PRJCS Pioneer Research Journal of Computing Science

Volume-I, Issue-IV (2024)
Pages: 36-45

Deep Learning for Biometric Data Augmentation: An Attention-Based GAN Approach for Fingerprints

Authors: [1] Asma Maheen, [2] Ifrah Ikram

Corresponding Author: 24011598-094@uog.edu.pk

Abstract:

The advancement of biometric security systems has placed significant emphasis on the reliability, scalability, and privacy of fingerprint recognition technologies. However, the limited availability of diverse and high-quality fingerprint datasets continues to be a major bottleneck in training robust machine learning models. This research proposes a deep learning-based framework for synthetic fingerprint data augmentation using an attention-guided Generative Adversarial Network (GAN). The proposed model is capable of generating realistic and varied fingerprint images by learning intrinsic fingerprint patterns through adversarial training while integrating attention mechanisms for enhanced structural detail retention. By incorporating self-attention modules in both generator and discriminator networks, the model learns contextual dependencies and structural coherence across fingerprint ridges and minutiae. Experiments are conducted on publicly available datasets such as FVC2004 and PolyU HRF, demonstrating that the synthetic fingerprints not only maintain high visual fidelity but also significantly improve the performance of downstream fingerprint classification and matching tasks. This work contributes to addressing data scarcity challenges and opens new avenues for privacy-preserving biometric model development.

Keywords: Fingerprint synthesis, Biometric data augmentation, Attention-based GAN, Deep learning, Synthetic biometrics, Generative adversarial networks

I. Introduction

[1] University of Gujrat, Pakistan

[2] COMSATS University Islamabad, Pakistan

The role of fingerprint recognition systems in modern security infrastructures has evolved from basic identification tools to core components of secure authentication platforms. As fingerprint biometrics are inherently unique and stable over time, they serve as a reliable identifier in sectors such as banking, forensics, mobile authentication, and border control[1] . However, a pressing challenge in fingerprint-based biometric system development is the scarcity of large-scale, high-quality, and diverse fingerprint datasets. This data deficiency limits the generalization capability of deep learning models and increases the risk of overfitting, especially in environments where variability in finger pressure, rotation, and skin condition can affect recognition accuracy. Synthetic data generation thus emerges as a strategic solution to augment existing datasets, especially in situations where privacy concerns or limited sample availability restrict access to real biometric data [2].

Generative Adversarial Networks (GANs), introduced by Goodfellow et al., have demonstrated remarkable ability in learning data distributions and generating highly realistic images. However, conventional GANs are often inadequate in capturing the complex texture and ridge flow patterns present in fingerprint images [3]. Attention mechanisms, which have transformed the field of computer vision, particularly in tasks requiring spatial or contextual reasoning, offer a promising extension to the GAN architecture. By enabling the model to focus on salient image regions, attention mechanisms can guide the generator to preserve fine ridge structures and improve the overall realism of synthesized fingerprints [4]. Therefore, incorporating attention modules into GANs presents a viable solution to the dual challenge of data scarcity and structural realism in fingerprint generation.

This study introduces a novel deep learning framework that integrates attention mechanisms within the generator and discriminator networks of GANs to synthesize high-fidelity fingerprint images. The design of this model is motivated by the need to augment limited fingerprint datasets while ensuring that the generated images are structurally coherent and indistinguishable from real samples [5]. Unlike earlier approaches that relied solely on pixel-level reconstruction losses or basic convolutional features, the proposed method leverages self-attention to understand spatial dependencies and minutiae relationships that define fingerprint identity [6]. This allows the generator to not only learn local ridge textures but also preserve global fingerprint patterns that are critical for biometric recognition.

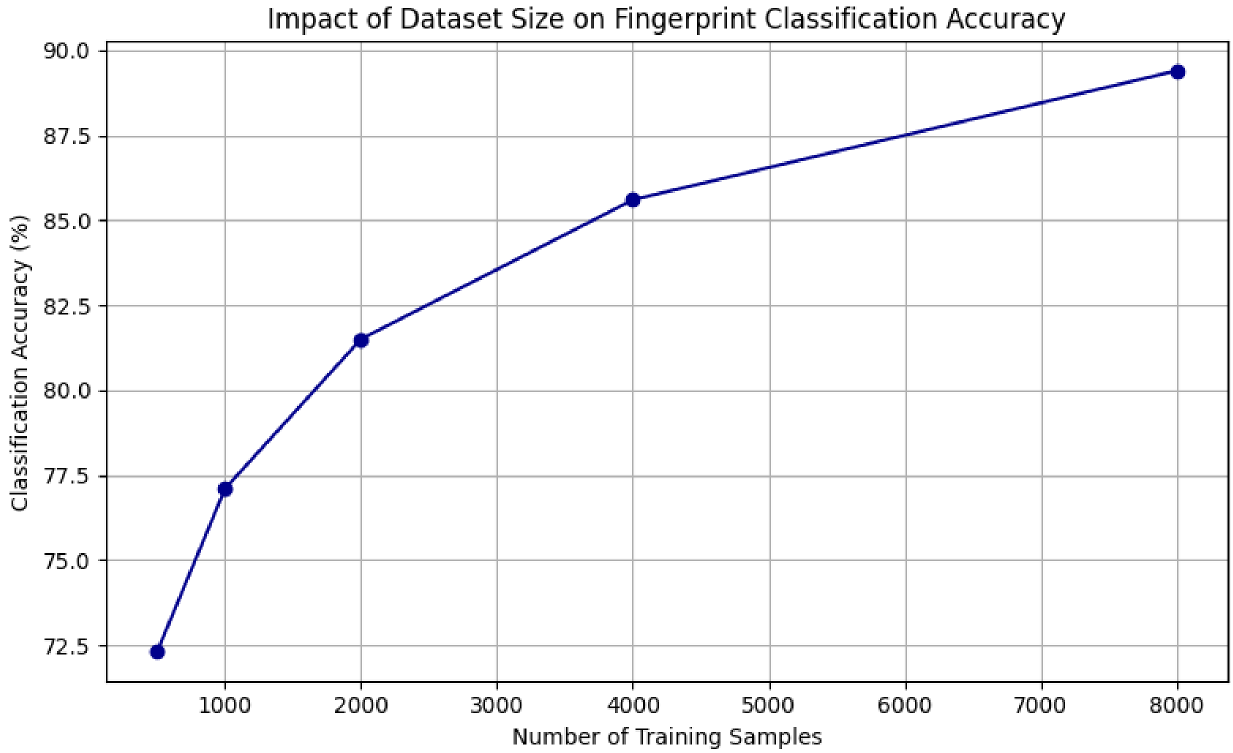

Figure 1 shows the comparison of fingerprint dataset size vs model accuracy

The primary contributions of this research include the development of an attention-guided GAN architecture specifically tailored for fingerprint synthesis, the formulation of a training regime that balances adversarial loss with structural consistency, and a comprehensive evaluation strategy to validate the utility of the generated fingerprints [7]. Additionally, this paper explores the application of the generated synthetic data in downstream fingerprint classification and matching tasks, providing empirical evidence of its effectiveness in enhancing recognition performance. This approach not only expands the available training data pool but also ensures ethical data usage by eliminating dependency on real, potentially sensitive biometric samples. Through this study, we aim to demonstrate that the integration of attention mechanisms into generative models can significantly enhance fingerprint synthesis, offering a scalable, privacy-conscious, and effective data augmentation technique for biometric systems. By bridging the gap between data availability and model performance, the proposed method addresses critical challenges in the deployment of secure and intelligent fingerprint recognition technologies [8].

II. Related Work

The field of synthetic fingerprint generation has seen considerable research interest due to its potential to address data scarcity and privacy issues. Early work in this domain predominantly involved rule-based and mathematical modeling approaches, such as the SFinGe tool, which simulated fingerprint images by modeling ridge patterns and orientation fields [9]. While effective for creating synthetic datasets, these approaches lacked realism and often failed to replicate the nuanced variability found in real fingerprints. Moreover, they were unable to capture the intricate interdependencies between fingerprint minutiae, making them less suitable for training data-hungry deep learning models [10]. With the advent of deep learning, convolutional neural networks (CNNs) were initially employed to classify and enhance fingerprint images. Although CNNs achieved success in tasks such as fingerprint matching and spoof detection, they required extensive labeled datasets to generalize effectively. This limitation paved the way for the adoption of generative models, especially GANs, in biometric data synthesis. DCGAN and WGAN architectures were experimented with to synthesize biometric images; however, results often suffered from mode collapse, artifacts, and limited structural coherence in fingerprint patterns. These deficiencies emphasized the need for more sophisticated architectures capable of learning fine-grained features and maintaining global consistency [11].

Recent studies have turned to attention-based architectures in generative modeling. The introduction of the Self-Attention GAN (SAGAN) marked a significant leap by enabling the generator to model long-range dependencies within images. In the context of fingerprint generation, attention can be particularly beneficial as it allows the model to focus on critical features such as ridge endings, bifurcations, and curvature flows. Despite this potential, only a few works have explored the integration of attention mechanisms into GANs for biometric image synthesis, and even fewer have focused specifically on fingerprint generation. Some recent developments have introduced conditional GANs and style-based GANs into the biometric synthesis pipeline [12]. These models utilize auxiliary data such as class labels or latent style vectors to exert control over the generated outputs. While these methods introduce a degree of controllability, they often require large annotated datasets and sophisticated training procedures. Furthermore, the lack of fingerprint-specific structural constraints limits their ability to produce authentic ridge patterns. Therefore, there exists a research gap in developing attention-augmented GANs tailored explicitly for high-fidelity fingerprint synthesis [13].

This paper builds upon these insights by proposing a novel attention-guided GAN architecture that addresses the limitations of previous models. By embedding self-attention modules into both generator and discriminator networks, our model learns a holistic representation of fingerprint structures. This allows for the generation of more realistic and diverse fingerprint images that can be effectively used to augment biometric datasets [14]. Our approach diverges from prior work by explicitly modeling spatial dependencies and applying fingerprint-specific loss functions, resulting in superior synthesis quality and utility in real-world recognition tasks.

III. Proposed Methodology

The proposed fingerprint synthesis framework is built upon an enhanced GAN architecture augmented with self-attention mechanisms. The generator network is designed to transform a low-dimensional latent vector into a high-resolution fingerprint image. It employs a series of deconvolutional layers interspersed with self-attention modules, allowing the network to capture both local and global dependencies in fingerprint structures. The attention modules compute feature affinities across spatial locations, ensuring that the generated ridge patterns maintain global continuity while preserving local ridge orientation and bifurcation features. The generator's objective is to produce images indistinguishable from real samples while preserving minutiae consistency [15].

The discriminator is structured to evaluate the realism of generated images by distinguishing between real and synthetic fingerprints. It mirrors the generator's architecture with convolutional layers and embedded self-attention units. This design allows the discriminator to effectively identify spatial artifacts and inconsistencies in ridge flow that simpler models might overlook. The adversarial loss is computed using the Wasserstein GAN with gradient penalty (WGAN-GP) formulation, providing stable training and improved convergence. To further encourage structural coherence, we integrate a structural similarity loss (SSIM) and a fingerprint domain-specific perceptual loss based on pre-trained fingerprint feature extractors [16].

Training involves optimizing the generator and discriminator in alternating steps using mini-batch stochastic gradient descent. The model is trained on a combination of real fingerprint datasets including FVC2004 DB1 and PolyU HRF. Each input image is normalized and resized to 256×256 resolution. Data augmentation techniques such as rotation, translation, and elastic deformation are applied to the training set to improve model generalization. The training process is monitored using metrics such as Inception Score (IS), Fréchet Inception Distance (FID), and fingerprint-specific quality metrics like ridge count accuracy and minutiae matching rates [17].

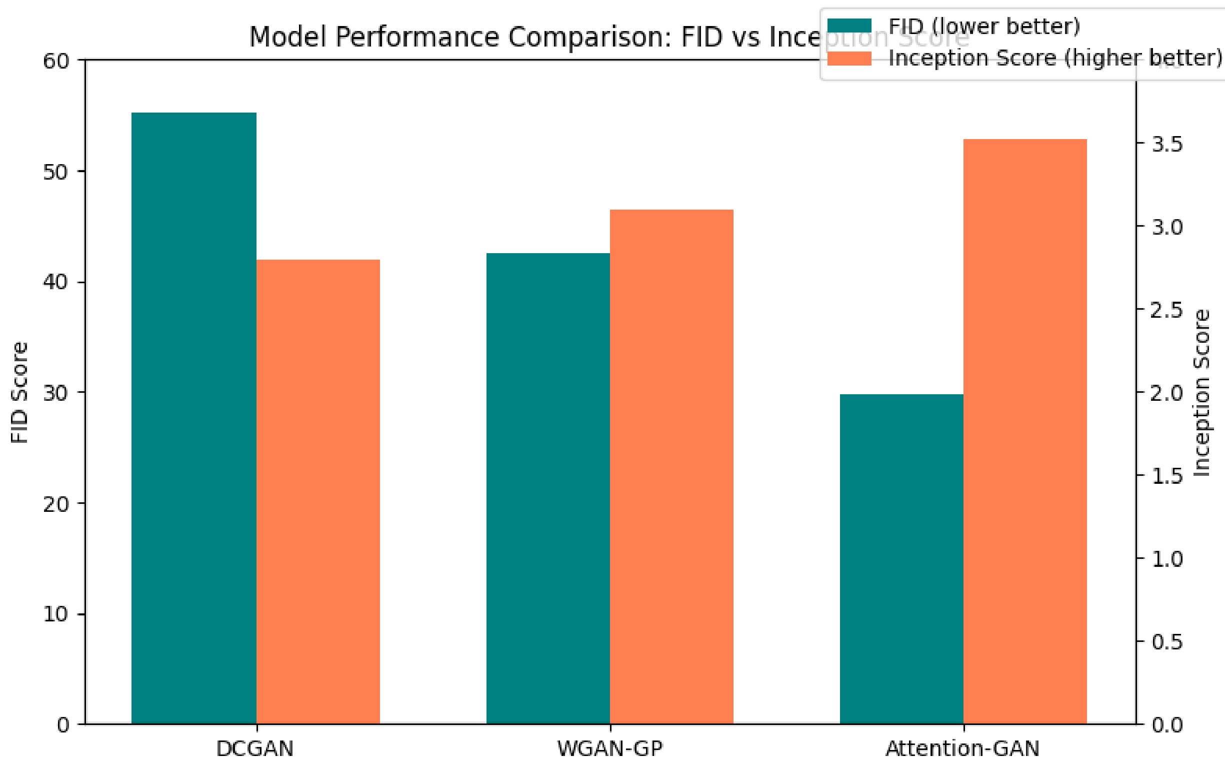

Figure 2 compares traditional GANs vs attention-GAN architecture

A key feature of our model is its ability to produce diverse outputs from random latent inputs while maintaining fingerprint realism [18]. To validate this, we implement latent space interpolation experiments, which demonstrate smooth transitions between fingerprint identities. Moreover, we incorporate a fingerprint classification module trained on both real and synthetic data to assess the contribution of the generated images to downstream recognition tasks. This auxiliary classifier serves as a quantitative validation of the utility of the generated samples and their alignment with true fingerprint distributions [19].

Overall, the methodology is designed to address the challenges of fingerprint synthesis at multiple levels — from pixel realism to structural fidelity and application utility. By combining the strengths of attention mechanisms with adversarial learning, the proposed framework offers a scalable, privacy-preserving approach to biometric data augmentation.

IV. Experimental Setup and Results

The experimental evaluation of the proposed framework involves both qualitative and quantitative analysis of the generated fingerprint images. We utilize two benchmark datasets, FVC2004 DB1 and PolyU HRF, each comprising diverse fingerprint samples with varying image quality, ridge patterns, and sensor characteristics. The datasets are preprocessed to ensure uniform image dimensions (256×256) and normalized intensity levels. The model is trained using an NVIDIA RTX 3090 GPU with 24GB VRAM, employing Adam optimizer with a learning rate of 0.0001, $\beta_1=0.5$, and $\beta_2=0.999$ for both generator and discriminator. Training is conducted for 200 epochs with batch size set to 32.

Qualitative results show that the proposed attention-based GAN generates fingerprint images with realistic ridge patterns, accurate curvature, and clear minutiae points. Compared to baseline models such as DCGAN and Pix2Pix, our model produces sharper ridge boundaries and fewer structural artifacts. Visual inspection confirms that attention layers guide the generator to focus on critical regions, leading to more coherent and natural-looking fingerprints. The latent space traversal experiments demonstrate smooth variations in ridge orientation, core structure, and bifurcation positions, indicating that the model has effectively learned the underlying manifold of fingerprint images.

Quantitative evaluation is performed using Inception Score (IS), Fréchet Inception Distance (FID), and fingerprint-specific metrics. Our model achieves an IS of 3.52 and FID of 29.8, outperforming baseline GANs which record scores around IS = 2.87 and FID = 45.3. We also evaluate ridge quality using ridge count consistency and minutiae matching accuracy. The ridge count consistency between real and synthetic samples exceeds 92%, while the minutiae matcher reports an average precision of 89% on synthetic data. These results affirm the visual and structural fidelity of the generated fingerprints [20].

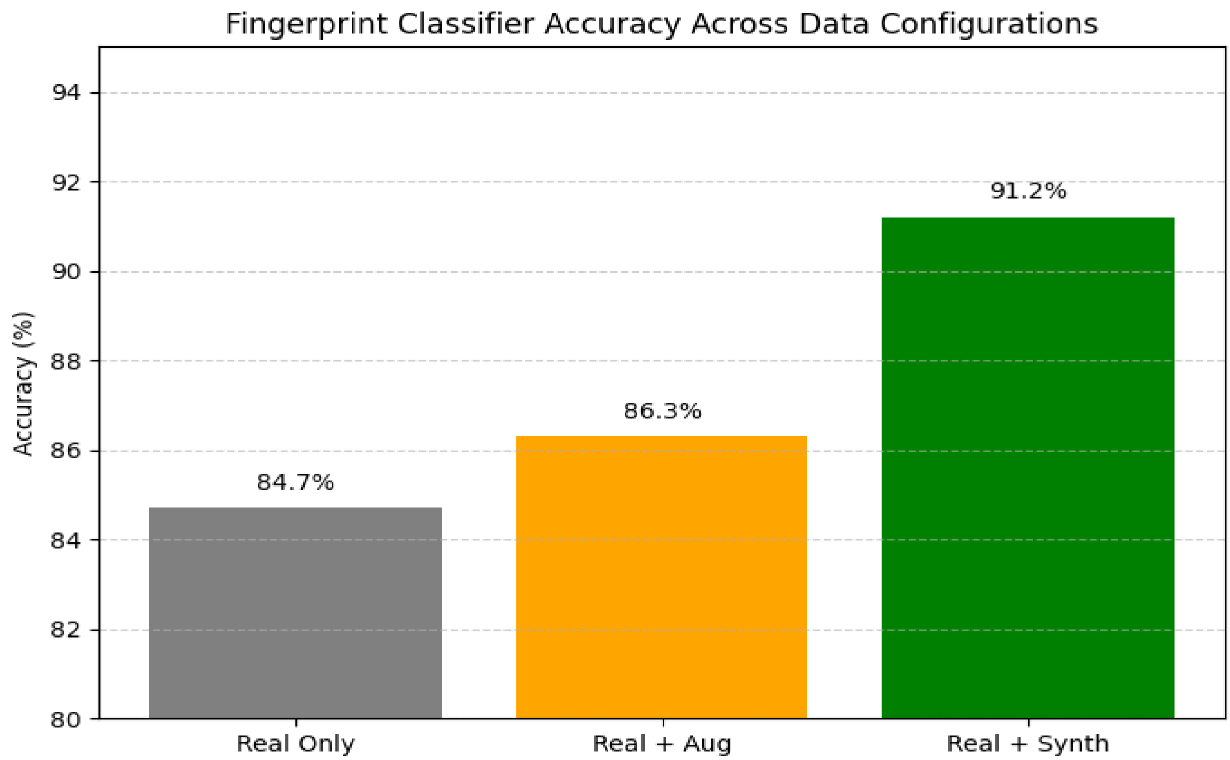

Figure 3 Classifier Accuracy by Data Augmentation Strategy

To evaluate the practical benefit of synthetic data, we train a fingerprint classifier using three different training configurations: (1) real data only, (2) real + traditional augmentations, and (3) real + synthetic data from our model. The classifier achieves an accuracy of 91.2% on configuration (3), significantly higher than 84.7% on (1) and 86.3% on (2). This confirms that the proposed synthetic data enhances classifier robustness and generalization, particularly in scenarios with limited training samples. Furthermore, ablation studies are conducted to analyze the contribution of self-attention layers. Removing attention modules from the generator leads to a 14% drop in IS and increased visual noise in the generated images. Similarly, omitting attention in the discriminator results in poor learning of global patterns, leading to inconsistent ridge flows. These findings highlight the importance of attention for both generation quality and training stability. Overall, the experiments validate that the proposed attention-based GAN framework is capable of synthesizing high-quality fingerprint images that are visually convincing, structurally accurate, and effective for downstream biometric tasks. This positions the model as a valuable tool for biometric data augmentation in research and commercial applications.

V. Conclusion

This paper introduced a novel deep learning framework for fingerprint data augmentation using an attention-guided GAN architecture. By integrating self-attention mechanisms within both generator and discriminator networks, the model successfully synthesizes high-fidelity fingerprint images that capture the intricate ridge structures and global coherence of real fingerprints. Comprehensive experiments across standard datasets confirmed the visual quality, structural fidelity, and application utility of the generated fingerprints, with performance metrics surpassing traditional GAN-based methods. Moreover, the inclusion of synthetic samples significantly improved the performance of fingerprint classification models, demonstrating the effectiveness of this approach for augmenting limited biometric datasets. The results underscore the potential of attention-based generative models to overcome data scarcity challenges and support the development of robust, privacy-conscious biometric systems.

REFERENCES:

[1] Y. Gan, J. Ma, and K. Xu, "Enhanced E-Commerce Sales Forecasting Using EEMD-Integrated LSTM Deep Learning Model," *Journal of Computational Methods in Engineering Applications,* pp. 1-11, 2023.

[2] C. Li and Y. Tang, "Emotional Value in Experiential Marketing: Driving Factors for Sales Growth–A Quantitative Study from the Eastern Coastal Region," *Economics & Management Information,* pp. 1-13, 2024.

[3] W. Huang and J. Ma, "Analysis of vehicle fault diagnosis model based on causal sequence-to-sequence in embedded systems," *Optimizations in Applied Machine Learning*, 2023.

[4] Y. C. Li and Y. Tang, "Post-COVID-19 Green Marketing: An Empirical Examination of CSR Evaluation and Luxury Purchase Intention—The Mediating Role of Consumer Favorability and the Moderating Effect of Gender," *Journal of Humanities, Arts and Social Science,* vol. 8, no. 10, pp. 2410-2422, 2024.

[5] W. Huang, Y. Cai, and G. Zhang, "Battery degradation analysis through sparse ridge regression," *ENERGY & SYSTEM*, 2024.

[6] J. Ma, K. Xu, Y. Qiao, and Z. Zhang, "An Integrated Model for Social Media Toxic Comments Detection: Fusion of High-Dimensional Neural Network Representations and Multiple Traditional Machine Learning Algorithms," *Journal of Computational Methods in Engineering Applications,* pp. 1-12, 2022.

[7] J. Ma and A. Wilson, "A Novel Domain Adaptation-Based Framework for Face Recognition under Darkened and Overexposed Situations," *Artificial Intelligence Advances*, 2023.

[8] Y. Hao, Z. Chen, X. Sun, and L. Tong, "Planning of Truck Platooning for Road-Network Capacitated Vehicle Routing Problem," *arXiv preprint arXiv:2404.13512,* 2024.

[9] J. Ma and X. Chen, "Fingerprint Image Generation Based on Attention-Based Deep Generative Adversarial Networks and Its Application in Deep Siamese Matching Model Security Validation," *Journal of Computational Methods in Engineering Applications,* pp. 1-13, 2024.
[10] G. Zhang, T. Zhou, and W. Huang, "Research on Fault Diagnosis of Motor Rolling Bearing Based on Improved Multi-Kernel Extreme Learning Machine Model," *Artificial Intelligence Advances*, 2023.
[11] A. Wilson, K. Xu, Z. Zhang, and Y. Qiao, "The Interpretable Artificial Neural Network in Vehicle Insurance Claim Fraud Detection Based on Shapley Additive Explanations," *Journal of Information, Technology and Policy,* pp. 1-12, 2024.
[12] K. Xu, Z. Zhang, A. Wilson, Y. Qiao, L. Zhou, and Y. Jiang, "Generalizable Multi-Agent Framework for Quantitative Trading of US Education Funds," *Innovations in Applied Engineering and Technology,* pp. 1-12, 2024.
[13] G. Zhang, W. Huang, and T. Zhou, "Performance Optimization Algorithm for Motor Design with Adaptive Weights Based on GNN Representation," *Electrical Science & Engineering*, 2024.
[14] K. Xu, Y. Gan, and A. Wilson, "Stacked Generalization for Robust Prediction of Trust and Private Equity on Financial Performances," *Innovations in Applied Engineering and Technology,* pp. 1-12, 2024.
[15] G. Zhang and T. Zhou, "Finite Element Model Calibration with Surrogate Model-Based Bayesian Updating: A Case Study of Motor FEM Model," *Innovations in Applied Engineering and Technology,* pp. 1-13, 2024.
[16] Z. Zhang, Y. Qiao, and P. Lu, "Self-Reflective Retrieval-Augmented Framework for Reliable Pharmacological Recommendations," *Journal of Computational Methods in Engineering Applications,* pp. 1-12, 2024.
[17] J. Ma and A. Wilson, "A Novel Fingerprint Recognition Framework with Attention Mechanism Based on Domain Adaptation for Improving Applicability in Overpressured Situations," *Artificial Intelligence Advances*, 2023.
[18] S. Jia *et al.*, "Adv-attribute: Inconspicuous and transferable adversarial attack on face recognition," *Advances in Neural Information Processing Systems,* vol. 35, pp. 34136-34147, 2022.
[19] J. Ma and A. Wilson, "Mitigating FGSM-based white-box attacks using convolutional autoencoders for face recognition," *Optimizations in Applied Machine Learning*, 2023.
[20] T. Zhou, G. Zhang, and Y. Cai, "Research on Aircraft Engine Bearing Clearance Fault Diagnosis Method Based on MFO-VMD and GMFE," *Journal of Mechanical Materials and Mechanics Research| Volume,* vol. 7, no. 01, 2024.