. Even though they can provide evenly distributed GPR scans, the systems are not portable and thus are unsuitable for large-scale subsurface surveys.

To face the challenges faced by existing studies, the objective of this study was to develop a system to perform high-accuracy real-time positioning, and to guide the GPR antenna travelling along the planned traverse based on GPS or ATTS. The productivity of a quick scan and the sensitivity of detailed imaging are always a trade-off during any GPR field survey. This GPR system better balances the downsides of the trade-off. A laboratory test and a field test were conducted to validate the program, and the C-scan with and without the guidance system was compared in terms of feature connectivity and images resolution, which demonstrates the improvement provided by the proposed method.

# 2. The Virtual Guidance System

#### 2.1. LabVIEW Virtual Guidance System

The guidance system was developed using the LabVIEW environment [19]. This guidance system was built based on the real-time tracking software developed by Chang [16]. The guidance system uses the real-time coordinate data recorded by real-time tracking software for application in the guidance process. The workflow of the program is divided into two main stages: the first stage involves boundary and traverse set-up, and the second stage deals with the traverse guidance. The workflow is shown in Figure 1.



Figure 1. General workflow of the guidance program.

# 2.2. Latency Check

As the real-time positioning data are transferred by wireless methods between the TTS and the control unit, latency problems may arise. According to Chang [15], latency can be determined by testing the system in a rectangular site. As shown in Figure 2, a large rectangle  $(1.81 \times 2.605 \text{ m})$  with designed coordinates served as the reference, and a trial survey guided by the TTS was conducted along the rectangle. The recorded coordinates of the trial survey were compared with the reference coordinates (Figure 3). We discovered that the integrated position by automatic tracking and GPR were always ahead of the true positions in the same direction as antenna movement, under the range of  $\pm 18$  to  $\pm 28$  mm. As the calculated positions shifted in the same direction as antenna movement, the latency error was improved by shifting the calculation during the data processing stage.



**Figure 2.** Photo of the large rectangle survey line. The black dots are ticks for 0.2 m intervals [15]. The trial started from the top right corner, and surveyed in a clockwise direction.



**Figure 3.** Deviation distribution of the large rectangle (red rectangle in Figure 2) with TTS logging rate = 0.5 s [15].

To set up the survey boundary, the start and end coordinates of the first traverse, the distance between the first and last traverses (survey width), and the spacing between the traverses were pre-set in the program, while the start and end coordinates of the last traverse were calculated based on Equations (1a–g). The survey boundary set by this method must be a rectangle with evenly spaced traverses as shown in Figure 4. The start and end coordinates of each traverse were calculated based on Equations (2) and (3).

$$x_c = x_b \pm \sqrt{s^2 / (1 + \left(\frac{1}{m^2}\right))}$$
 (1a)

$$y_c = y_b \pm \frac{1}{m} \sqrt{s^2 / (1 + \left(\frac{1}{m^2}\right))}$$
 (1b)

$$x_d = x_a \pm \sqrt{s^2 / \left(1 + \left(\frac{1}{m^2}\right)\right)} \tag{1c}$$

$$y_d = y_a \pm \frac{1}{m} \sqrt{s^2 / (1 + \left(\frac{1}{m^2}\right))}$$
 (1d)

$$m = \frac{y_b - y_a}{x_b - x_a} \tag{1e}$$

$$x_{start\ n} = \left(1 - \left(\frac{nd_s}{s}\right)\right) x_a + \left(\frac{nd_s}{s}\right) x_d \tag{1f}$$

$$y_{start\ n} = \left(1 - \left(\frac{nd_s}{s}\right)\right) y_a + \left(\frac{nd_s}{s}\right) y_d \tag{1g}$$

$$x_{end\ n} = \left(1 - \left(\frac{nd_s}{s}\right)\right) x_b + \left(\frac{nd_s}{s}\right) y_c \tag{2}$$

$$y_{end\ n} = \left(1 - \left(\frac{nd_s}{s}\right)\right) y_b + \left(\frac{nd_s}{s}\right) y_c \tag{3}$$

$$N = \frac{s}{d_s} + 1 \tag{4}$$

where  $(x_a, y_a)$ ,  $(x_b, y_b)$ ,  $(x_c, y_c)$ , and  $(x_d, y_d)$  are the coordinates of the 4 corners of the survey area; *s* is the width of the survey area; *m* is the slope of the line between a and b; and  $(x_c, y_c)$  and  $(x_d, y_d)$  are calculated by Equations (1a) to (1e) using the given values of  $(x_a, y_a)$  and  $(x_b, y_b)$  and width *s*. The start or end coordinates of each traverse line perpendicular to line ab are given by  $(x_{start n}, y_{start n})$  and  $(x_{end n}, y_{end n})$  with the spacing  $d_s$ . The number of traverses *N* between point a and point d is calculated by Equation (4).



Figure 4. Illustration of GPR traverse survey parameters.

In practice, the operator must obtain the start and end coordinates of the first traverse from ATTS, and enter the survey area's width *s* and grid spacing  $d_s$ . The survey area's boundaries as well as its start and end points for the two traverse directions are then generated automatically, as shown in Figure 4. At this stage, a cross-grid is set up in the system.

# 2.3. Positioning Correction Guidance

In the second stage, the system guides the operator while they move the GPR antenna. The system is designed to provide three different iterative steps for different circumstances (Figure 5): (1) offset distance detection from the designed track to the current point (blue box); (2) angle comparison between the correct direction and the direction from the start point to the current point (green box); (3) comparison of the correct direction and the current direction according to Equations (1) and (2), bounded by the red box. The graph window at the center of the interface displays the survey trajectory.



**Figure 5.** Interface of the guidance system (blue box: first method distance offset; green box: second method of WCB comparison; red box: third method direction comparison).

#### 2.3.1. Offset Distance Detection

In the first step, the perpendicular distance D from the real-time coordinate to the designed path is calculated using Equation (5):

$$D = \frac{m \times x_n - y_n + c}{\sqrt{m^2 + 1}}$$
(5)

The offset distance can thus be calculated, and if the offset distance is larger than the threshold value, an on-screen directional sign with "move left" or "move right" will guide the operator back to the desired traverse using the positive or negative results of the offset.

# 2.3.2. WCB Correction

In the second step, the whole circle bearing (WCB) from the starting point of a traverse to the end point of a traverse is calculated using Equation (6). When the GPR moves along the traverse, it calculates the WCB from the traverse's starting point to the current position in real time by comparing the difference between the WCB at two points, A and B, captured one second apart. The angular offset is calculated by Equation (7) and is shown on the meter, thus allowing the operator to adjust their walking direction back to the right track.

WCB From A to 
$$B = \tan^{-1}\left(\frac{X_B - X_A}{Y_B - Y_A}\right)$$
 (6)

where  $(X_A, Y_A)$  and  $(X_B, Y_B)$  are the coordinates of points A and B in Figure 6.

$$Direction \ pointing = Current \ WCB - Correct \ WCB$$
(7)



Figure 6. Illustrations of method 2 (a) and method 3 (b).

If the direction pointing is a negative number, the GPR is on the left side of the correct traverse, and if positive, it is on the right side (see green rectangle A in Figure 5).

#### 2.3.3. Comparison of Direction

In the third step, two meters are used. The lower meter shows the WCB from the start to the end of a traverse, while the upper meter displays the WCB from the position one second before to the current position, which indicates the GPR's current direction. By comparing the pointers of the two meters, the operator can check whether they are walking along the right track. If two meters are not pointing in the same direction, then the GPR walking direction needs to be adjusted. Once the GPR stops moving, the upper meter displays "NaN", as per the red rectangle B in Figure 5.

#### 3. Validation Experiment

A laboratory test and a field test were conducted to validate the performance of the new system. The laboratory test imitated a small-scale GPR survey aimed at imaging a relative homogeneous subsurface. The field test imitated a real large-scale GPR survey.

#### 3.1. Instrumentation

The group of instruments used in our validation experiments is shown in Figure 7. The GPR unit was tracked using a Leica (Leica geosystems limited. Switzerland) Viva TS15 total station with a 360 prism, and the data logging rate was 0.1 s. The GPR unit used for subsurface data collection was an IDS RIS-ME-HIMod (600 and 200 MHz).

### 3.2. Laboratory Test

A laboratory test was conducted in the underground utility survey laboratory of PolyU (Figure 8a). The large testing tank was filled with soil, and its dielectric constant was assumed to be 10. For a 600 MHz antenna, velocity =  $(0.3 \text{ m/ns})/\sqrt{10} = 0.094 \text{ m/ns}$ , then  $\lambda = 0.094 \text{ m/ns}/0.6 \text{ GHz} = 0.158 \text{ m}$ . Based on the 3D-imaging criteria in [6], the profile spacing (PS) is required to be less than or equal to  $4\lambda$ , which is then 0.632 m. The profile spacing as shown above by the grid laid out on the ground was 0.1 m < 0.632 m.

#### 3.3. Field Test

A field test was carried out on Palm Canyon Drive, Royal Palms, Yuen Long (Figure 8b). The survey results captured both with and without the guidance system were compared. More specifically, in order to imitate reality, the data collection was conducted by an operator

who was unfamiliar with the grid-free GPR survey methodology, and therefore received some simple onsite training to reduce the possibility of operator-induced bias. The operator only looked at the GUI of the guiding system when traversing the GPR. The dielectric constant of the host material in the field test site was assumed to be 6, and the maximum PS according to the 3D-imaging criteria [12] was 0.816 m for 600 MHz antenna, following the same calculation as the laboratory test, reported in laboratory test part. The grid spacing was therefore designed to be 0.6 m, which is smaller than the 0.816 m required in [12].



Figure 7. Main instrumentation used in this study and data flow.



Figure 8. Illustrations of test sites: (a) laboratory test; (b) field test.

# 3.4. GPR Signal Processing and C-Scan Generation

C-scans were generated using GPR-SLICE [20]. To eliminate the effect from the latency, a scan lag function was used to shift each A-scan to the correct position, then each set of data was processed according to [21] in order to generate a C-scan for data analysis. In the process, the slice thickness (ST) and the interpolation search radius (SR) were considered and calculated from the wavelength ( $\lambda$ ) and profile spacing (PS).

# 4. Result and Analysis

The system's advantages are demonstrated in two main ways: the survey path accuracy and the C-scan quality. The record drawing served as a reference when attempting to assess the accuracy of these two aspects of GPR survey data capture and imaging. The surveys were projected to the HK80 coordinate system.

# 4.1. Survey Path Analysis

The survey paths guided by the new system were expected to be straighter and more evenly spaced.

# 4.1.1. Laboratory Test Path Result

In the laboratory test, three survey-gridding methods were tested: in the first case, the GPR was used on a fixed grid without guidance (T1); in the second case, the GPR was used in a grid-free survey without guidance (T2); and in the last case, the GPR was used with the virtual guidance program (T3). All three tests used a 0.2 m profile spacing and the walking path shown in Figure 9.



**Figure 9.** (**a**,**c**,**e**) The survey paths of methods T1, T2, and T3, respectively. (**b**,**d**,**f**) Comparisons of these paths with the designed path (red).

Figure 9 shows that in methods T1 and T3, the survey paths were both close to the designed path. Additionally, the pattern of the traverses in methods one and three were more regular. However, in path T2, without any guidance system or ground markings, even within a small survey area, the survey traverses were irregular. When compared with the designed path, the shift in the traverses in T2 produced larger errors than those of the other two survey paths.

According to Figure 10, the method using a free grid without any guidance system had a significantly larger offset. Moreover, the average offset of T2 was 0.049 m, while that of T3 and T1 were 0.010 and 0.022 m, respectively. Under the condition of a PS equal to 0.2 m, the relative errors of T1, T2, and T3 were 24.5%, 50%, and 5%, respectively. The greatly reduced error of the guidance system successfully proves its capability to improve the survey path accuracy of GPR survey.



Figure 10. Distribution of the offset errors from three paths in the laboratory test.

#### 4.1.2. Field Test Path Result

After the laboratory test in a relatively homogeneous and controlled environment, the program was validated in a real-site setting with an operator who was not familiar with the use of grid-free surveys. In the field test, two survey methods were tested: grid-free without the guidance system (T2) and grid-free with the guidance system (T3). The PS values of both paths were 0.6 m.

As shown in Figure 11, method T3 presents a more regularly spaced grid. Although method T2 also looks straight, the spacing between each traverse is not as regular as T3.

Figure 12 displays the accuracy of paths T2 and T3 in the field test. Most errors in T2 fell in the range of 0.15–0.2 m, but in path T3, most of the errors fell within the range of 0–0.05 m. The mean offset of T2 was 0.322 m, while that of T3 was 0.061 m. This result illustrates that the guidance system successfully helped the operator walk on a more regular path when conducting the GPR survey than was possible when using the grid-free method without guidance.

# 4.1.3. Path Pattern

The result of the survey path analysis not only illustrates the offset accuracy, but also presents some examples of survey path walking patterns during grid-free surveys. A large proportion of the offset errors occurred around the starting point of each traverse. When the entrance of each path's starting point is incorrect, even if the operator walks on a straight line on the traverse, the survey path is still offset from the designed one. This situation results in uneven traverse spacing in grid-free surveys. It is also difficult for an operator to maintain the WCB of the walking direction. Sometimes, even when the operator sets off from the correct starting point, they may still walk in a direction that diverges from



the true one, and the later part of the survey path would thus have a large offset from the designed one. This problem is more obvious in surveys with a long traverse.

**Figure 11.** (**a**,**c**) The survey paths of methods T2 and T3, respectively; (**b**,**d**) the comparisons of such paths with the designed path (red).

# 4.2. Enhancing Quality of C-Scan Images

The quality of C-scan images resulting from T1–T3 was also compared and analyzed. To analyze the C-scan quality, the C-scan resolution and connectivity of the feature were both considered. The aim of utility surveys is to locate buried objects. If the resolution is high enough, then the location of objects of different sizes can be recognized in C-scans. The greater the range of target features that are distinguishable (e.g., pipes and voids), the better the quality of the C-scan. It is important to assess the connectivity of the GPR reflections generated by utilities, as they are normally presented as straight and continuous

features in C-scans. If the scan positions are incorrect, for example, due to latency, the mapped utilities present as a zig-zagged shape.



Figure 12. Distribution of offset errors from two paths on the site test.

4.2.1. Laboratory Test C-Scan Result Analysis

Three C-scans (Figure 13) were generated according to the 3D-imaging criteria in [6], using the same parameters of 0.16 m SR (search radius) and 0.22–0.25 m ST (slice thickness). Then, the scans were analyzed based on the following two aspects.



Figure 13. (a-c) C-scans for methods T1, T2, and T3, respectively.

In terms of connectivity, the plate boundary could be clearly identified from the C-scans of the traditional fixed-grid method (T1) and the grid-free method with guidance system (T3), as both C-scans showed a clear continuous strong reflection at the position of the plate boundary. However, for the C-scan from the grid-free unguided method (T2), the strong reflection was not continuous; instead, there were some discontinuous strong reflections present in the C-scan, and it was therefore hard to identify the plate boundary.

The second consideration is resolution, and the C-scans from methods T1 and T3 produced a higher resolution than from T2. Although the plate joint could still be identified in the T2 C-scan, compared with T1 and T3, the image in T2 was significantly less clear.

Therefore, from the C-scan results, we concluded that grid-free surveying with the guidance system (T3) can achieve a result similar to the fixed-grid method (T1). Conversely, for an unguided grid-free survey, the quality of results may be comparatively poorer than the other two methods, but the resolution may still be sufficiently good to show features in the C-scan. For the fixed grid (T1) and grid-free with guidance system (T3) surveys, the

boundaries can be clearly visualized. In contrast, in the C-scan of the unguided grid-free survey, the boundaries are unclear or cannot be recognized.

# 4.2.2. Field Test C-scan Result Analysis

The field test produced a result similar to the laboratory test (Figure 14). In terms of connectivity, the pipeline can be clearly identified on the C-scans from the grid-free guidance system method (T3), as the C-scan shows a clear continuous strong reflection running up the center of the road. However, on the C-scan of the unguided grid-free method (T2), the strong reflection is not as continuous as that of T3. Although the pipe can still be identified, the discontinuity of the strong reflection may affect the diagnosis of the pipe's condition.



**Figure 14.** (**a**,**c**) C-scans of method T2; (**b**,**d**) C-scans of method T3; (**a**,**b**) for a depth of 0.8–0.9 m; (**c**,**d**) for a depth of 0.9–1.0 m.

As far as resolution is concerned, the pipeline was very clearly defined in the C-scan of T3, while the resolution of T2 was comparatively poorer. When the pipe running up the center of the road was inspected, the C-scan of T3 appeared to be much clearer than that of T2, such that even the side branch of the pipe was clearly identified in the T3 C-scan image. Moreover, in the top right part of the survey area, three pipes were clearly identified from the T3 C-Scan, whereas in T2, the three were merged together. These results confirm that the C-scan of T3 has a higher resolution than that of T2.

Therefore, the guidance system clearly enhances the image quality in terms of both feature connectivity and image resolution.

# 5. Discussion and Conclusions

In this paper, a novel GPR guidance system was presented, and its applicability was validated by a series of experiments. With a predesigned orthogonal grid with regular spacing, the developed system collects real-time positioning data and estimates the offset between the actual position and desired position. Real-time corrective guidance can be provided to the operator, and thus the time spent on marking out an on-site grid can be saved, while also reducing imaging quality degradation. The laboratory and site validation experiments both showed promising results as the survey paths were more regular and corresponded with the desired grid. C-scan images generated by the guided survey paths produced better depictions of the real subsurface environment.

With the virtual guidance system, the survey paths can be as regular as those produced with the traditional fixed-grid method, and the accuracy of the survey grid can be improved while the time required for the site survey can be reduced. While the virtual guidance system can help plan the desired grid and guide the operator to walk along the grid, marking the grid on the ground is no longer necessary. The results of C-scan analyses also show that compared with uneven survey grid paths, the C-scans based on more regular survey paths yield higher-resolution images and the image utility can be clearly identified due to better connectivity. Even under real site conditions, the system can help the operator to walk following a more regular survey grid and produces a better C-scan image. This shows that the guidance system can successfully improve the accuracy of GPR survey grid positioning and image quality.

To further enhance the utility imaging quality in terms of above-ground positioning, three improvements are suggested. Firstly, an inertial measurement unit (IMU) can be added for detecting real-time orientation change due to topographic changes. Secondly, an automatic robotic system equipped with the guiding system described in this paper can be designed and built for surveys without an operator. Then, not only can humanpower costs be saved, but the C-scan imaging quality can be enhanced significantly as the survey grid traversed by robot can be set even denser than the proposed less-than-4 $\lambda$  rule to eliminate human operation error. Lastly, we suggest combining the system with a mobile mapping system (MMS). Together with the MMS, total station and local control points are not required because the integrated system also captures the surface information for self-georeferencing GPR data, which can provide us comprehensive information about the target area.

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