A Migration-Assisted Deep Learning Scheme for Shape and Permittivity Reconstruction of Tree Defects

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***Abstract*—This paper proposes a migration-assisted deep learning scheme to reconstruct the positions, shapes, and permittivities of trees' internal defects via radar B-scans. First, a structural similarity index measure (SSIM)-based autofocusing technique (AFT) is proposed to determine the effective permittivity of tree trunk's wood layers. The migrated image obtained via setting the effective permittivity retains most of the shape information of the defect. Then, a U-shaped convolutional neural network with the multiple receptive field module is used to denoise the migrated image and reconstruct the shape and permittivity of irregular defects. The preliminary results demonstrate that the proposed scheme successfully reconstructs the images of the tree defects with a mean square error of 0.0059 and an SSIM of 0.9283.**

I. Introduction

The radar has been widely used for the health screening of trees. Recent studies have demonstrated that migration-based imaging techniques, such as the modified Kirchhoff migration [1], are capable of tentative shape reconstruction of the internal defects of tree trunks. However, these techniques cannot retrieve the permittivity information of the defect, which could be highly useful for assessing the type of defect (cavity/decay) and its severity (for decays). Although the full-wave inversion overcomes such a drawback, its high computational cost due to the iterative execution of the forward solver makes it inapplicable for real-time reconstruction of the defects [2]. To this end, current imaging techniques applied to tree defect imaging either provide inaccurate shape reconstruction without permittivity information or are computationally costly.

Deep learning techniques have proven their capability for real-time reconstruction of subsurface objects' shapes and permittivities. However, several challenges hinder their direct application to imaging tree defects. In particular, the host medium around subsurface objects is usually regarded as homogeneous or 'partially' heterogeneous media [3, 4]. On the other hand, the host medium around tree defects consists of dense, concentric, and irregular wood layers. The multiple reflections from these layers disguise the signatures of the reflections from the defects in the B-scans, resulting in inaccurate inversion of defects. Moreover, while subsurface targets are often assumed objects with canonical shapes, the internal defects of tree trunks are crafted totally in random shapes by nature. To this end, robust deep learning schemes are needed for imaging irregular tree defects within irregular concentric tree layers.

This study proposes a migration-assisted deep learning scheme for accurately reconstructing the shape and permittivity of irregular tree defects. In the proposed scheme, a structural similarity index measure (SSIM)-based autofocusing technique (AFT) is first proposed and used to determine the proper effective permittivity of the trees' layers. The migrated image obtained using this effective permittivity contains most of the boundary information of the irregular defect. Next, the migrated image is inputted to a U-shaped convolutional neural network with multiple receptive field modules, called MRF-UNet, which removes the distortion induced by the noise and clutter in the B-scan and reconstructs the permittivity and shape of the defect with high precision. Our preliminary results show that the proposed scheme achieves a mean square error (MSE) of 0.0059 and an SSIM of 0.9283 for permittivity and shape reconstruction of irregular defects inside tree trunks with multiple layers. The performance comparison of the network with different inputs reveals the significance of embedding the proposed SSIM-based AFT in the scheme, which enhances the performance of the scheme by 4.51% and 39.80% in SSIM and MSE, respectively.

II. Methodology

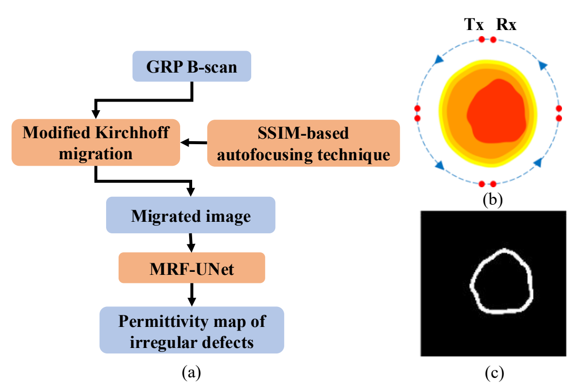


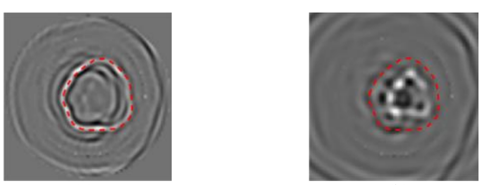
Figure 1. (a) The flow chart of the proposed migration-assisted deep learning scheme, (b) the circular scanning of a tree trunk, and (c) the ring mask of the defect in the tree trunk.

The flowchart of the proposed scheme is shown in Fig. 1(a). The B-scan of a tree trunk is first obtained by moving a pair of transmitter (TX) and receiver (RX) along a circular trajectory [Fig. 1(b)]. Then, modified Kirchhoff migration [1] is employed to migrate the signals in the B-scan to the true positions of the sources on the boundaries of defects. To achieve that, the effective permittivity of the layered tree trunk has to be known and is determined by the proposed SSIM-based AFT. In this technique, the migration is executed for a range of permittivity values and the SSIM between each migrated image and a ring mask that preserves the edge of the defect is evaluated. The ring mask is generated by first detecting the edge of the defect via an edge detector and then expanding the single-pixel detected boundary to a ring with a certain thickness [Fig. 1(c)]. Once the set of SSIM of all permittivity candidates is calculated, the permittivity value yielding maximum SSIM is assigned as the effective permittivity of the wood layers, and the corresponding migrated image is inputted to the MRF-UNet.

In the second stage, the MRF-UNet [4] denoises the input migrated image and outputs the image of the tree defect with accurate shape and permittivity. The network includes an encoder-decoder structure with skip connections in between. The MRF module is the fundamental component in both encoders and decoders, which captures the global features with high-level semantic information and perceives the local features with high precision. The MSE calculated using the true and predicted images serves as the loss function to optimize the parameters of MRF-Net.

III. Results and Discussions

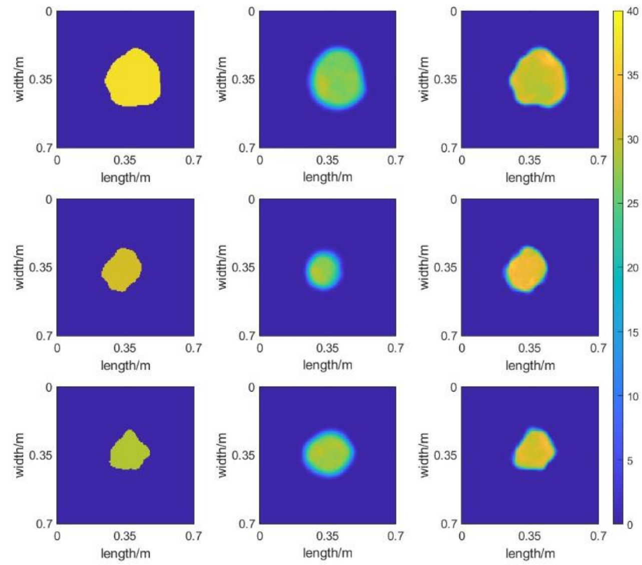
To test the performance of the proposed scheme, an open-source 3-D forward solver is executed to generate 1500 sets of B-scans of 3-D layered tree trunks with internal defects. A Hertzian dipole (TX) transmits a Ricker signal with a center frequency of 1.5 GHz and the receiver (RX) is positioned 5 cm away from TX. Before applying the migration, preprocessing techniques, including direct coupling removal, time-zero, and singular value decomposition, are applied to remove the clutter and reveal the signatures of the reflections from the defects. The migrated image obtained by the proposed SSIM-based AFT successfully reveals the defect's shape, as shown in Fig. 2(a). However, the image generated using the conventional entropy-based AFT [Fig. 2(b)] can roughly reveal the location of the defect.



(a) (b)

Figure 2. Migrated image processed by (a) the proposed SSIM-based and (b) entropy-based AFTs.

Furthermore, the images of three defects predicted by the MRF-UNet are shown in Fig. 3. Both irregular shape and corresponding permittivity map in Fig. 3(c), obtained by the proposed MRF-Unet with SSIM-based AFT migrated input image, are closer to the ground truth in Fig. 3(a). On the other hand, the performance of the MRF-Unet with conventional entropy-based AFT migrated input image is largely degraded (in Fig. 3(b)). The quantitative comparison in Table I indicates that the proposed SSIM-based AFT improves the performance of the scheme by 4.51%, 39.80%, and 32.23% in SSIM, MSE, and MAE compared to entropy-based AFT, respectively.



(a) (b) (c)

Figure 3. Permittivity maps of the irregular defects: (a) Groud truth and predicted image by MRF-UNet with (b) entropy-based AFT migrated input image and (c) the proposed SSIM-based AFT migrated input image.

Table I. Performance Metrics of the MRF-Unet with Different Migrated Input Images

Migrated image obtained by	SSIM (↑)	MSE (↓)	MAE (↓)
Entropy-based AFT	0.8882	0.0098	0.0242
SSIM-based AFT	0.9283	0.0059	0.0164

IV. Conclusion

In this study, a migration-assisted deep learning scheme for reconstructing the permittivity maps of tree defects was proposed. The numerical results and comparative studies demonstrated the capability and performance of the scheme for imaging the tree defects.

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