Two-Stage Deep Learning Algorithm for Reconstructing the Permittivity Maps in Through the Wall Imaging Scenarios

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Through-wall imaging (TWI) plays a crucial role in applications such as security, search and rescue operations, and infrastructure inspection. Traditional TWI methods face limitations such as low resolution, susceptibility to noise interference, and high computational demands. Ground-penetrating radar (GPR) has emerged as a promising alternative to conventional TWI technologies due to its portability, relatively rapid data processing, and potential for high-resolution imaging (M. Saad, A. Maali, M. S. Azzaz, A. Bouaraba, and M. Benssalah, "Development of an IR-UWB radar system for high-resolution through-wall imaging," *Progress In Electromagnetics Research C*, vol. 124, pp. 81–96, 2022.). However, the raw data acquired using GPR is often significantly affected by noise, necessitating advanced signal processing techniques to extract meaningful information. Recent advancements in deep learning, particularly convolutional neural networks (CNNs), have shown remarkable effectiveness in processing noisy data and modeling complex nonlinear relationships (M. Küçükdemirci and A. Sarris, "GPR data processing and interpretation based on artificial intelligence approaches: future perspectives for archaeological prospection," *Remote Sensing*, vol. 14, no. 14, July 2022). Integrating GPR with deep learning methods represents a powerful synergy to overcome the inherent limitations of the traditional GPR. To date, no study has demonstrated such synergy for denoising GPR data and accurately reconstructing the permittivity maps of objects behind walls in the context of TWI.

This study proposes a two-stage deep learning framework combining signal processing with U-shaped CNNs (UNet) and multiple receptive fields (MRF), termed MRF-UNet (Q. Dai, Y. H. Lee, H. H. Sun, G. Ow, M. L. M. Yusof, and A. C. Yucel, "DMRF-UNet: A two-stage deep learning scheme for GPR data inversion under heterogeneous soil conditions," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 8, 2022). In the first stage, the MRF-UNet denoises raw GPR data, significantly reducing noise from surrounding structures and walls and yielding focused hyperbolic signatures of objects behind the walls. The F-K migration algorithm then localizes these objects by identifying their positions, mitigating ambiguities caused by noise. These migrated outputs serve as inputs for the second stage, where the same MRF-UNet structure reconstructs the permittivity maps of the objects. The framework employs multi-stage loss training, with 20% of the dataset used for denoising and the remaining 80% for permittivity reconstruction. Preliminary results show that, compared to fully data-driven approaches relying on noisy GPR data, the proposed method achieves a 24.25% increase in structural similarity index and an 8.79% decrease in mean squared error, significantly improving imaging accuracy.