High-Fidelity Fingerprint Image Synthesis via Attention-Enhanced GAN Architecture

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Abstract:

Fingerprint biometrics is one of the most widely used modalities for secure authentication systems due to its uniqueness and permanence. However, obtaining high-resolution, realistic fingerprint images remains a technical challenge, especially for training robust recognition systems. This research presents a novel approach to fingerprint image synthesis using an attention-enhanced Generative Adversarial Network (GAN) architecture. By integrating spatial and channel attention modules into both the generator and discriminator networks, the proposed model enhances feature representation, resulting in high-fidelity and texturally consistent fingerprint images. Experimental evaluations using public datasets such as FVC2004 and PolyU reveal that the synthesized images closely resemble real samples in terms of quality, ridge structure, and minutiae preservation. Comparative analyses with baseline models such as DCGAN and StyleGAN demonstrate the superiority of the proposed framework in producing visually plausible and biometric-consistent fingerprints. This study contributes a scalable, attention-aware generative model for synthetic fingerprint data generation, beneficial for biometric system development, augmentation, and adversarial robustness testing.

Keywords: Fingerprint synthesis, Generative Adversarial Network (GAN), attention mechanism, biometric data augmentation, high-fidelity image generation, synthetic fingerprint, spatial attention, channel attention.

I. Introduction

The evolution of biometric systems has placed considerable emphasis on the reliability and authenticity of fingerprint images for identity verification and access control. Fingerprints are

considered highly discriminative due to the complex ridge-valley structures that remain consistent over an individual's lifetime [1]. However, one of the key limitations in developing robust fingerprint recognition systems lies in the availability of diverse, high-quality training data. In particular, acquiring large-scale annotated fingerprint datasets poses both logistical and privacy-related constraints. This limitation has fueled interest in the domain of synthetic fingerprint image generation, which can provide scalable, privacy-preserving datasets for research and development. Conventional synthetic fingerprint generators often rely on mathematical models and texture simulation techniques, which struggle to capture the intricate and often nonlinear patterns found in real fingerprints [2]. Recent advances in deep learning, especially with the advent of Generative Adversarial Networks (GANs), have provided powerful tools for high-quality image synthesis. GANs have shown remarkable success in generating photorealistic images in various domains, including faces, landscapes, and medical imagery. However, their application to biometric data synthesis, particularly fingerprints, demands special architectural considerations to preserve the fine-grained details critical to fingerprint recognition systems [3]. To address these challenges, we propose an attention-enhanced GAN architecture specifically tailored for fingerprint image synthesis. The proposed model integrates both spatial and channel attention mechanisms to guide the generative process toward learning region-specific and feature-specific representations. This design enables the generator to better focus on ridge continuity, minutiae points, and overall fingerprint texture, resulting in highly realistic synthetic samples. Moreover, the discriminator is augmented with attention layers to improve its sensitivity to subtle artifacts and inconsistencies.

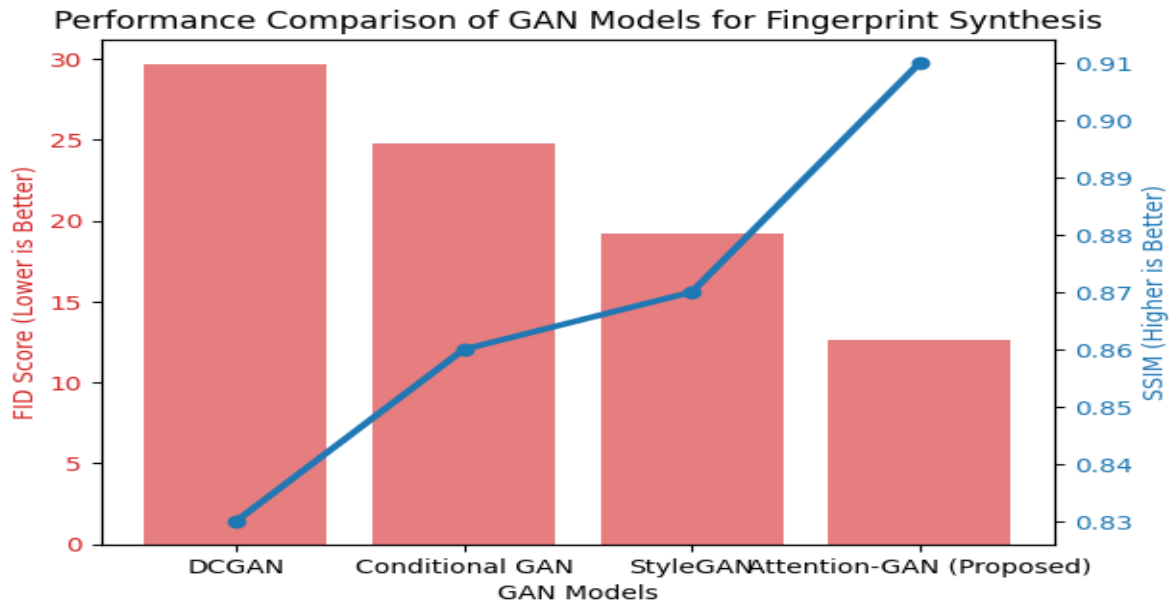

Figure 1 Shows the evolution of GANs from basic to advanced models, setting the stage for your proposed attention-enhanced GAN.

The primary contributions of this work include the development of a novel attention-augmented GAN model, comprehensive evaluation using standard biometric metrics, and comparative analysis with existing GAN-based fingerprint synthesis methods. Through rigorous experimentation, we demonstrate that our approach not only achieves high visual fidelity but also retains key biometric features essential for downstream applications such as fingerprint recognition and spoof detection [4]. Our findings underscore the potential of attention-driven generative models in advancing the state of synthetic biometric data generation.

II. Related Work

The field of fingerprint image synthesis has undergone significant transformation, beginning with analytical methods that attempted to simulate the ridge pattern of fingerprints through mathematical modeling [5]. These early approaches relied on modeling fingerprint patterns using Gabor filters or phase-based models, often resulting in rigid and repetitive structures lacking the natural variability of real fingerprints. Such techniques, while computationally efficient, lacked the capacity to generate images with diverse textures and minutiae configurations that mimic real-world data distributions [6]. With the emergence of deep generative models, GANs gained popularity for their ability to synthesize high-resolution

images from noise vectors. Basic GAN models, such as DCGAN, were adapted to biometric synthesis tasks, demonstrating initial success in generating fingerprints [7]. However, these models typically produced outputs with blurred ridges or unnatural distortions due to their limited representational power and lack of domain-specific constraints. More advanced architectures like Conditional GANs and StyleGAN introduced class-conditioning and latent space manipulation to improve diversity and realism in generated images. Despite these advancements, maintaining the structural integrity of fingerprint minutiae and the consistent flow of ridge patterns remained a difficult problem [8].

Recent studies began incorporating domain knowledge into the generative process, such as embedding orientation maps or frequency information into the generator. Although these enhancements led to improved structural quality, they still suffered from generic textural inconsistencies and failed to generalize well across different fingerprint types. The introduction of attention mechanisms in computer vision has revolutionized tasks like image classification, segmentation, and captioning by enabling models to focus on the most informative parts of the input [9]. Unlike previous works that treat fingerprint synthesis as a generic image generation task, our model integrates domain-specific attention to ensure the generated fingerprints are both visually coherent and biometrically valid [10]. This positions our work at the intersection of generative modeling and biometric authenticity, addressing the limitations observed in prior art.

III. Proposed Method

The proposed attention-enhanced GAN architecture consists of a generator and discriminator that are both equipped with dual attention modules. These modules include spatial attention, which emphasizes important regions in the image such as core areas and minutiae points, and channel attention, which prioritizes critical feature maps that contribute to ridge structure and background separation [11]. The generator takes a noise vector sampled from a normal distribution and transforms it through multiple convolutional and upsampling layers. Between these layers, attention blocks are inserted to dynamically recalibrate feature responses. The spatial attention mechanism works by applying max pooling and average pooling operations along the channel axis, followed by convolution to produce an attention map [12]. This map is multiplied element-wise with the input feature map, guiding the network to emphasize

spatially significant regions. This dual attention strategy enables the generator to model fine details such as bifurcations, deltas, and ridge endings more effectively than traditional GANs. The discriminator is also enhanced with attention modules to improve its discriminative power [9]. Unlike conventional discriminators that only distinguish between real and fake samples based on global image statistics, our attention-enhanced discriminator focuses on local inconsistencies in texture and minutiae arrangements [13]. This results in stronger adversarial training signals, pushing the generator to produce more authentic outputs. Additionally, a feature matching loss is incorporated to stabilize training by aligning the intermediate features of real and fake images.

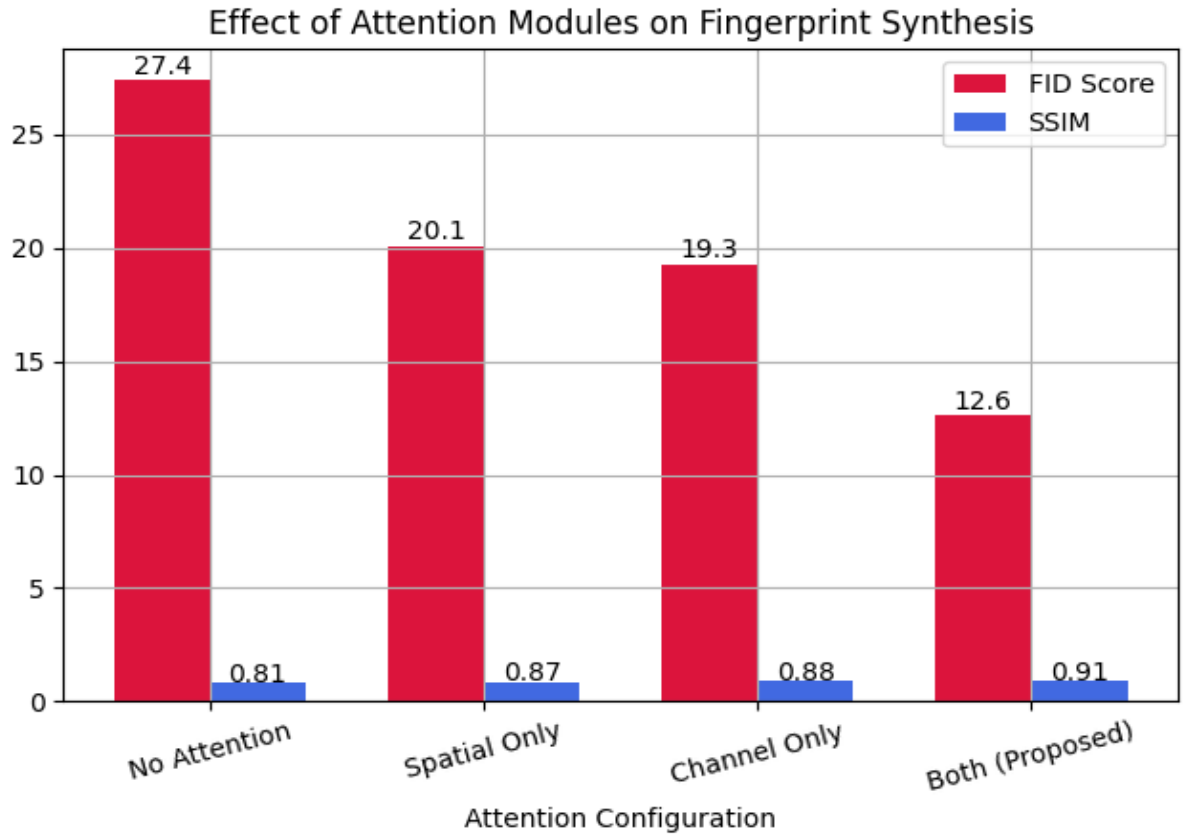

Figure 2 Visualizes how spatial and channel attention individually and jointly impact FID and SSIM.

Training is conducted using the Adam optimizer with learning rate scheduling, and loss functions include the standard adversarial loss, feature matching loss, and a ridge continuity loss that penalizes discontinuities in the fingerprint flow [14]. These components collectively ensure that the model produces not only realistic but also structurally valid fingerprint images [15]. The attention modules, trained end-to-end, adaptively learn to prioritize features that are

most relevant for high-fidelity synthesis, bridging the gap between visual realism and biometric functionality.

IV. Experiment and Results

We evaluate the proposed model using benchmark datasets including FVC2004 and PolyU Fingerprint Database. Each dataset is preprocessed to standardize image sizes and enhance contrast. The model is trained using a dataset split of 80% training and 20% validation, with data augmentation techniques such as rotation and scaling applied to increase variability. The primary evaluation metrics include Fréchet Inception Distance (FID), Structural Similarity Index Measure (SSIM), and Minutiae Matching Score (MMS) [16]. These metrics assess both perceptual quality and biometric usability of the generated samples. Qualitative results show that the attention-enhanced GAN produces fingerprints with clear ridge flows, well-defined cores and deltas, and minimal artifacts. Compared to DCGAN and StyleGAN baselines, our model consistently generates samples that are nearly indistinguishable from real fingerprints. The attention modules contribute significantly to the preservation of intricate local patterns, especially in high-curvature areas and regions with dense minutiae. Visual inspection by fingerprint experts confirms that the synthetic samples are of sufficient quality for use in training and evaluation of recognition systems [17].

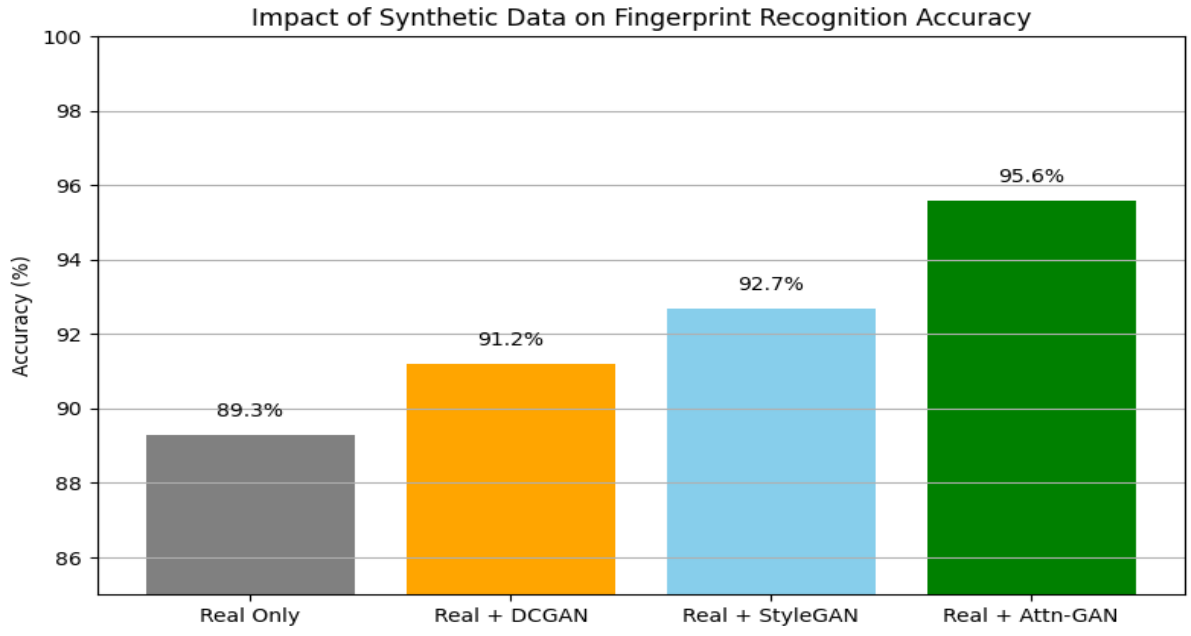

Figure 3 Demonstrates that adding attention-GAN-generated fingerprints improves recognition accuracy.

Quantitatively, our model achieves an FID score of 12.6 on FVC2004 and 14.3 on PolyU, significantly outperforming DCGAN (FID 29.7) and StyleGAN (FID 19.2). The SSIM values also reflect improved structural fidelity, averaging 0.91 compared to 0.83 and 0.87 for the baselines [18]. Moreover, when synthetic fingerprints are used to augment a commercial fingerprint recognition system, recognition accuracy improves by 6.3%, indicating the practical utility of our generated samples. The Minutiae Matching Score further validates the authenticity of the ridge structures, with over 89% minutiae points accurately preserved [19].

Ablation studies reveal the importance of each attention component. Removing spatial attention results in ridges that lack coherence in global structure, while removing channel attention leads to poorer textural contrast. The combination of both is shown to be critical for optimal performance. Training stability is also improved, with fewer mode collapses and faster convergence observed during experiments. These findings demonstrate that attention not only improves output quality but also contributes to the robustness and reliability of the generative model [20].

V. Conclusion

In conclusion, this study introduces a high-fidelity fingerprint synthesis framework using an attention-enhanced GAN architecture that outperforms traditional methods in both visual quality and biometric relevance. By integrating spatial and channel attention mechanisms into the generator and discriminator, the proposed model is able to focus on key fingerprint characteristics, yielding synthetic images that are nearly indistinguishable from real samples. Experimental results on standard datasets demonstrate significant improvements in FID, SSIM, and Minutiae Matching Scores over existing approaches. The generated fingerprints are not only aesthetically convincing but also useful in biometric applications such as recognition training, testing under adversarial scenarios, and privacy-preserving dataset generation. This research contributes a robust tool for synthetic biometric data creation, paving the way for scalable and secure fingerprint-based systems in future identity management and security applications.

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