OBJECT RECOGNITION BY GROUND-PENETRATING RADAR IMAGING SYSTEMS WITH TEMPORAL SPECTRAL STATISTICS

Sashi Ono and Hua Lee
Imaging Systems Laboratory
Department of Electrical and Computer Engineering
University of California, Santa Barbara

ABSTRACT

This paper describes a new approach to object recognition by using ground-penetrating radar (GPR) imaging systems. The recognition procedure utilizes the spectral content instead of the object shape in traditional methods. To produce the identification feature of an object, the most common spectral component is obtained by singular value decomposition (SVD) of the training sets. The identification process is then integrated into the backward propagation image reconstruction algorithm, which is implemented on the FMCW GPR imaging systems.

KEY WORDS

Object recognition, singular value decomposition, backward propagation method.

INTRODUCTION

Object recognition has become a suject of importance in imaging and sensing applications. In the past, the recognition process has been mainly conducted based on the objects' spatial features. In ground penetrating radar (GPR) imaging, the reconstruction is the microwave reflectivity profile of the object, which does not necessarily resemble the normal surface configuration. Thus, recognition based on spatial variation has not been an effective approach in the subsurface imaging applications.

One potential method for object recognition in GPR imaging is to perform object identification by using spectral contents. Each material type reacts to microwave illumination in a unique manner. It gives a distinct variation within the operating frequency band. Given a set of training signals, the unique spectral features can be obtained from the most significant commonality. This can be achieved by first forming a correlation matrix among the training signals. Subsequently, singular-value decomposition (SVD) procedure can be applied. The most common feature among the training sets can be identified by a linear combination of the training set using the elements of the eigenvector corresponding to the most significant SVD component as the coefficients of the combination. This signal pattern can then be utilized as the identification feature for recognition of that particular object type.

For GPR systems operating with FM-CW illumination, the image formation procedure is in the multi-frequency tomography format. Thus, the recognition with spectral contents is most suitable because of the structure of the backward propagation image formation algorithm, where the spectral variation of the reconstructed images is readily available. Therefore, with an identification feature pattern corresponding to an object type can be formed for each GPR image with minor modifications to the tomographic image reconstruction algorithm.

This paper includes theoretical analysis of the formulation of the identification features, algorithm structure associated with the backward propagation image reconstruction algorithms, and full-scale experiments with data from field tests.

OBJECT RECOGNITION IN GPR IMAGING

One of the important extensions of GPR imaging is the capability of object recognition. The basic procedure of a recognition task is the matching of the detected signals against the identification pattern. The identification pattern is often termed the ID feature, or ID vector for multi-dimensional cases. The crucial step in object recognition is not necessarily the matching process. Instead, it is the formulation and formation of the ID features, which is the key to the successful execution of the recognition task.

The development of the pattern recognition associated with imaging systems has been largely in the stage of recognizing objects based on two- or three-dimensional spatial features. This approach is based on the functions and concepts of the human visual and perception procedures. However, this technique has limited capability because GPR images are quite different from typical visual images due to the bandwidth, resolution, operating configurations of the data-acquisition systems, as well as the physical interactions between the targets and microwave illumination. Thus, in this paper, we utilize an alternative approach to facilitate the recognition process, which is to operate the recognition procedure based on the spectral statistics at a target position, instead of the spatial features.

The image reconstruction procedure is implemented based on the multi-frequency tomographic version of the backward propagation algorithm. The final image is the superposition of all the coherent sub-images. This means that, at any target location, the spectral content of the superposition is readily available.

As mentioned earlier, the most crucial step is the formation of the ID features, which can be conducted in different ways. One is to formulate the ID features completely based on theoretical models. Another approach is to construct the ID features from a set of so-called training vectors. If feasible, the collection of the training vectors is typically performed through laboratory experiments in a controlled manner to ensure high accuracy. Previous results have shown that when trained correctly, the SVD method can reach equilibrium in as few as 50 training sets. Yet, when the theoretical model or laboratory experimental data are not available, field-test data can be used as the training vectors, which is common in practice.

The most common and robust approach to the formation of an ID vector from a set of training vectors is direct averaging. In many applications, it is adequate in terms of accuracy and convergence especially when the training data are obtained in controlled laboratory experiments and the data size is sufficiently large. When we utilize field-test data for training, this approach is often ineffective due to the phase perturbation associated in wave propagation and variation of magnitude due to different range distances. Thus, instead, a SVD technique is used for the training process for improved accuracy and consistency.

From a set of training vectors, we first form a cross-correlation matrix R from corresponding data to one unique target type. *R* is an NxN square Hermitian-symmetric matrix and the elements of the matrix represent the correlation among the training vectors.

$$R = E\{ SS^H \} \quad (1)$$

where S is the vector representing the collection of training vectors. Subsequently, a SVD is performed and the correlation matrix R is partitioned in the form of

$$R = U \Lambda U^H \quad (2)$$

where U is the orthonormal matrix, which is the collection of the eigenvectors, and Λ is a square matrix and its diagonal elements are the singular values. The variation of the singular values provides important information in terms of the quality of the training vectors. If the training vectors are of good quality, the singular values will be clustered with one or very few dominant components. If the training vectors are not well correlated, the singular values spread. This also means the magnitude of the most significant singular value is an indication of the level of commonality among the training vectors, which represents the degree of confidence as well as the upper bound of the recognition process.

Subsequent to the decomposition, the elements of the eigenvector corresponding to the most significant singular value are used as weighting coefficients of the linear combination of the training vectors to form the ID vector of the corresponding object type,

$$s^* = s_1/u_{11} + s_2/u_{12} + \ldots + s_N/u_{1N} \qquad (3)$$

where u_{1k} is the kth element of the eigenvector corresponding to the most significant singular value. In practice, the elements can be complex. The magnitude of the elements provides the normalization factor to equalize the variation among the training vectors and the phase provides the correction of various phase perturbations in wave propagation and data acquisition.

As we complete the backward propagation image formation procedure, a GPR image is formed. If any particular location is of interest, it can be selected for the recognition procedure. Once a target location is selected, the algorithm traces back to obtain its spectral contents prior to the superposition process to be used as the test vector. Then the test vector is normalized and matched against the ID vector by a simple inner-product operation. Since both the test and ID vectors are normalized, the magnitude of the inner product is bounded between 1.0 and zero, which represents the probability of the match.

It should be noted that the recognition produces a quantitative indicator as the probability of the match, instead of the traditional binary outcomes in many recognizers, which provides the opportunity for further analysis and investigation. In many GPR field operations, this technique provides (1) the confidence level of the ID vector from the magnitude of the most significant singular value and (2) the numerical results of the matching process, which is proven to be of great importance. It should be also pointed out that the computation of the recognition procedure is the inner product of the normalized spectral content of a particular location with the ID feature. Thus, the result of the recognition process is independent of the variations in the image profiles.

The technical description of this section is focused on the formation of ID vector and matching operation corresponding to one object type. Yet, with minor modifications, this concept can be extended to the recognition tasks for multiple object types by expanding the SVD procedure to analyze the commonality as well as difference among the ID vectors corresponding to multiple object types for further improvement of the performance of the recognition tasks.

EXPERIMENTS AND RESULTS

To evaluate the feasibility of object recognition with GPR imaging systems practice, the object recognition algorithm was applied to identify buried specimens underground. The SVD training approach was selected for the experiments to formulate the identification feature of the recognition process. Then the identification features are subsequently incorporated into the image reconstruction process.

A a field test, forensic specimens were buried at two locations and GPR data were acquired on a monthly basis over a period of 24 months. The data acquisition process was conducted at the Anthropological Research Facility operated by the University of Florida. The stepped-frequency GPR system was operating over the spectral range of 200-700 MHz with 85 frequency steps. A 6.1 meter by 4.9 meter grid was constructed over the test site. Ten transects were taken at each site with the middle two transects crossing over the width of the test side. Data were acquired with an increment of 15cm along each gridline and 60cm spacing between grid lines. The initial results successfully demonstrated the feasibility of detecting the specimens.

The utilization of recognition procedure in conjunction of the image reconstruction algorithm results in a significant reduction of false-target identification rate. The object recognition image shows the correlation between the target's spectral content and the identification feature with a *percent match*. The percentage-match indicator provides added flexibility to visualization.

Figure (1): Florida test site with data collection grid marked.

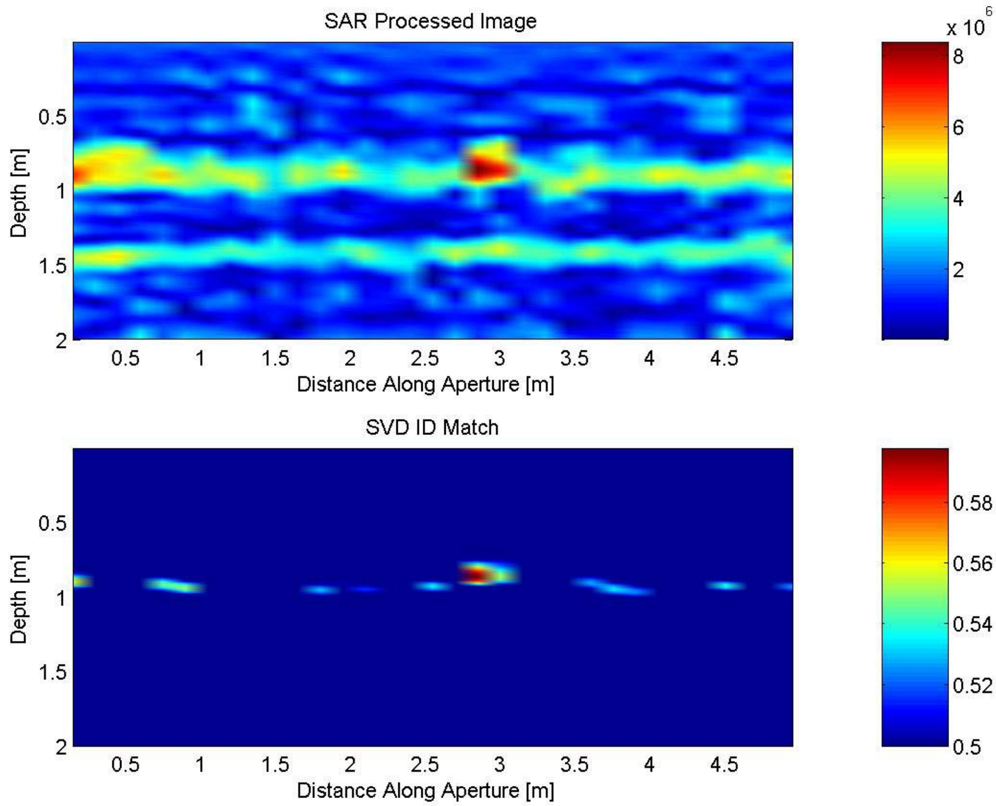

Figure 1: (top) Image formed by backward propagation algorithm.
(bottom) Resultant profile of recognition process.

CONCLUSION

This paper describes an important extension of the GPR imaging capability into object recognition. Instead of the conventional recognition techniques by spatial features and shapes, this approach is based on the spectral feature of the object within the operating frequency band. Because of the unique computation structure of the backward propagation image reconstruction algorithm, the object recognition process can be fully integrated into the overall image formation process without substantial increase of computation complexity.

ACKNOWLEDGMENT

This research was supported by the US Department of Energy.

REFERENCES

[1] Koppenjan, S. K., Allen, C. M., Gardner, D., Wong, H., Lee, H., and Lockwood, S. J., Multi-frequency synthetic-aperture imaging with lightweight ground penetrating radar systems, *Applied Geophysics*, 43, pp. 251-258, 2000.

[2] Lockwood, S. J. and Lee, H., Pulse-echo microwave imaging for NDE of civil structures, image reconstruction, enhancement, and object recognition, *International Journal of imaging systems and technology*, 8(4), 407-412, 1997.

[3] Lee, H., Formulation of the generalized backward projection method for acoustical imaging, *IEEE Transactions on Sonics and Ultrasonics*, 31(3), pp. 157-161, 1984.

[4] Lee, H., Acoustical image reconstruction algorithms: structure, performance sensitivity, and limitation, *Proceedings of 1987 SPIE International Symposium on Pattern Recognition and Acoustical Imaging*, vol. 768, pp. 34-43, 1987.

[5] Mast, J., Lee, H., Chew, W., and Murtha, J. P., Pulse-echo holographic techniques for microwave subsurface NDE, *Proceedings of the Conference on Nondestructive Evaluation of Civil Structures and Materials*, pp. 177-191, 1990.

[6] Mast, J., Lee, H., and Murtha, J. P., Application of microwave pulse-echo radar imaging to the nondestructive evaluation of buildings, *International Journal of Imaging Systems and Technology,* 4(3), pp. 164-169, 1992.

[7] Mast, J., Lee, H., and Murtha, J. P., "High-resolution microwave subsurface nondestructive evaluation of civil structures and materials", *International Advances in Nondestructive Testing,* vol. 17, 207-250, 1994.

[8] Gibson P.J. "The Vivaldi Aerial" *Conference proceedings of the 9th European Microwave Conference*, pp. 101-105, 1979.

[9] Koppenjan, S.K., Schultz, J.J., Falsetti, A.B., Collins, M.E., Ono, S. and Lee, H., "The Application of GPR in Florida for Detecting Forensic Burials", *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems* (SAGEEP), 2003.