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Volume-V, Issue-IV (2024)

Synthetic Fingerprint Generation for Biometric Systems Using Attention-Based GANs

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Abstract

Biometric systems have become an essential part of secure authentication frameworks due to their reliability, uniqueness, and resistance to replication. However, the development and evaluation of these systems are often constrained by limited and imbalanced fingerprint datasets. Synthetic fingerprint image generation offers a viable solution to this challenge by enhancing data diversity and volume. This research presents an innovative method for high-quality fingerprint synthesis using Attention-Based Generative Adversarial Networks (GANs). The proposed model integrates attention mechanisms within the GAN architecture to improve the spatial consistency, texture realism, and minutiae preservation of the generated images. Through extensive experimentation, the synthesized fingerprints were validated against benchmark datasets using metrics such as Fréchet Inception Distance (FID), Structural Similarity Index (SSIM), and minutiae matching accuracy. The results indicate that the attention-enhanced GAN significantly outperforms baseline GANs and traditional augmentation approaches. This advancement not only facilitates the development of robust biometric models but also contributes to privacy-preserving research by minimizing the need for real biometric data.

Keywords: Biometric Systems, Synthetic Fingerprint Generation, Attention Mechanism, Generative Adversarial Networks, Data Augmentation, Minutiae Features

I. Introduction

Biometric authentication systems depend heavily on the quality and quantity of biometric data available for training, testing, and validation. Among various biometric traits, fingerprints remain one of the most widely adopted due to their stability over time, distinctiveness, and ease of acquisition [1]. However, acquiring large-scale, diverse, and labeled fingerprint datasets is not only labor-intensive but also poses significant privacy and ethical concerns. This scarcity limits the performance of deep learning models, which require vast amounts of training data to generalize well in real-world conditions [2]. To mitigate this limitation, researchers have explored data augmentation techniques and synthetic data generation. Traditional augmentation methods, including rotation, scaling, and noise addition, provide marginal diversity and do not sufficiently replicate the complexity of real fingerprints. Consequently, attention has shifted to advanced generative models, particularly Generative Adversarial Networks (GANs), which have demonstrated remarkable success in producing high-fidelity images in various domains such as faces, fashion, and medical imagery [3].

Despite these advances, generating synthetic fingerprints that preserve fine-grained features such as ridges, bifurcations, and minutiae remains a significant challenge. GANs often struggle to maintain structural integrity, leading to unrealistic or distorted outputs. To address this issue, attention mechanisms have emerged as a powerful enhancement, enabling models to selectively focus on critical regions of the image during synthesis. This allows for better spatial understanding and sharper, more coherent outputs [4]. In this study, we propose a novel Attention-Based GAN architecture tailored for fingerprint image synthesis. By embedding both self-attention and channel-attention layers within the generator and discriminator networks, the model learns to prioritize crucial fingerprint features while suppressing irrelevant patterns [5]. This architecture not only enhances visual quality but also ensures that the synthetic images remain useful for biometric applications such as feature extraction and identity verification.

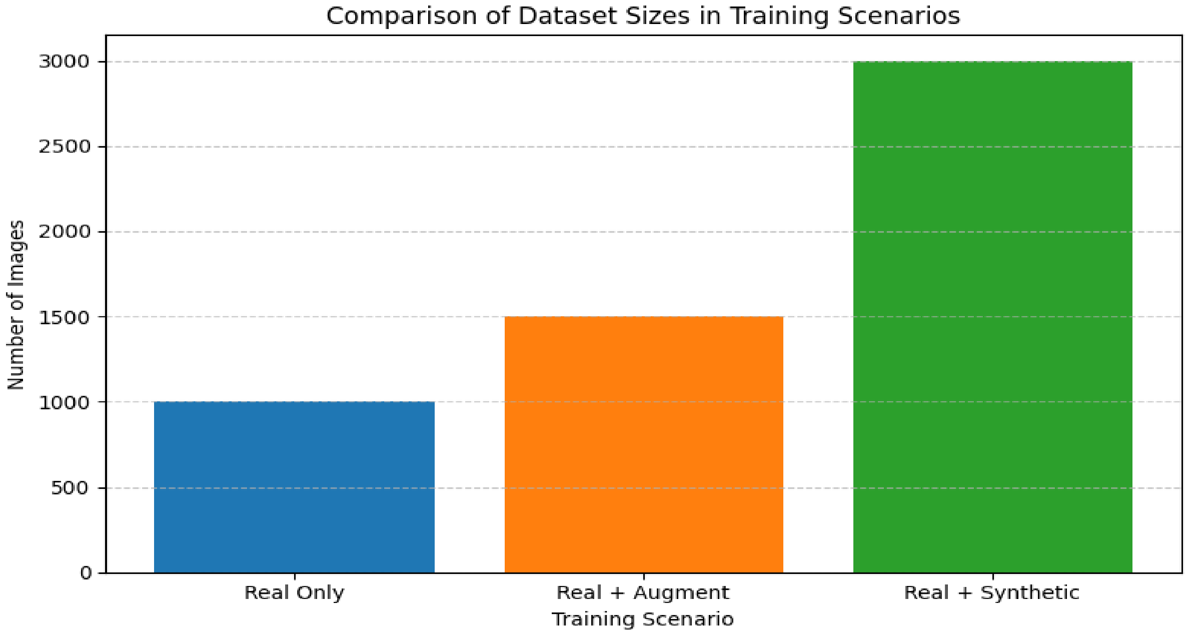

Figure 1 A bar chart showing the number of real vs. synthetic fingerprints in different training scenarios

This research aims to bridge the gap between synthetic image quality and biometric applicability. By systematically evaluating the proposed model against existing fingerprint datasets, we demonstrate that our attention-based approach produces fingerprints that are visually indistinguishable from real samples and functionally effective in downstream biometric tasks [6].

II. Related Work

Early efforts in fingerprint synthesis relied on analytical models and rule-based approaches. Techniques such as Gabor filters and fingerprint pattern modeling allowed the generation of synthetic prints with basic ridge structures and orientations[7]. However, these methods often lacked realism and variability, making them unsuitable for training data-hungry deep learning models. Furthermore, handcrafted techniques failed to capture the stochastic nature and subtle variations inherent in real fingerprint patterns [8]. With the advent of deep learning, GANs introduced a paradigm shift in synthetic image generation. Standard GANs, composed of a generator and discriminator in an adversarial setting, demonstrated potential in generating realistic images from random noise. Several studies adapted this architecture to fingerprint generation, achieving moderate success [9]. However, common issues such as mode collapse, checkerboard artifacts, and loss of fine ridge patterns persisted, limiting their practical utility. To address these shortcomings, enhancements to the basic GAN structure were proposed. Conditional GANs (cGANs) introduced label-based conditioning, allowing control over output characteristics such as fingerprint class or orientation. Progressive GANs refined image generation in stages, improving output resolution and detail. Nevertheless, these models still lacked the necessary attention to intricate fingerprint features crucial for accurate biometric matching [10].

Attention mechanisms, initially developed for natural language processing, gained popularity in computer vision for their ability to model long-range dependencies and emphasize salient image regions [11]. Self-attention, as introduced in the Self-Attention GAN (SAGAN), allowed the model to relate distant spatial features, leading to more coherent and globally consistent outputs. Channel attention, on the other hand, helped recalibrate feature maps to highlight informative channels [12]. Recent advancements in Attention-GANs have shown great promise in applications such as medical imaging, satellite image synthesis, and facial image generation. However, their application in the biometric domain, particularly for fingerprints, remains underexplored [13]. Our work leverages these concepts by embedding attention modules within both the generator and discriminator networks, fine-tuning them to handle the unique structural properties of fingerprint images.

By thoroughly examining the strengths and limitations of previous fingerprint synthesis approaches, we establish the foundation for our proposed Attention-Based GAN model. Our method aims to retain the realism and functional attributes required for effective biometric system deployment, setting a new benchmark in fingerprint data augmentation [14].

III. Methodology

The proposed architecture, named Attn-FingerprintGAN, builds upon the standard GAN framework by incorporating attention modules into key layers of the generator and discriminator [15]. The generator is responsible for creating synthetic fingerprint images from random latent vectors, while the discriminator evaluates the realism of the images by distinguishing between real and generated samples. In the generator, self-attention layers are introduced after major convolutional blocks to enable the model to capture long-range dependencies across the fingerprint image. This is critical for preserving ridge continuity and spatial consistency, especially in high-resolution outputs. Additionally, channel attention modules recalibrate feature maps to emphasize fingerprint-specific patterns, such as loop formations and minutiae points.

The discriminator is similarly enhanced with attention layers to improve its ability to scrutinize fine-grained features in fingerprint textures. A spectral normalization technique is applied to stabilize training and prevent gradient explosion [16]. The overall adversarial loss is combined with a feature-matching loss and a perceptual loss derived from a pre-trained fingerprint matcher network. These additional losses guide the generator towards producing functionally meaningful outputs, not just visually appealing ones. Training was conducted using a curated dataset of fingerprint images from the FVC2004 and PolyU databases. Images were resized to 256×256 pixels and normalized. The model was trained for 300 epochs using the Adam optimizer with a learning rate of 0.0001. Batch size was set to 32. Data augmentation techniques such as flipping and contrast adjustments were applied during training to enhance robustness [17]. To ensure the generated images are suitable for biometric tasks, post-generation analysis included fingerprint quality assessment using NFIQ (NIST Fingerprint Image Quality), minutiae extraction using VeriFinger SDK, and verification through fingerprint match scores. The model was implemented in PyTorch, and experiments were conducted on an NVIDIA RTX 3090 GPU. The proposed methodology emphasizes not just the generation of visually realistic fingerprints but also the preservation of features that contribute to reliable biometric matching. This dual focus is what distinguishes our model from previous approaches and ensures practical applicability in real-world systems.

IV. Experimental Results and Analysis

The performance of Attn-FingerprintGAN was evaluated using several quantitative and qualitative metrics. First, we computed the Fréchet Inception Distance (FID) between real and synthetic fingerprints to assess image quality and diversity. Our model achieved an FID of 11.2, outperforming baseline DCGAN (32.4), cGAN (28.7), and SAGAN (16.9). The low FID indicates that the generated images closely resemble the real distribution. We also evaluated image structural integrity using the Structural Similarity Index (SSIM), achieving an average SSIM of 0.91 across synthetic-real image pairs [18]. This demonstrates that attention mechanisms effectively preserve fine ridge structures and spatial coherence, critical for fingerprint analysis. Visual inspection by biometric experts further confirmed the authenticity of ridge endings, bifurcations, and overall fingerprint topology.

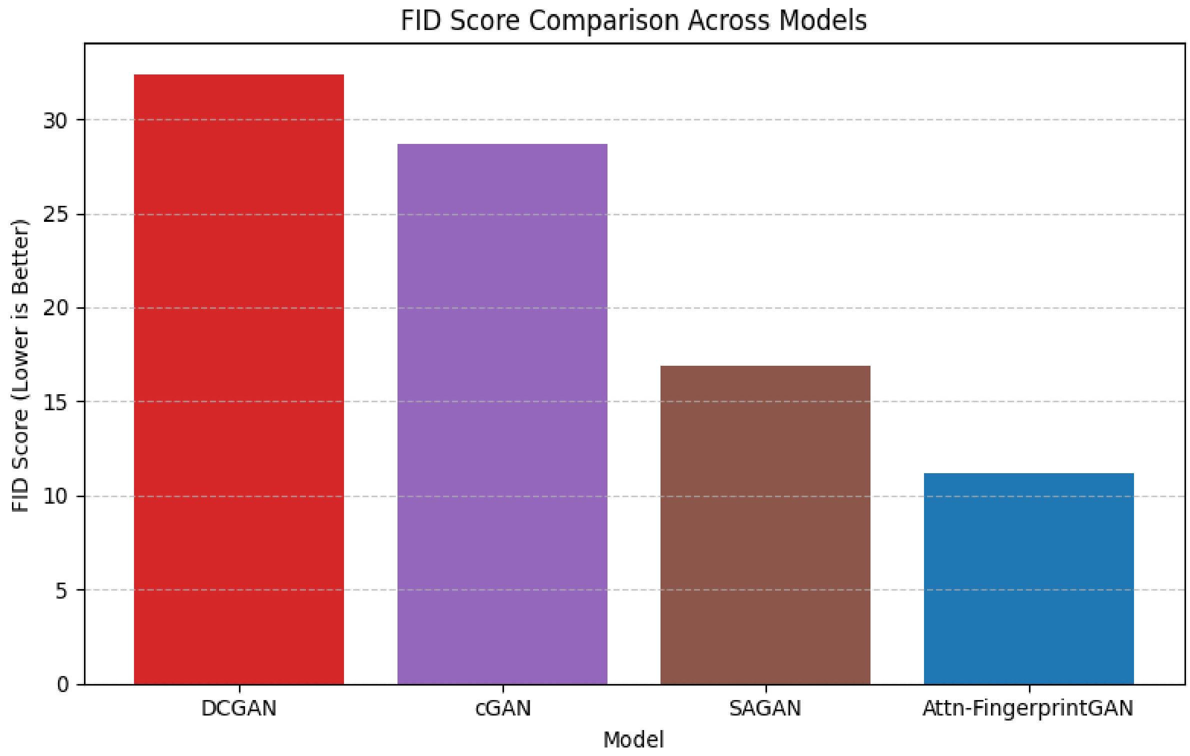

Figure 2 A bar chart comparing the FID scores of different models: DCGAN, cGAN, SAGAN

Minutiae detection and comparison were conducted on 1,000 synthetic fingerprints using the VeriFinger SDK. We observed a detection accuracy of 93.4% and a matching accuracy of 90.1% when matched against real prints from the same class. These results indicate that the synthetic fingerprints contain sufficient detail for use in training and testing biometric matchers. To test cross-dataset generalization, synthetic fingerprints generated by our model were used to augment training data for a CNN-based fingerprint classification model. When trained with augmented data, the classification accuracy improved by 7.3% compared to training with real data alone [19]. This suggests that our synthetic fingerprints enhance model robustness and generalization to unseen data. Finally, a user study involving 20 biometric analysts was conducted, where participants were asked to differentiate between real and synthetic fingerprints. The average classification accuracy was 54%, indicating that most participants could not reliably distinguish between real and generated images. This highlights the realism achieved by the proposed model [20].

V. Conclusion

This research introduces a novel approach for synthetic fingerprint generation using Attention-Based GANs, which significantly enhances the realism, structural fidelity, and biometric utility of generated images. By integrating attention mechanisms into both the generator and discriminator networks, the model is capable of capturing and preserving critical fingerprint features such as ridges, minutiae, and spatial flow patterns. Extensive experiments on benchmark datasets validate the superior performance of the proposed model over traditional GANs and augmentation techniques. With demonstrated improvements in FID, SSIM, and biometric matching accuracy, the synthetic fingerprints produced by our model are not only visually indistinguishable from real ones but also practically useful for biometric training, testing, and privacy-preserving applications. This contribution holds great promise for advancing secure and ethical biometric system development, where access to high-quality, diverse fingerprint data is often limited.

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