Elongated Object Orientation Estimation Based on Deep Neural Networks

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***Abstract*— The horizontal and vertical orientation angles of an elongated subsurface object are key parameters for object identification and imaging in ground-penetrating radar (GPR) applications. Conventional methods can only extract the horizontal orientation angle or estimate both angles in narrow ranges. To address these issues, we present a multi-polarization aggregation and selection neural network (MASNet) to estimate both angles of an elongated subsurface object in the entire spatial range. The network takes the multi-polarimetric radargrams as inputs, integrates their characteristics in the feature space, and selects discriminative features of reflected signal patterns for accurate orientation estimation. Numerical results show that the MASNet achieves high estimation accuracy with an angle estimation error of less than 5°. The promising results obtained in the study encourages new solutions for GPR-related tasks by integrating multi-polarization information with deep learning techniques.**

Keywords—ground-penetrating radar; multi-polarization; multi-mask neural network; orientation estimation; elongated subsurface object

I. Introduction

Ground-Penetrating Radar (GPR) has been widely used as a non-destructive method to detect or image subsurface objects. When detecting elongated targets such as metal bars, pipes, and tree roots, the information on the objects' horizontal and vertical orientations greatly facilitates the mapping of the underground environment [1].

Traditional method to estimate the objects' orientation angles is to scan multiple parallel traces to reveal the objects' extension direction [2]. However, it is time-consuming and less practical in complex terrains. Alford rotation algorithm was leveraged to extract elongated objects' horizontal orientation based on the depolarization property of the elongated objects [3], [4]. Eigenvalues of the scattering matrix were also used to find the horizontal orientation angle of the major axis of unexploded ordnance targets [5]. To extract both the horizontal and vertical angles of an underground elongated object, a mathematical model was formulated in [1], which links the characteristic hyperbolic reflection shape with the object orientation angles.

The aforementioned conventional methods, however, fail to estimate both the horizontal and vertical angles in the entire spatial range. To be specific, the Alford rotation algorithm and the eigenvalue method can only estimate the horizontal angle but not the vertical angle, and the mathematical model only estimates the horizontal and vertical angles in a constrained range of 0°-90° and 0°-45°, respectively. Therefore, it is still a challenge to accurately and simultaneously estimate both horizontal and vertical angles of an elongated underground object.

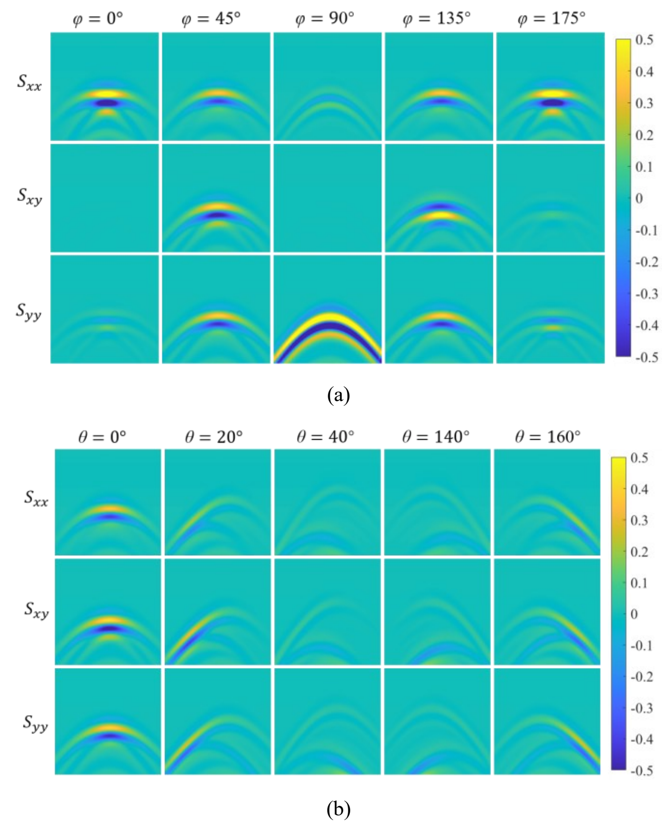

Fig. 1. B-scan images of the scattering components S_{xx}, S_{xy}, and S_{yy} in the cases of (a) $\theta = 0°$, φ changes, and (b) $\varphi = 45°$, θ changes.

In this work, we propose a multi-polarization aggregation and selection neural network (MASNet) to integrate the information carried in multi-polarimetric scattering components for the accurate estimation of horizontal and vertical angles of an elongated subsurface object. Numerical experiments demonstrate that the trained MASNet can automatically and accurately estimate the orientation angles with a maximum error less than 5° in the entire spatial range, which outperforms the conventional methods.

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II. METHODOLOGY

When using multi-polarimetric GPR system to detect an elongated subsurface object, different scattering components show different responses due to the depolarization property of the elongated object. Fig. 1 show the B-scan images of the scattering components S_{xx}, S_{xy}, and S_{yy} when detecting a finite-length metal bar at different horizontal angle φ and vertical angle θ. As can be observed, the three scattering components S_{xx}, S_{xy}, and S_{yy} show different reflection intensity and reflection shape to object with different φ and θ. Also, the orientation information they carry complement each other. Therefore, it is necessary to take the complementary information into account simultaneously to accurately estimate both the horizontal and vertical angles of an elongated object.

The MASNet is specially designed to make full use of the complementarity and specificity of different polarization components for accurate estimation of horizontal and vertical angles of an elongated object. The network structure of MASNet is shown in Fig. 2. To be specific, the MASNet includes three parts: 1) *multi-polarimetric feature aggregation* to extract the features from the input multi-polarimetric data, 2) *distinguished feature selection* to suppress the redundant information and select more distinguished features for orientation estimation, and 3) *multi-task angle estimation* to simultaneously estimate the horizontal and vertical angles.

The mean squared error (MSE) is used as the loss function to drive the optimization of the MASNet, which is expressed as:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}((H_i - gtH_i)^2 + (V_i - gtV_i)^2), \qquad (1)$$

where N is the number of training data, H and V stand for the estimated horizontal and vertical angle, respectively. The corresponding ground truth is represented by gtH and gtV.

III. NUMERICAL RESULTS

To train the MASNet, 1260 sets of B-scan images of a subsurface metal bar with different horizontal and vertical orientation angles (φ, θ) are generated using gprMax [6]. Each set contains the images of the scattering components S_{xx}, S_{xy}, and S_{yy}. Each image is resized to 64×64 and normalized into [0, 1]. 60 sets of B-scan images of the metal bar with random orientation angles are generated as the testing data. The testing images are also normalized and resized to 64×64.

The well-trained MASNet is used to estimate orientation angles of the 60 sets of testing data. 8 estimation results are listed in Table I for illustration. The estimation accuracy of all 60 estimation results is evaluated using mean absolute error (MAE) of the angles in degree. The average MAE for φ and θ are 1.2° and 0.9°, respectively. The maximum angle difference between the true angle and the estimated angle is less than 5°, showing unprecedented high accuracy. The numerical results prove that the MASNet can achieve accurate 3-dimensional orientation estimation.

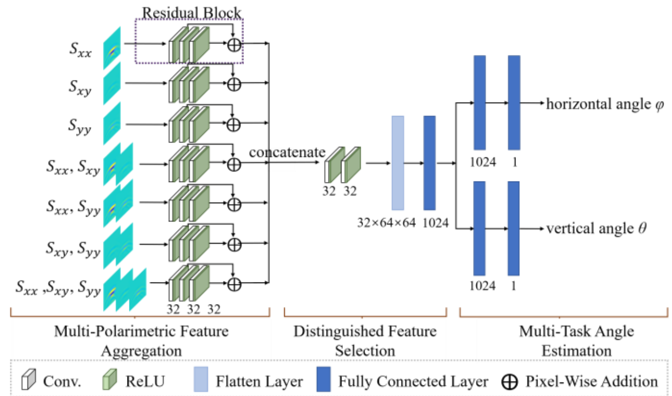

Fig. 2. The framework of the MASNet.

TABLE I
8 EXAMPLES OF THE ESTIMATED (φ, θ)

True angles	Estimated angles	True angles	Estimated angles
(16°, 135°)	(15.0°, 135.3°)	(26°, 26°)	(28.2°, 24.2°)
(33°, 66°)	(32.8°, 66.0°)	(46°, 152°)	(44.7°, 154.0°)
(71°, 157°)	(70.0°, 155.3°)	(91°, 60°)	(90.5°, 61.7°)
(113°, 132°)	(111.8°, 133.3°)	(166°, 126°)	(162.5°, 126.9°)

IV. CONCLUSION

In this paper, we present a novel neural network architecture for estimating orientation angles of an elongated subsurface object. The network learns the relationship between the object orientation and the reflected signal patterns in multi-polarimetric radargrams. Numerical experiments show that the network is capable of accurately estimating the orientation angles of the corresponding target with multi-polarimetric radargrams as inputs. Compared with conventional methods, the proposed method achieves the highest estimation accuracy and covers the entire spatial angle ranges.

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