Guest Editorial
Artificial Intelligence: New Frontiers in Real-Time Inverse Scattering and Electromagnetic Imaging

UNDERSTANDING and solving complex problems in the physical world has been an intelligent endeavor of humankind. Moreover, the study of artificial intelligence (AI) embodies the dream of designing machines like humans. Research in deep-learning (DL) techniques has attracted much attention in many application areas. With the help of big data technology, massive parallel computing, and fast optimization algorithms, DL has greatly improved the performance of many problems in speech and image processing, power transportation networks, and bio-electromagnetics, among others.

Nowadays, DL is rapidly emerging in the antennas and propagation community as an extremely powerful paradigm for solving high-complexity electromagnetic inverse scattering (IS) and imaging problems with unprecedented computational efficiency without sacrificing accuracy and reliability.

As a matter of fact, DL is a promising solution to achieve accurate pixel-wise reconstructions with real-time estimation performance, a desirable feature in many applications such as biomedical imaging, works of art and archaeological inspection, industrial nondestructive testing and evaluation, trough-the-wall imaging, and subsurface imaging. With the spreading of DL techniques, improvement in learning capacity may allow machines to "learn" from a large amount of physical data and "master" the physical laws under controlled boundary conditions.

The objective of this Special Issue is to report recent advancements in theory and applications of AI, machine learning (ML), and DL to solve electromagnetic IS and imaging problems within the research scope of antennas and propagation with extremely fast but reliable techniques. With this Special Issue, we hope to bring more attention and research efforts in our society to this emerging multi-disciplinary field, resulting in an evolution of the state of the art. It features 19 works from top research teams spread worldwide. An overview of such articles is given in the following to help the reader in having a clear summary of the different contributions.

I. Overview of the Special Issue

A. Methodological Papers

In [A1], Guo *et al.* propose an innovative physics-embedded deep neural network (DNN) to solve electromagnetic (EM) forward scattering problems (FSPs) with high computational efficiency. More in detail, the conjugate gradient method, traditionally used to solve the volume integral equation (VIE), is unfold into an iterative DNN capable of accelerating the computation of the total field within a 2-D domain starting from the incident field and the dielectric profile within it. To embed wave physics into the network, the Green's function is exploited as an explicit operator to describe wave physics and inject *a-priori* knowledge on the scattering problem. The results clearly indicate that the proposed methodology is effective and computationally efficient, with problem-scale independent capabilities, being for such a reason a promising candidate for the DNN-driven fast solution of inverse scattering problems (ISPs). As a matter of fact, the same team of researchers described in [A2] how to effectively embed such a DNN-assisted forward solver within an IS network. The arising imaging methodology is capable of outputting accurate guesses of the unknown scatterers, achieving super-resolution reconstructions with high computational efficiency. Both numerical and experimental benchmarks assess the capabilities of the developed data-driven and physics-assisted method, opening the doors to robust and reliable real-time microwave imaging (MI).

Within this framework, Luo *et al.* propose in [A3] a novel two-step DNN-based methodology for solving phaseless-data ISPs. More specifically, a phase retrieval network (PRNet) and an image reconstruction network (IRNet) are cascaded to 1) recover both the magnitude and the phase of the scattered field starting from the measured magnitude of the total field and to 2) retrieve an image of the investigation domain from such guesses. The physical relationship between the EM field and the unknown constitutive parameters is reserved thanks to the exploitation of a complex-valued DNN architecture. Both numerical and experimental results verify the high efficiency, robustness, and generalization capabilities of the method, which exhibits high accuracy when dealing with strong scatterers, as well.

Following a different approach, Sabbaghi *et al.* discuss in [A4] how to design a DNN-based strategy for efficiently predicting the number of conducting wires randomly located within the investigation domain. Towards this end, a convolutional neural network (CNN) is exploited to build a reliable supervised (data-driven) predictor solving a classification problem where the unknown number of wires (N) is *a-priori*

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upper-bounded. The reported results clearly verify the accuracy of the method, which is able to reach an accuracy of 96% when $N \leq 10$.

An innovative MI framework has been presented by Ruiz *et al.* in [A5] for the effective, reliable, and user-independent shaping of unknown targets starting from the collected scattered field. More precisely, a U-Net DNN architecture is combined with a qualitative reconstruction method (i.e., the orthogonality sampling method, OSM). Thanks to the proposed approach, it is possible to avoid case-dependent and user-biased results due to the traditional manual hard-thresholding of the OSM results, by letting the DNN automatically separate the targets from the background. The good performance of the proposed DNN-assisted qualitative imaging approach has been verified with both synthetic and experimental data.

Another interesting DL framework to solve ISPs integrating a complex-valued convolutional neural network (DConvNet) into the supervised descent method (SDM) is proposed by Yao *et al.* in [A6]. After the offline training phase, high-accuracy reconstructions are efficiently yielded in the online step exploiting the learned descent directions by the SDM and the real-time DConvNet forward scattering predictions.

Chen *et al.* propose in [A7] a new semi-physics-driven artificial neural network (ANN)-based method for solving ISPs. The method consists of cascading two sub-nets, the first of which aims at converting the scattered field to a preliminary coarse guess of the dielectric permittivity in the investigation domain. Then, such a guess is input to the second sub-net to further refine the unknown target profile. To inject EM physics within the inversion loop, the approximate sensitivity matrix is embedded within the first sub-net, whose parameters are fixed and not determined from training data. Thanks to such a strategy, robust and reliable guesses of the unknown targets can be yielded with a significantly lower amount of training samples with respect to a purely data-driven DL inversion method.

The MI of hybrid scatterers made of arbitrary combinations of dielectric parts and perfect electric conductors is dealt within the DL framework by Song *et al.* in [A8]. Toward this end, the solution of ISPs with mixed boundary conditions is performed by effectively combining the back propagation (BP) method with an attention-assisted generative adversarial network (GAN). More specifically, the BP retrieves a rough image of the zero-order T-matrix coefficients, which is then refined by the GAN, where a spatial attention mechanism is exploited to enforce the learning of salient high-level features of the unknown scatterers, resulting in high-accuracy images with both numerical and experimental data.

The solution of 3-D ISPs with dielectric anisotropic scatterers is addressed by Fei *et al.* in [A9]. A novel DNN-based method relying on a Residual U-Net (ResU-Net) is proposed by replacing the conventional CNN convolution kernels with residual kernels. After a preliminary off-line training phase, during the online test phase, such a ResU-Net is exploited to instantaneously invert multiple anisotropic model parameters of 3-D homogeneous unknown objects. Moreover, the ResU-Net is combined with a variational Born iterative method to enable the computationally effective imaging of inhomogeneous or multiple homogeneous targets.

Finally, an innovative System-by-Design (SbD)-based method is presented by Salucci *et al.* in [A10] for the computationally-efficient AI-driven solution of fully nonlinear ISPs. Thanks to the SbD, the effective, robust, and time-efficient exploitation of an evolutionary algorithm (EA) is enabled for the global minimization of the data mismatch cost function. Toward this end, a smart re-formulation of the ISP based on the *a-priori* information on the unknown targets is exploited to define a minimum-dimensionality and representative set of degrees-of-freedom. Then, the AI-driven integration of a customized global search technique with a fast digital twin predictor is exploited to effectively and efficiently invert both synthetic and real scattering data.

B. Applicative Papers

In [A11], Shao and Zhou propose the use of a GAN to generate 2-D virtual breast phantoms that are similar to the real ones, which can be used to develop ML-based microwave breast imaging (MBI). Each phantom consists of several images with each representing the distribution of a dielectric parameter in the breast map. This approach permits to obtain the large number of digital dielectric breast phantoms required in ML-based MBI for the training set, difficult to be achieved from practice. With the GAN-based approach developed in this work, one may generate an unlimited number of breast images with much more variations than with traditional strategies.

Still, in the field of application of breast imaging, CNNs are proposed in [A12] by Quin *et al.* to achieve joint inversion of microwave and ultrasonic data. Source and field quantities, obtained via backpropagation, are used as inputs. Thus, the network outputs the distribution maps of electric and acoustic parameters directly to achieve real-time imaging. The authors test the network with simulations on breast phantoms extracted from a repository. The results show that with both microwave and ultrasonic data, a proper estimation of the breast structure and detection of small tumors can be achieved.

In order to improve the resolution of imaging techniques, in [A13], Xiao *et al.* propose a hybrid neural network electromagnetic inversion scheme (HNNEMIS) with shallow and deep neural networks. It is applied to solve super-resolution 3-D electromagnetic inversion for microwave human brain imaging, alleviating the required huge computational costs and solving this high-contrast ISP. The authors propose a semi-join back propagation neural network (SJ-BPNN) for nonlinearly mapping of the measured scattered electric field to two output channels (i.e., permittivity and conductivity of the scatterers). Then, the U-Net is employed to further enhance the imaging quality of the output from SJ-BPNN.

Considering a different application, in [A14], Tan *et al.* propose an ML-based method for real-time, high-accuracy and efficient classification method on frequency-modulated-continuous-wave (FMCW) automotive radar in the 77 GHz band. They establish the mapping relationship from the physical space to the range-Doppler (R-D) image, so they extract four relevant physical features of targets, such as speed, reflectivity, area, and incidence angle. Starting from them, the classification is performed into five categories, including pedestrian, bike, sedan, truck/bus, and other static objects. The overall accuracy bof the real data is about 99% even with complex multiple-target cases.

A novel application shown in this Special Issue is the classification of pottery in the framework of archaeology studies, as proposed by Zidane *et al.* in [A15], using Low-Terahertz measurements in the D-band. The authors process the measurements and then the result is classified with an optimized multilayer perceptron with up to 99% of accuracy. The technique is useful to develop compact and portable systems for the pottery classification instead of current required and bulky equipment such as Computerized Tomography scanners or synchrotrons.

In [A16], Dai *et al.* propose a two-stage DNN, called DMRF-UNet, to reconstruct the permittivity distributions of subsurface objects from ground-penetrating radar (GPR) B-Scans under heterogeneous soil conditions. In the first stage, a Ushape DNN with multi-receptive-field convolutions (MRF-UNet1) is built to remove the clutters due to the inhomogeneity of the heterogeneous soil. Then, the denoised B-scan from the MRFUNet1 is combined with the noisy B-scan to be inputted to the DNN in the second stage (MRF-UNet2). The MRF-UNet2 learns the inverse mapping relationship and reconstructs the permittivity distribution of subsurface objects.

Wei *et al.* propose in [A17] a complex-valued U-net (CU-net) to solve ISPs, so that the complex scattered data carrying information of the object can be directly used for inversion without any preprocessing, improving the accuracy of the final result. The performance is demonstrated with a finite periodic set of circular cylindrical dielectric rods, which is detected for textural abnormalities, including missing, flaw, and displacement of the rods. The distances between rods and diameters of rods are both subwavelength, beyond the Rayleigh criterion.

Finally, in order to overcome the classic limitations of using sparse data to reconstruct images, in [A18], Zhang *et al.* propose the application of DL to microwave-induced thermoacoustic tomography (MITAT) with specific application to breast cancer detection. The network proposed is a domain transform network called FPNet+ResU-Net. They demonstrate the technique with both simulation and ex-vivo experiments with breast phantoms, obtaining images with better quality and less artifacts than those obtained by a traditional imaging algorithm.

C. Summary and Discussion

To conclude the Special Issue, a tentative review of recent progress in applying AI, ML, and DL to solve ISPs and imaging problems is presented by Salucci *et al.* in [A19]. After a brief introduction and a description of several AI-assisted inversion frameworks, the authors categorize recent publications into three groups. Fully data-driven learning approaches approximate the IS process with an ML model that maps the measured scattered field into properties of the scatterers. With the help of DNNs and large datasets, this approach has been more powerful than before. Knowledge-assisted learning approaches approximate the IS operators with a combination of data-driven and physics-driven models. The entire procedure is partitioned into several steps. Some steps are modeled based on EM physics while the others are modeled using ML techniques. The choice of the models in each step is determined based on their complexity. This approach improves the learning and generalization ability of the solution procedure, as compared with the fully data-driven approach. Yet, the physics-embedded learning approach incorporates the physical models into the DNNs. This approach provides a way of designing physics-based neural networks suitable to solve problems involving both numerical simulation and data processing. Therefore, it is very suitable for solving IS problems. In this paper, recent progress in the application of DL to solve EM inverse scattering and imaging problems is also reviewed.

In the long run, a hybridization of fundamental physical principles with "knowledge" from big data could unleash numerous engineering applications that used to be impossible due to the limit of data information and the ability of computation. As a result, more advanced IS and electromagnetic imaging techniques can be developed with improved accuracy, robustness, and computational efficiency.

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Appendix: Related Articles

[A1] R. Guo *et al.*, "Physics embedded deep neural network for solving volume integral equation: 2D case," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6135–6147, Aug. 2022.

[A2] R. Guo *et al.*, "Physics embedded deep neural network for solving full-wave inverse scattering problems," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6148–6159, Aug. 2022.

[A3] F. Luo *et al.*, "Cascaded complex U-Net model to solve inverse scattering problems with phaseless-data in the complex domain," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6160–6170, Aug. 2022.

[A4] M. Sabbaghi, J. Zhang, and G. W. Hanson, "Machine learning target count prediction in electromagnetics using neural networks," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6171–6183, Aug. 2022.

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[A6] H. M. Yao, R. Guo, M. Li, L. Jiang, and M. Ng, "Enhanced supervised descent learning technique for electromagnetic inverse scattering problems by the deep convolutional neural networks," *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6195–6206, Aug. 2022..

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[A10] M. Salucci, L. Poli, P. Rocca, and A. Massa, “Learned global optimization for inverse scattering problems—Matching global search with computational efficiency,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6240–6255, Aug. 2022.

[A11] W. Shao and B. Zhou, “Dielectric breast phantoms by generative adversarial network,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6256–6264, Aug. 2022.

[A12] Y. Qin, P. Ran, T. Rodet, and D. Lesselier, “Breast imaging by convolutional neural networks from joint microwave and ultrasonic data,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6265–6276, Aug. 2022.

[A13] L.-Y. Xiao, R. Hong, L.-Y. Zhao, H.-J. Hu, and Q. H. Liu, “A hybrid neural network electromagnetic inversion scheme (HNNEMIS) for super-resolution 3-dimensional microwave human brain imaging,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6277–6286, Aug. 2022.

[A14] K. Tan, T. Yin, H. Ruan, S. Balon, and X. Chen, “Learning approach to FMCW radar target classification with feature extraction from wave physics,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6287–6299, Aug. 2022.

[A15] F. Zidane *et al.*, “Artificial intelligence-based low-terahertz imaging for archaeological shards classification,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 8, pp. 6300–6312, Aug. 2022.

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