

Machine Learning Through Physics-Informed Neural Networks: Progress and Challenges

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Abstract: Physics-Informed Neural Networks (PINNs) represent a groundbreaking approach wherein neural networks (NNs) integrate model equations, such as Partial Differential Equations (PDEs), within their architecture. This innovation has become instrumental in solving diverse problem sets including PDEs, fractional equations, integral-differential equations, and stochastic PDEs. It's a versatile multi-task learning framework that tasks NNs with fitting observed data while simultaneously minimizing PDE residuals. This paper delves into the landscape of PINNs, aiming to delineate their inherent strengths and weaknesses. Beyond exploring the fundamental characteristics of these networks, this review endeavors to encompass a wider spectrum of collocation-based physics-informed neural networks, extending beyond the core PINN model. Variants like physics-constrained neural networks (PCNN), variational hp-VPINN, and conservative PINN (CPINN) constitute pivotal aspects of this exploration. The study accentuates a predominant focus in research on tailoring PINNs through diverse strategies: adapting activation functions, refining gradient optimization techniques, innovating neural network structures, and enhancing loss function architectures. Despite the extensive applicability demonstrated by PINNs, surpassing classical numerical methods like Finite Element Method (FEM) in certain contexts, the review highlights ongoing opportunities for advancement. Notably, there are persisting theoretical challenges that demand resolution, ensuring the continued evolution and refinement of this revolutionary approach.

Keywords: Physics-Informed Neural Networks, Machine Learning, Numerical Methods, Partial Differential Equations.

1. Introduction

Deep neural networks have excelled across diverse domains like remote sensing[1, 2], computer vision[3, 4], risk prevention[5], optimization[6, 7], pattern recognition[3, 8, 9], regression tasks[10] and Hyperspectral Imaging[11-14] are executed. In applied mathematics, the application of deep learning techniques to classical problems, such as partial differential equations (PDEs), marks a significant trend. Traditional numerical approaches become difficult when faced with PDEs featuring substantial nonlinearities, convection dominance, or shocks. Enter deep learning, presenting a new paradigm in scientific computing due to the remarkable universal approximation and expressiveness of neural networks. Recent studies underscore the potential of deep learning in constructing meta-models for rapid predictions in dynamic systems, adeptly capturing intricate nonlinear input-output relationships. Yet, grappling with the intricacies of high-dimensional complex systems encounters the challenge of dimensionality, a hurdle notably articulated by Bellman in optimal control problems. Nevertheless, machine learning-based algorithms offer promising prospects for tackling PDEs [15].

Forecasts suggest that machine learning-driven PDE-solving methods will remain a focal point as deep learning evolves through methodological, theoretical, and algorithmic advancements[15, 16]. Early attempts at solving differential equations employed simplistic neural network models like Multi-Layer Perceptron's (MLPs) with minimal hidden layers[17]. Contemporary approaches, leveraging NN techniques, harness optimization frameworks and auto-differentiation techniques, exemplified by Berg and Nyström's unified deep neural network method for estimating

PDE solutions[16, 18, 19]. Additionally, the envisioned potential of deep neural networks to construct interpretable hybrid Earth system models for Earth and climate sciences further underscores their significance[18].

Presently, the literature lacks a standardized nomenclature for integrating prior physical knowledge with deep learning. Terms like 'physics-informed,' 'physics-based,' 'physics-guided,' and 'theory-guided' are variably used. Some researchers[20] introduced a comprehensive taxonomy, termed 'informed deep learning,' organizing it into three core conceptual stages: delineating the type of deep neural network used, representing physical knowledge, and integrating this information. Inspired by their framework, this exploration will delve into Physics-Informed Neural Networks (PINNs), introduced in 2017, elucidating how neural network features are employed, how physical information is incorporated, and which physical problems have found resolution within the literature.

2. Physics-Informed Neural Networks Concept

Physics-Informed Neural Networks (PINNs) serve as a potent scientific machine learning tool tailored for solving problems entrenched in Partial Differential Equations (PDEs). The crux of PINNs lies in approximating PDE solutions by training neural networks to minimize a loss function that encapsulates critical elements: initial and boundary conditions across the space-time domain, alongside the PDE residual pinpointed at selected collocation points within the domain. These deep-learning networks, constituting PINNs, yield estimated solutions at designated points within a differential equation's integration domain post-training.

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